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ENVIRONMENTAL MONITORING OF REMEDIAL DREDGING AT THE NEW BEDFORD HARBOR, MA, SUPERFUND SITE

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Abstract. New Bedford Harbor (NBH), MA, is a Superfund site because of high polychlorinated biphenyl (PCB) concentrations in the sediment. From April 1994 to September 1995, a remedial dredging operation (termed the "Hot Spot") removed the most contaminated sediments (PCB concentrations greater than 4000 μg/g) from the upper harbor. During remediation, a monitoring program assessed the potential environmental impacts to NBH and adjacent Buzzards Bay. The monitoring program was developed with input from federal, state, and local authorities. Site-specific decision criteria were established to assess net PCB transport, water column toxicity, and PCB bioaccumulation in blue and ribbed mussels (*Mytilus edulis* and *Geukensia demissa*, respectively). The remediation was completed without exceeding PCB net transport or acute toxicity effects specified in the decision criteria. In addition, PCB bioaccumulation in mussels during this time period was not significantly greater than pre- or post-operational measurements. The results indicated that approximately 14 000 cubic yards of highly PCB contaminated sediment were permanently removed with minimal environmental effects. The lessons learned during this operation, as well as previous pilot studies at the site, will be used to make full-scale remedial efforts in NBH more efficient and environmentally protective.

Keywords: monitoring, New Bedford Harbor, PCB transport, remedial dredging, site-specific criteria

1. Introduction

Dredging is currently the most commonly selected option for remediating contaminated sediment. According to an EPA report (Zarull *et al.*, 1999), 36 of 38 contaminated sediment remediation projects identified in the Great Lakes involved dredging and disposal (nine of these were dredging, treatment, and disposal). However, there is an ongoing debate about the potential negative effects (e.g., resuspension and transport of contaminants) and positive benefits (e.g., permanently removing contaminants from an aquatic system) of dredging contaminated sediments (den Besten *et al.*, 2000; Voie *et al.*, 2002; Weston *et al.*, 2002). To address these questions, several dredging projects have conducted pilot studies and instituted environmental monitoring programs during and immediately after dredging (Hauge *et al.*, 1998;

Vale *et al.*, 1998). Several of these projects showed that remedial dredging could be conducted safely with proper controls (Nelson and Hansen, 1991). For example, the mass balance model used in the Fox River, WI, demonstration project showed that the mass of polychlorinated biphenyls (PCB) transported during dredging was relatively small compared to pre-dredging PCB transport (i.e., background conditions) and the overall total PCB mass removed from the river (Steuer, 2000).

Most remedial projects where significant monitoring data exist have occurred in riverine-freshwater systems (White and Ballattino, 1998). Many coastal marine areas also contain contaminated sediments which must be removed either because they are a direct threat to human health and the environment (e.g., Superfund sites) or because they impede navigation and shipping. Assessing the effects of dredging in these areas is often confounded by the bidirectional tidal flow in these systems. Further, as is the case at many contaminated sediment sites, the criteria that might ordinarily be used to monitor and assess the effects of dredging operations (e.g., water quality criteria – WQC) are often exceeded under background conditions, necessitating site-specific assessment measures.

New Bedford Harbor, MA, U.S.A. (NBH) is a tidal estuary located along Buzzards Bay in Southeast Massachusetts. As a result of industrial development around the harbor, sediments were contaminated with high concentrations of many compounds, including PCBs (USEPA, 1990). Some NBH sediment had PCB concentrations in excess of 100 000 μg/g. Consequently, NBH was placed on the U.S. Environmental Protection Agency's (USEPA) National Priority List as a Superfund site in 1983. A pilot study was conducted in 1988–1989 to determine the engineering feasibility (i.e., dredge type and efficiency) and environmental consequences (i.e., biological effects) of removing these contaminated sediments by dredging (Nelson and Hansen, 1991). The development and use of site-specific decision criteria, coupled with real-time monitoring, demonstrated that the NBH sediments could be successfully dredged, while minimizing effects to the environment (Nelson and Hansen, 1991). Based in part on these results, dredging was selected as the remedial option to remove the most contaminated sediments from NBH.

The first operational unit to be dredged in NBH was a 5-acre area containing the PCB-contaminated sediment with the highest concentrations, termed the "Hot Spot" (USEPA, 1990). These sediments were generally fine-grained silts and clays, contained total PCB concentrations greater than 4000 μg/g, and represented a significant proportion of the total mass of PCBs in the harbor. The overall remedial objectives were to: 1) remove this mass of PCBs without increased PCB transport to less contaminated areas in the lower harbor and Buzzards Bay, and 2) not cause additional environmental risks due to increased toxicity and bioaccumulation. The Hot Spot dredging began in April 1994 and was completed in September 1995.

