Marine Pollution Bulletin 60 (2010) 2289–2296

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Chemical contamination assessment of the Hudson–Raritan Estuary as a result of the attacks on the World Trade Center: Analysis of trace elements

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ARTICLE INFO

Keywords:
Trace elements
World Trade Center
Mussel Watch Program
Monitoring
Mussels
Hudson–Raritan Estuary

ABSTRACT

The attack on the World Trade Center (WTC) resulted in the destruction of buildings, and the release of tons of dust and debris into the environment. As part of the effort to characterize the environmental impact of the WTC collapse, Mussel Watch Program trace element measurements from the Hudson–Raritan Estuary (HRE) were assessed for the years before (1986–2001) and after (2001–2005) the attack. Trace element measurements in the HRE were significantly higher than Mussel Watch measurements taken elsewhere in the Nation. Post-attack trace element measurements were not significantly different from pre-attack measurements. The impacts of WTC collapse may have been obscured by high ambient levels of trace elements in the HRE.

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1. Introduction

The attack on the World Trade Center (WTC) destroyed several buildings and significantly damaged others, resulting in thousands of tons of particulate matter and debris being released to surrounding environments: including cement, dust, fiberglass, asbestos and smoke. The combustion of building materials (furniture, office equipment, and plastics) released a myriad of toxic chemicals that continued to burn and smolder for months (Lioy et al., 2002; Clark et al., 2001; McGee et al., 2003).

The smoke and ash from the destruction and burning of the WTC were quantified in assessments (Lioy et al., 2002; McGee et al., 2003). Some assessments determined occupational health threats associated with the release of WTC material to the surrounding environment (Landrigan et al., 2004). According to the US EPA, trace elements in air that were at detectable levels after the attack were not above the regulatory standards (US EPA, 2002). In addition, Nordgren et al. (2002) speculated that post-attack fires vaporized trace elements and thereby reduced runoff to the surrounding estuary. Levels of many toxic trace elements in the atmosphere near the WTC spiked in late September and early October (Lioy et al., 2002), but quickly returned to their normal levels by late October (Service, 2003).

A distinct depositional layer, derived from WTC material dispersed throughout the surrounding environment, was found in sediment samples taken within weeks of the attacks on the WTC (Oktay et al., 2003). Studies identified the threat and constitution of WTC releases. The question we address is, whether WTC attack derived material significantly elevated ambient levels of trace elements found in the Hudson–Raritan Estuary (HRE).

The 21-year record of Mussel Watch monitoring data in the Hudson–Raritan Estuary offers a unique opportunity for comparing before and after measurements to assess environmental contamination resulting from the attack on the WTC. We present here a thorough characterization of trace element concentrations before and after the attack, and assess ambient levels of contamination in the HRE. This study of trace elements is the second part of the Mussel Watch Program assessment of the WTC collapse; part 1 addressed organic contaminants (Lauenstein and Kimbrough, 2007).

2. Methods

2.1. Site selection

The WTC was located on the banks of the upper Hudson–Raritan Estuary (HRE), in the Manhattan section of the New York City. The Hudson and Newark Rivers drain major urban areas and are responsible for the majority of the freshwater inputs to the estuary. The historic Fort Wadsworth divides the estuary into upper and lower bays. Significant amounts of water also come from storm water and waste water treatment facilities. The Hudson–Raritan drainage basin is one of the most urbanized and industrialized areas in the nation; as a result, it is also one of the most polluted estuaries (Kimbrough et al., 2008).

Five long-term monitoring sites, collected from 1986 to 2005, were used to provide pre- and post-attack measurements. Four sites are located in the lower bay; one site is located in the upper

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0025-326X/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.marpolbul.2010.07.009

bay (Table 1; Fig. 1). The attack occurred in the upper bay, where only one long-term monitoring site exists, Liberty Island (HRUB). To increase spatial coverage in the upper bay, five additional WTC sites were collected in 2001 and 2003 (Table 1; Fig. 1).