This paper first describes the environmental monitoring program developed for the Hot Spot remedial project. One important aspect of this monitoring plan was the need to develop site-specific decision criteria because many typical assessment measures (e.g., WQC) were exceeded under background (i.e., baseline) conditions. For example, ambient water column PCB concentrations in NBH were 2–3 orders of magnitude greater than existing marine WQC. The criteria used to assess dredging impacts fell into two categories. First, PCB net transport criteria were developed to monitor contaminant migration from the more severely contaminated upper harbor to cleaner areas in the lower harbor and adjacent Buzzards Bay (Figure 1). Second, biological criteria, including several toxicity tests and PCB bioaccumulation in blue and ribbed mussels (*Mytilus edulis* and *Geukensia demissa*, respectively), were established to evaluate whether the biota were adversely affected by the operation. The objectives and decision criteria were agreed upon by each of the regulatory agencies involved in overseeing the dredging, including USEPA Region I, U.S. Army Corps of Engineers' North Atlantic Division New England District (CENAE), and the Commonwealth of Massachusetts. The paper then presents and discusses the results of the monitoring program relative to the site-specific criteria and provides an evaluation of both the dredging operation and the overall monitoring approach.

2. Materials and Methods

2.1. Sampling Locations

The rationales for the decision criteria and station locations used in the Hot Spot dredging are similar to those used previously in the pilot study (Nelson and Hansen, 1991). For example, the overall pilot study philosophy was adopted: moderate, short-term increases in water column contaminant concentrations and some associated toxicity and bioaccumulation were acceptable in the near-field (i.e., adjacent to the dredging) as long as no far-field (i.e., lower harbor or Buzzards Bay) effects were observed. Therefore, decision criteria were established at the same two strategic stations employed in the earlier pilot study (Nelson and Hansen, 1991): the Coggeshall St. Bridge (NBH-2) and the Hurricane Barrier (NBH-4) (Figure 1). Station NBH-2 is located at the transition point between the upper and lower harbors. Criteria were established there to assess: 1) net transport of PCBs to the lower harbor, 2) acute toxicity in the water column, and 3) PCB bioaccumulation in mussels.

At Station NBH-4, the transition between NBH proper and Buzzards Bay (outer harbor), decision criteria were established for sub-lethal biological effects and mussel PCB bioaccumulation. No net transport criteria were established at NBH-4 because the pilot study demonstrated that when PCB concentrations were controlled at NBH-2, no corresponding signal was observed at NBH-4 (Nelson and Hansen, 1991). Finally, a reference site (NBH-5) was located near West Island in Buzzards Bay for comparison with the biological tests at NBH-2 and NBH-4.

In addition to the stations sampled for the decision criteria, supplemental water column monitoring occurred at two other upper harbor locations to assist in