2.2. Sample collection

The Mussel Watch Program measures contaminants in blue mussels, oysters and zebra mussels to gain a national perspective. Only the blue mussels (*Mytilus edulis*) are collected in the HRE; hence, they are compared nationally to contaminant concentrations in other mussels (*Mytilus* spp.). Currently, specimen sampling occurs biennially, half of the sites are collected every year in the winter months at approximately the same date to achieve consistency and reduce variability. The mussels are collected by hand or dredged from intertidal to shallow subtidal zones, brushed clean, packed in iced containers and shipped to analytical laboratories within two days of collection. For detailed sample collection methodology see McDonald et al. (2006); Lauenstein et al. (1997) and Lauenstein and Cantillo (1993a,b,c,d, 1998). The Mussel Watch Program samples resident populations of bivalves, as a result, measurements are missing for some years when mussels could not be found at a specific site. For example in 2001, blue mussels were not found at the Raritan Bay, NY (Staten Island) site, but, they existed there during previous years.

2.3. Analytical methods

Samples were analyzed for the trace elements Ag, As, Cd, Cr, Cu, Hg, Pb, Ni, Se, Sn and Zn (Table 2). Sample preparation, extraction

Table 1
Locations of the long-term monitoring and recent WTC sites that were monitored by the Mussel Watch Program within the Hudson–Raritan Estuary (HRE). Four long-term monitoring sites are located in the lower bay (L). Only one long-term site is located in the upper bay (U), where the attacks took place. The additional five recent sites were added to provide increased spatial resolution in the upper bay for a more complete assessment. Mussels (M) and/or sediments (S) were measured at each site.

Site location	Site code	Bay location	2002	2004	Latitude	Longitude
Long-term monitoring sites						
Jamaica Bay, NY	HRJB	L	M,S	M	40.5705	−73.8780
Upper Bay, NY (Liberty Is.)	HRUB	U	M,S	M	40.6791	−74.0477
Lower Bay, NY (Swinburne Is.)	HRLB	L	M,S	M	40.5664	−74.0508
Raritan Bay, NY (Staten Is.)	HRRB	L	M,S	M	40.5008	−74.1622
Sandy Hook, NJ	NYSH	L	M,S	M	40.4947	−74.0478
Recent WTC monitoring sites						
HRE World Trade Center	HRWT	U	S		40.7127	−74.0170
HRE Battery Park, NY	HRBP	U	M	M	40.7045	−74.0183
HRE Governors Island, NY	HRGI	U		M	40.6933	−74.0190
HRE Ellis Island, NY	HREI	U	M,S		40.6993	−74.0426
HRE Shore Road, NY	HRSR	U	M	M	40.6081	−74.0348
HRE Fort Wadsworth, NY	HRFW	U	M	M	40.6150	−74.0614

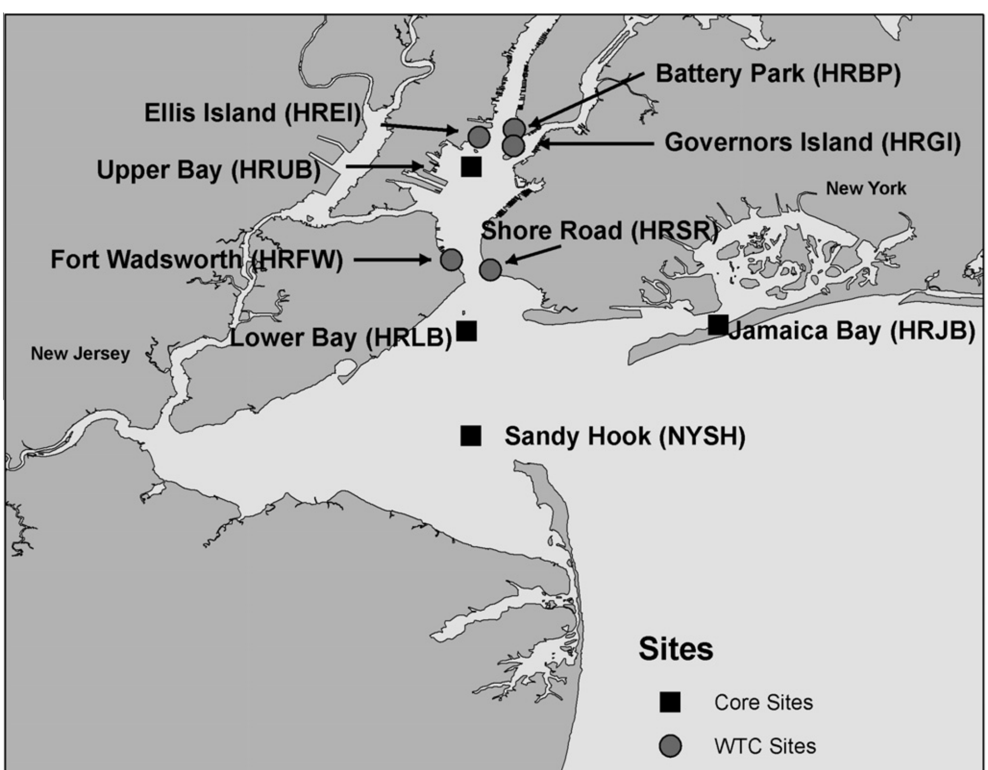

Fig. 1. The five long-term monitoring sites of the Mussel Watch Program are denoted by a white box. These long-term monitoring sites have been observed since 1986. Seven recent WTC sites (first sampled in 2001), denoted by black circles, were used to increase spatial resolution in the upper bay near the site of the WTC.

Table 2
Trace elements measured in blue mussels and sediments from the Hudson–Raritan Estuary.

Analyte	Symbol
Arsenic	As
Cadmium	Cd
Chromium	Cr
Copper	Cu
Lead	Pb
Nickel	Ni
Mercury	Hg
Selenium	Se
Silver	Ag
Tin	Sn
Zinc	Zn

Table 3
Results from the Wilcoxon statistical test that was used to compare national (*Mytilus* spp. only) and HRE median measurements from 1986 to 2005. Significance was set at the $p < 0.05$ level. Cadmium was the only trace element that did not have a significant difference between measurements. All trace elements were significantly higher in the HRE except for arsenic, which was significantly lower.

Analyte name	National median	HRE median	χ^2	Probability
Arsenic	9.62	8.57	15.3	0.01
Cadmium	1.94	2.22	1.9	0.34
Chromium	1.91	2.90	36.7	0.01
Copper	8.71	14.56	144	0.01
Lead	1.63	6.65	156	0.01
Nickel	1.86	2.95	53.7	0.01
Mercury	0.12	0.26	104	0.01
Selenium	2.68	3.33	30.4	0.01
Silver	0.122	0.77	72.8	0.01
Tin	0.11	0.56	133	0.01
Zinc	116	143	2.7	0.01

techniques and analytical methods are too voluminous to report in this document. Detailed analytical methods used by the Mussel Watch Program are detailed elsewhere (Kimbrough and Lauenstein, 2006) and can be downloaded online at http://NSandT.noaa.gov. The Mussel Watch Program uses a performance based quality assurance (QA) process to ensure data quality. Analytical laboratories used by the Mussel Watch Program are required to participate in exercises with assistance from the National Institute of Standards and Technology (NIST) and the National Research Council of Canada (NRC) to ensure data are comparable.

2.4. Statistical methods

Mussel Watch trace element measurements were not normally distributed when assessed using the Shapiro–Wilks test ($p = 0.001$). To prevent results from being biased by outliers, non-parametric tests were used. Spearman rank correlation test was used to assess trace element temporal trends nationally and for the HRE. Differences between categories (pre- and post-attack concentrations, upper and lower bay concentration, HRE and national *Mytilus* sp. concentrations) were assessed using the non-parametric Wilcoxon sign ranks test. Significance of all tests was achieved at the probability <0.05 level.

3. Results and discussion

3.1. National comparison

Trace element concentrations in Hudson–Raritan Estuary and national *Mytilus* spp. were compared using data from 1986 to 2006 (Table 3). HRE measurements were significantly higher than national measurements for all trace elements with the exception of cadmium and arsenic (Table 3). No significant difference in cadmium concentration was observed between HRE and national measurements (Table 3). Arsenic was the only trace elements with national measurements that were significantly higher than HRE measurements.

Trace elements in the HRE have historically been elevated (US EPA, 2007). Urban and industrial sources have released contaminants into the HRE for decades (Ayres and Rod, 1986; Wall et al., 1998), resulting in high levels of contaminants in comparison to the Nation (Deason, 2003; Kimbrough et al., 2008). The Hudson and Newark Rivers are responsible for 60% freshwater input to the estuary. High concentrations of contaminants are correlated with large human population density and proximity to large rivers (Chase et al., 2001). Stream data from the aforementioned studies show elevated levels of trace elements derived from urban land use. While elevated trace element concentrations are common in many urbanized estuaries, including the HRE, naturally elevated levels of cadmium and arsenic can be found on the west coast of the US (Kimbrough et al., 2008), explaining why levels of cadmium and arsenic in the HRE were not significantly higher than what was found nationally.