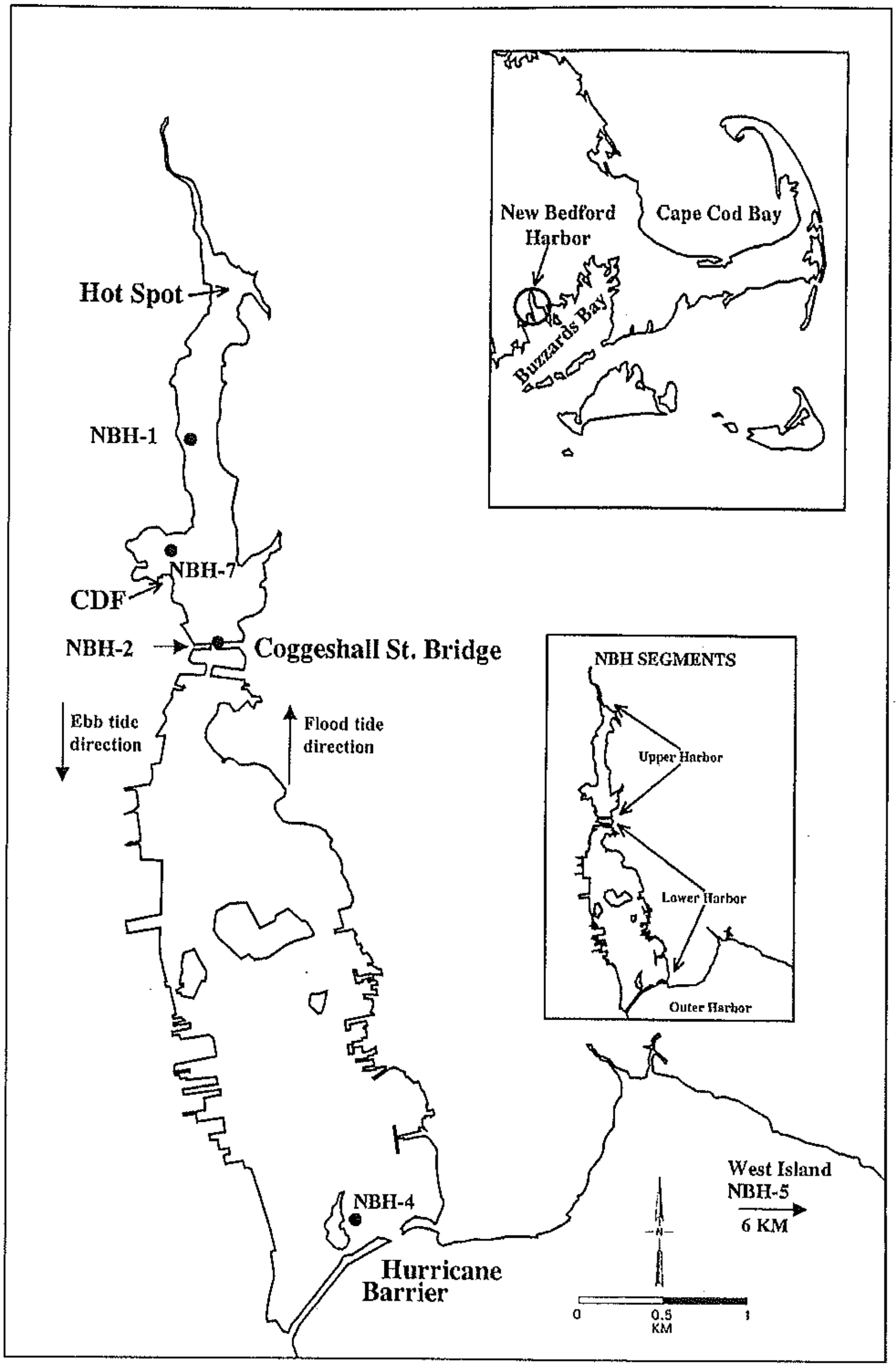

Figure 1. New Bedford Harbor MA site map and monitoring stations. CDF: confined disposal facility.

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determining potential sources of toxicity. One station, NBH-1, was located south of the dredging operation to identify dredging-related effects. A second station, NBH-7, was established in the vicinity of the confined disposal facility (CDF), where the dredged material was first pumped, the particulates allowed to settle out, and the process water treated and discharged back into the harbor (Figure 1). Without monitoring at these additional sites, it would be difficult to accurately identify the source if any criteria were exceeded. For example, toxicity or increased water column PCB concentrations measured at NBH-2 could be associated with either the dredging operation, the CDF effluent, or an event completely unrelated to the remediation (e.g., high winds).

2.2. Water Sample Collection

An intensive water column sampling effort was conducted twice daily at NBH-2 during ebb tide and flood tide when dredging occurred. Water samples were pumped simultaneously through Teflon® hoses at 13 distinct points in the water column at the Coggeshall St. Bridge (Figure 2) after each 6-inch fall or rise in the tide, as measured by a tide gauge at the bridge. Tidal amplitude was used instead of time intervals because water rise and fall at NBH-2 was not uniform over a tidal cycle. These samples were composited to form one ebb tide and one flood tide sample which were then split for chemical analyses, and subsequent PCB transport calculations, as well as for biological testing. At Station NBH-4, water was collected at three depths, 1 meter below the surface, 1 meter above the bottom and mid-depth at hourly intervals during the ebb tide and composited for biological testing. At stations NBH-1 and NBH-7, water also was collected at hourly intervals at three depths where possible (mid-depth only in shallow areas) over the ebb tide and the

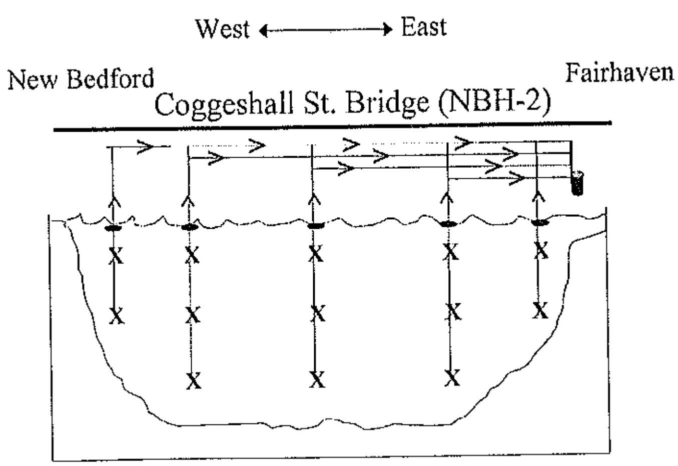

Figure 2. Multi-point sampling array at the Coggeshall St. Bridge (Station NBH-2).

composite used for chemical analysis and biological testing. Finally, water was collected at station NBH-5 once during the ebb tide for biological testing only.