3.2. Trend comparison

Trace element concentrations in mussels were assessed using five long-term sites in the HRE that exhibited high variability from year to year, no significant trends were found (Table 4; Fig. 2A–C). Nationally, only two significant trends exist; selenium had an increasing trend ($\rho = 0.68$, $p = 0.01$) and zinc had a strong decreasing trend ($\rho = -0.87$; $p = 0.01$) in mussels (*Mytilus* spp.). No trends were found for HRE trace elements. The absence of an increasing or decreasing trend is also seen in most trace elements nationally (O'Connor and Lauenstein, 2006).

In response to the Clean Water Act, Local governments implemented aggressive programs to reduce trace element loading and improve the water quality in the HRE by upgrading and adding sewage treatment plants. In a report by US EPA's Office of Water (US EPA, 2000), it was revealed that water quality has dramatically improved with reduced sediment concentration of copper (Cu), lead (Pb), and nickel (Ni). These results contrast with Mussel Watch tissue concentration data, which indicate that most trace elements display a variable trend from 1986 to 2005. This lack of a significant decreasing trend observed in the MW tissue data from the HRE suggests that contaminated bottom sediment may be a potential source of bioavailable trace elements. The HRE is a dynamic system that could cause sediment resuspension and

Table 4
Spearman statistical test was used to determine if trace element trends were decreasing or increasing. Only selenium (increasing) and zinc (decreasing) had significant trends.

Analyte	National		HRE	
	Spearman ρ	Probability	Spearman ρ	Probability
Arsenic	0.10	0.78	−0.36	0.31
Cadmium	−0.54	0.11	−0.64	0.05
Chromium	0.14	0.70	0.05	0.88
Copper	−0.43	0.21	0.44	0.20
Lead	0.44	0.21	0.10	0.78
Mercury	−0.04	0.91	−0.58	0.08
Nickel	−0.12	0.75	0.13	0.73
Selenium	0.68	0.03	0.41	0.24
Silver	−0.10	0.10	0.36	0.31
Tin	0.14	0.70	0.35	0.33
Zinc	−0.87	0.01	−0.52	0.52

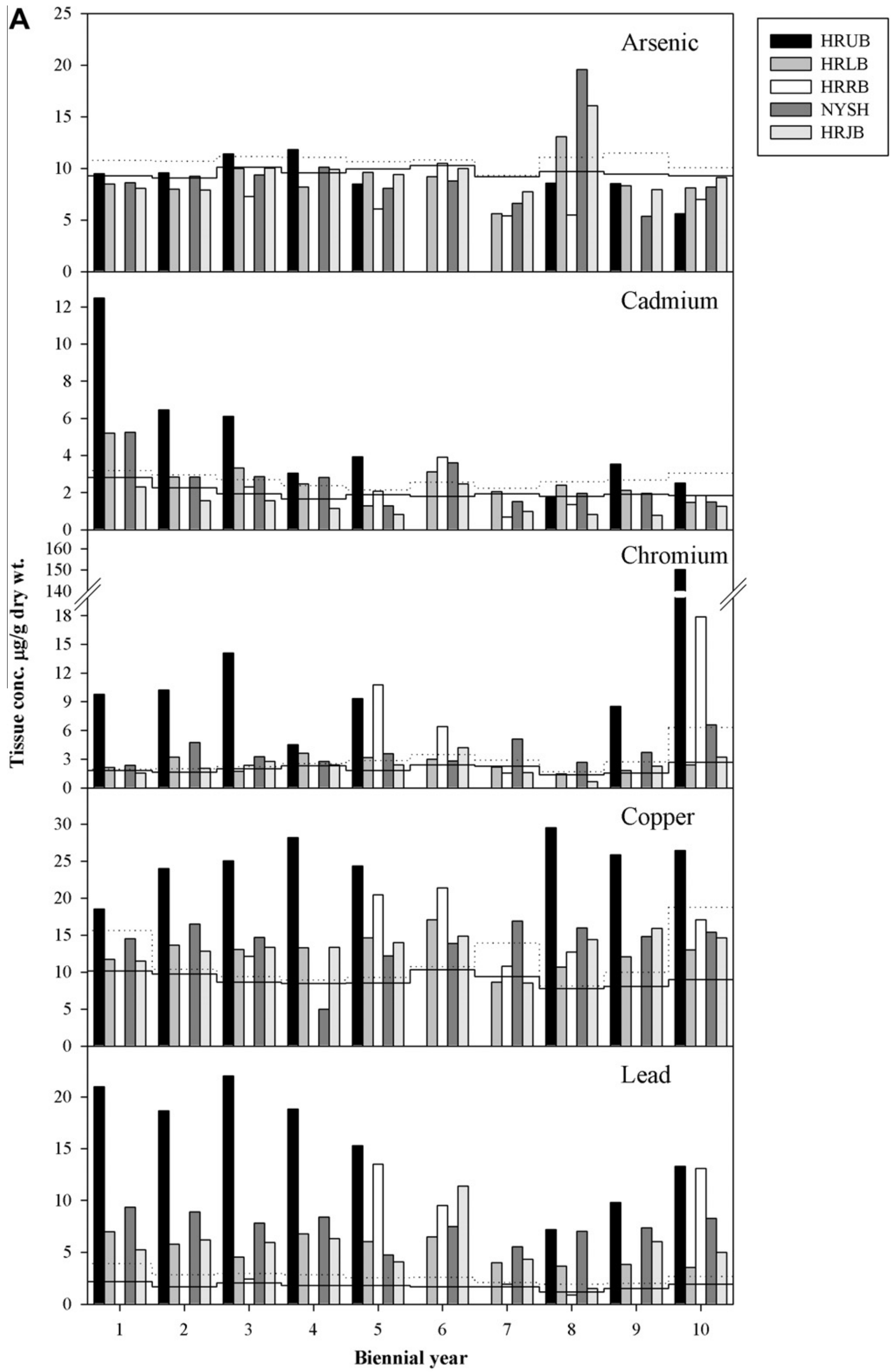

Fig. 2. (A–C) Trace metal tissue measurements for the five long-term Mussel Watch monitoring sites (1986–2003). The solid line represents the national median and the dotted line represents the national mean (only *Mytilus edulis*).

seasonal salinity change that may affect chemical behavior of contaminants in the water column (Feng et al., 1998).

3.3. Spatial distribution

Two spatial tests that utilized historic (1986–2000) and post WTC (2001) tissue and sediment measurements were done to compare the upper and lower bays. Historically (1986–2000), upper bay tissue measurements for most trace elements (cadmium, chromium, copper, lead, mercury, nickel, selenium, silver, zinc) were higher than tissue measurements from the lower bay with the exception of arsenic and zinc (Table 5A). In contrast to the historic measurements, only five of the 2002 trace element measurements (arsenic, cadmium, copper,