2.3. Water sample analyses and decision criteria

This section describes water sample analyses as well as how those data were used in the decision-making process to assess dredging effects. In general, daily results were compared against previously identified site-specific decision criteria at stations NBH-2 and NBH-4 (described later). If criteria were exceeded, the data were reviewed to ascertain possible causes, discuss potential operational modifications where applicable, and decide if increased sampling frequency should occur.

2.3.1. *Chemical Analysis*

For each tidal chemistry composite, the sample was thoroughly mixed and 1-L filtered through a Type A/E Gelman glass fiber filter to obtain both dissolved and particulate PCB concentrations, then summed to get a total value. This additional step was taken because whole water analysis was found to underestimate total PCB concentration when particulate concentrations were high due to incomplete extraction of the particulate fraction. An internal standard (CB198) was added to each sample before extraction with acetone and methylene chloride. Extracts were solvent exchanged to hexane and analyzed by GC-ECD (gas chromatograph equipped with an electron capture detector). Eighteen individual PCB congeners were quantified in the dissolved and particulate fractions of the seawater.

PCBs have been quantified several ways in NBH, including as total Aroclor® and congeners. When quantifying total PCB concentration as Aroclor®, results can vary depending on the analytical method used (i.e., which congeners are selected to represent the Aroclor® mixture). Congener-specific analysis is more accurate because single congener standards and reference materials (with congener-specific certified values) are readily available. Therefore, this monitoring program quantified the 18 individual congeners (Table I) utilized in the National Oceanic and Atmospheric Administration's (NOAA) National Status and Trends Program to assess marine environmental quality (Calder, 1986). In addition, a subset of samples collected during the pilot study measured both congener and Aroclor® content and was used to estimate a conversion factor to relate total PCB congener concentrations in this study to total Aroclor® content, thus facilitating comparison with historical data.

2.3.2. *PCB Net Transport Analysis and Decision Criteria*

Analysis: PCB net transport was determined at NBH-2 by multiplying the average PCB water column concentration (μg/L) from each ebb and flood tide chemistry composite sample by the volume of water flowing under the Coggeshall St. Bridge (Figure 1) during that tidal cycle to obtain the total mass of PCBs (kg) transported. The mass for the flood tide was subtracted from the mass for the previous ebb tide to obtain a net value for PCB transport. PCB analysis was conducted on a 24-h

TABLE I
Eighteen PCB congeners and substitution patterns used in this study

Name	Substitution Pattern
CB008	2,4′-
CB018	2,2′,5-
CB028	2,4,4′-
CB044	2,2′,5,5′-
CB052	2,2′,3,3′-
CB066	2,3′,4,4′-
CB101	2,2′,4,5,5′-
CB105	2,3′,4,4′,5-
CB118	2,2′,4,4′,5,5′-
CB128	2,3,3′,4,4′-
CB138	2,2′,3,4,4′,5′-
CB153	2,2′,3,4′,5,5′,6-
CB170	2,2′,3,3′,4,4′-
CB180	2,2′,3,4,4′,5,5′-
CB187	2,2′,3,3′,4,4′,5-
CB195	2,2′,3,3′,4,4′,5,6-
CB206	2,2′,3,3′,4,4′,5,5′,6-
CB209	decachlorobiphenyl

turn-around basis, thus ensuring that net transport was assessed rapidly for each dredging day. If elevated contaminant levels were detected, data were reviewed from NBH-1 and NBH-7 to provide an indication of the contamination source.

In addition to those days when PCB net transport was measured directly, additional net transport estimates were calculated for days when dredging occurred but monitoring at NBH-2 did not. A mean PCB flux value for all previous dredging days was used for those days and was considered to be environmentally conservative because it included those dredging days when the more contaminated sediment was dredged. Therefore, the overall project-related net PCB transport value included all dredging days, both when direct monitoring occurred and when it did not.