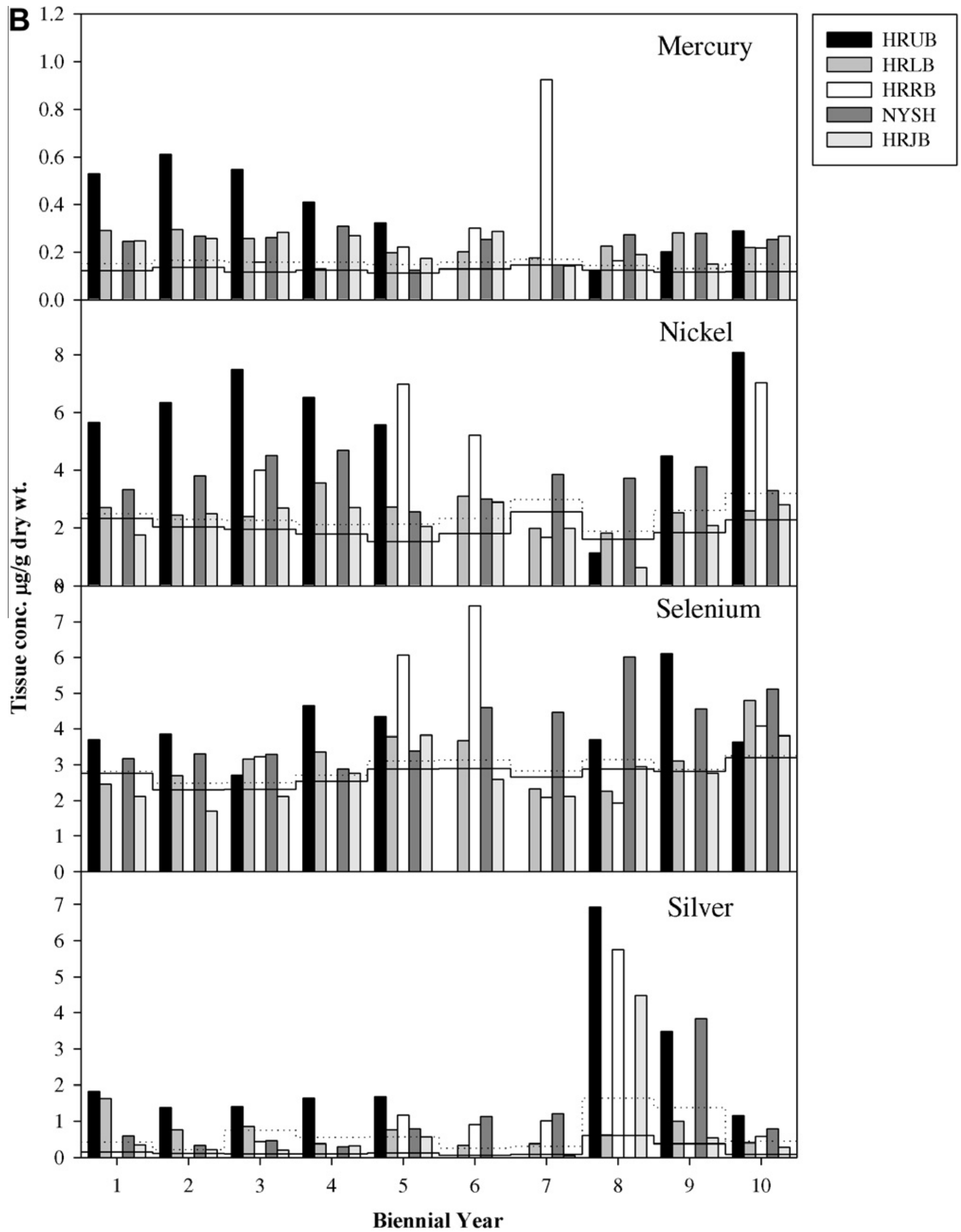

Fig. 2 (*continued*)

mercury and zinc) had tissue concentrations that were significantly higher in the upper bay, the others were not significantly different (Table 5B).

Previous work by Feng et al. (1998) established that trace element contamination was greater in the upper relative to the lower bay; they attributed this observation to urban runoff and wastewater discharge. The elevated trace element concentrations measured after the collapse of the WTC in 2001 (Table 5) are therefore not attributed solely to the attack. The presence of high trace element concentrations in both tissue and sediment in the upper bay, close to the attack site, does not strongly associate the WTC attack as a source of contamination. To further assess the influence of the WTC collapse on the overall trace element concentrations, an additional step was taken to compare pre-attack and post-attack measurements.

3.4. Pre and post-attack comparison

Historic and post-attack measurements in the HRE are not significantly different (Table 6). Measurements taken after the collapse of the WTC are similar to historic measurements from the upper bay (Fig. 3). Post-attack concentrations are shown graphically as box and whisker plot distributions that incorporate measurements from the 5th to 95th percentiles (Fig. 3). Several sites had one or more post-attack trace element concentrations that exceeded the 95th percentile; however, concentrations of these magnitudes had also been observed in years prior to the attack. Among these trace elements, only the concentration of selenium had notably decreased at these sites based on the 2004 data. Results in Table 6 indicated that none of the trace elements including selenium has a post-attack concentration that is significantly greater

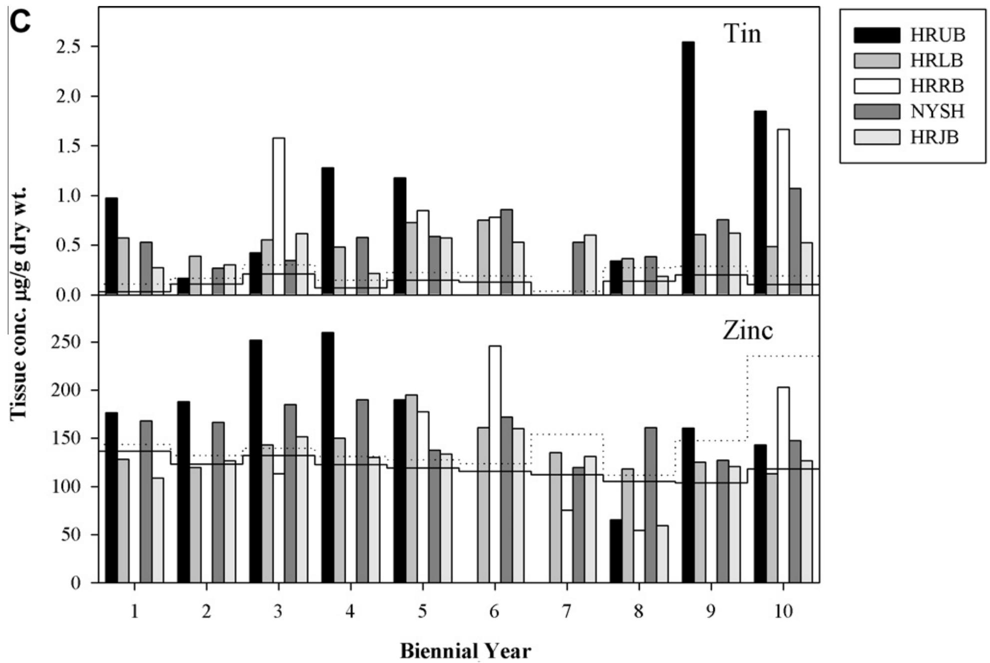

Fig. 2 (*continued*)

Table 5
The Wilcoxon statistical test was used to compare (A) all long-term site data and (B) upper and lower bay tissue measurements from 2001. Significance was achieved at the $p < 0.05$ level.

Analyte	Upper bay (µg/g)	Lower bay (µg/g)	χ^2	Probability
(A) Long-term data				
Arsenic	9.25	8.80	1.18	0.28
Cadmium	4.15	1.97	16.49	0.01
Chromium	9.58	2.62	16.29	0.01
Copper	24.88	13.33	28.38	0.01
Lead	15.65	6.14	20.97	0.01
Mercury	0.40	0.24	10.34	0.01
Nickel	5.57	2.75	16.75	0.01
Selenium	4.07	3.12	5.51	0.02
Silver	1.63	0.48	20.53	0.01
Tin	0.91	0.48	3.16	0.08
Zinc	183	135	5.90	0.01
(B) 2002				
Arsenic	9.99	7.60	6.00	0.01
Cadmium	3.12	1.39	6.00	0.01
Chromium	2.90	1.83	0.20	0.65
Copper	19.5	11.7	4.86	0.03
Lead	6.10	3.76	2.94	0.09
Mercury	0.30	0.22	6.00	0.01
Nickel	4.53	2.53	2.69	0.10
Selenium	7.06	2.68	3.84	0.05
Silver	1.78	2.09	0.96	0.33
Tin	1.11	0.61	1.80	0.18
Zinc	158	115	6.00	0.01

Table 6
Wilcoxon statistical test was used to compare pre- and post-attack tissue measurements from 1999 to 2001. No difference was found for any of the trace element tests. Significance was achieved at the $p < 0.05$ level.

Analyte	Pre-attack (µg/g)	Post-attack (µg/g)	χ^2	Probability
Arsenic	13.10	8.47	1.50	0.22
Cadmium	1.74	2.04	0.38	0.54
Chromium	0.64	2.66	2.96	0.09
Copper	14.4	13.45	0.24	0.62
Lead	3.65	5.61	2.16	0.14
Mercury	0.19	0.28	2.16	0.14
Nickel	1.13	3.33	2.94	0.09
Selenium	2.94	3.83	0.96	0.33
Silver	4.48	2.42	0	1.00
Tin	0.34	0.68	2.94	0.09
Zinc	65.4	126	2.16	0.14

than those of pre-attack. This implies that the WTC attack did not have a significant impact on the HRE ambient trace element levels. These results support a previously published report by EPA (2002) which stipulated that contaminant emissions from the collapse site did not affect adjoining water bodies. Due to the high pre-existing concentration levels of trace elements in the HRE, any input of contaminants would have to be exceptionally large to raise ambient levels significantly. Although considerable amounts of trace elements comprise building material, electronic products, and furniture destroyed during the WTC attack, the results consistently indicated that collapse of the WTC did not add a measurable amount of trace element contamination to the Hudson–Raritan Estuary.

4. Conclusion

The results indicate that trace element concentrations in the Hudson–Raritan Estuary were not quantifiably higher as a result of the collapse of the WTC buildings. Pre- and post-attack concentrations in blue mussels were not statistically different. This finding corroborates published result by US EPA in 2002 that concluded contaminants from the collapse did not affected water bodies in the vicinity of the attack site. However, there is a net disparity in the spatial distribution of trace element in the estuary with the upper bay, which is closer to the collapse site, having significantly higher concentrations than the lower bay. Rather than being associated with the collapse, the high concentrations observed in the upper bay are likely linked to past pollution and sediment resuspension which is a frequent occurrence in the estuary. Trend analysis has revealed that for the past two decades, trace

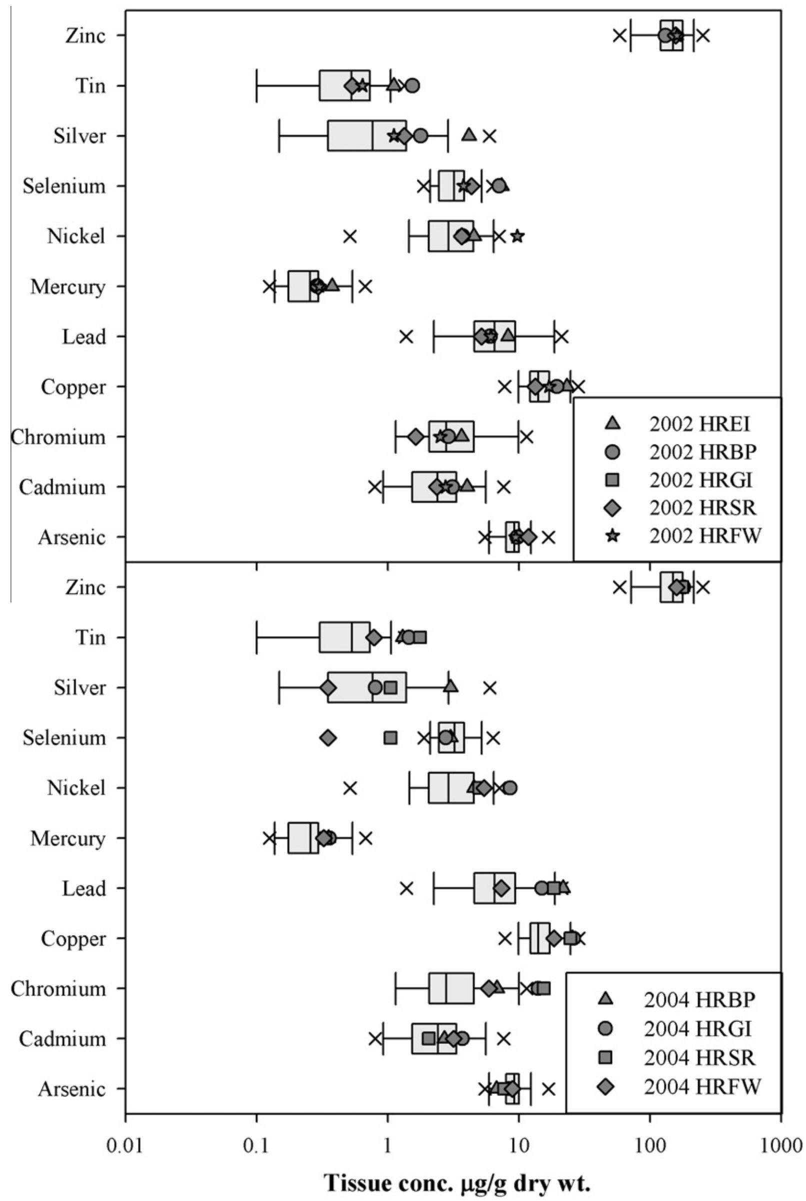

Fig. 3. Box and whiskers plots characterize all pre-attack HRE long-term measurements from 1986 to 2000. Whiskers represent the 5th and 95th percentile, and × represents outliers for historic HRE long-term site measurements (1986–2000). Symbols represent post-attack measurements form 2002 (A) and 2004 (B).

element levels remained fairly constant in the estuary and the WTC collapse did not induce any detectable upsurge of concentration. Although our results demonstrate that the collapse of the WTC did not have a detectable environmental impact on the coastal environment of the Hudson–Raritan Estuary, our conclusion should not be used to interpret the overall impact the attack might have on human health, especially rescue workers.

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