Decision Criterion: Previous studies by the U.S. Army Corps of Engineers and USEPA indicated a continuous transport of PCBs to the lower harbor under background conditions (Bergen *et al.*, 1993b). Therefore, it was necessary to establish some "acceptable" decision criterion that limited PCB net transport associated with the Hot Spot dredging to a level where no additional remediation in the lower harbor would be required.

Several approaches were considered to establish a dredging-related PCB transport criterion value, including single-point determinations and cumulative transport. During the pilot study, the PCB decision criterion at NBH-2 compared daily water column concentration measurements against a statistically significant increase over pre-operational (i.e., baseline) conditions (Nelson and Hansen, 1991). In the pilot study, the dredged sediment PCB concentrations were relatively low (~200 μg/g), the project duration was short, and PCB water column concentrations were measured daily. Therefore, the probability of transporting large amounts of PCBs (i.e., an amount that would require additional remediation) to the lower harbor was minimal.

This was not the case with the Hot Spot remediation. The sediment PCB concentrations were 2–3 orders of magnitude greater than those dredged during the pilot study and the duration of the project was much longer. Therefore, a criterion based on a single episodic value could be misleading with respect to cumulative PCB transport to the lower harbor. For example, if the PCB water column concentration remained at 1.3 μg/L during the entire Hot Spot remediation, a period of 18 months, it would not violate the previous pilot study decision criterion of 1.4 μg/L. However, the total net transport would be much greater under that scenario than if PCB water concentrations were near background (~0.2 μg/L) during most of the dredging and only exceeded the pilot study criterion intermittently. Therefore, both magnitude (i.e., concentration) and duration (i.e., time) components were incorporated into net transport criterion for the Hot Spot remediation. A more conservative approach (i.e., environmentally protective) than the single episodic value was adopted: a maximum cumulative transport (MCT) of PCBs. This MCT approach was based on defining a PCB mass that, if transported to the lower harbor, would have no "significant" impact. This mass of PCBs became the decision criterion value and the cumulative total PCB net transport at NBH-2 was compared with this upper limit throughout the operation.

The challenge in proposing a MCT for PCBs was defining that mass of transported PCBs which would have no significant impact on the lower harbor. Because this absolute estimate of acceptable PCB transport is very difficult if not impossible to calculate, best professional judgement was exercised to define an "unacceptable MCT" that met the objective of no additional remediation in the lower harbor. The average surficial PCB sediment concentration in the lower harbor was estimated to be approximately 14 μg/g (Nelson *et al.*, 1994), based on historical data. Given that concentration, it was considered that a 1 μg/g increase in the sediment concentrations would neither be detectable analytically (based on sampling and analytical variability) nor cause additional damage ecologically. Therefore, the MCT criterion value for NBH-2 was operationally defined as that mass of PCBs transported from the upper harbor, above background concentrations, that would increase the mean lower harbor sediment concentration by more than 1 μg/g.

The mass of PCBs in lower NBH sediments was calculated as follows. The total sediment surface area in the lower harbor was determined using a digitizing planimeter. Sediment volume was determined by multiplying the surface area by the depth of the biologically active zone taken to be 4 cm. The resultant volume was converted to dry weight mass units using an estimate of sediment density

($1\ cm^3 = 2.2$ g dry wt.). The total mass of the top 4 cm of sediment in the lower harbor was calculated to be approximately 240×10^6 kg; therefore, 240 kg of PCB would have to be transported to the lower harbor to increase the total PCB sediment concentration by 1 μg/g. This PCB mass of 240 kg became the MCT decision criterion value for NBH-2.

2.4. Biological Monitoring

The biological tests provided an integrated assessment of water column effects. Because it is impossible to quantify every contaminant that could be remobilized by dredging, organism response was used to integrate the entire suite of potentially harmful effects of the dredging operation. Two types of biological measurements were utilized during the Hot Spot remediation: toxicity tests and mussel bioaccumulation.

2.4.1. *Toxicity Tests and Decision Criteria*

Biological criteria at Station NBH-2 (Coggeshall St. Bridge) were established to prevent acute concentrations of water-borne contaminants from discharging to the lower harbor. Based on the species sensitivity of tests conducted during the pilot study (Nelson and Hansen, 1991), three toxicity tests were selected to assess acute effects at NBH-2 during the Hot Spot remediation: the sea urchin (*Arbacia punctulata*) sperm cell fertilization test (USEPA, 1988), the 7-day mysid (*Americamysis bahia*, formerly known as *Mysidopsis bahia*) survival test (USEPA, 1988), and the red alga (*Champia parvula*) survival test (USEPA, 1988). The decision criteria to assess significant effects were acute responses >20% of those at the West Island reference station (NBH-5; see Figure 1) for any two species, or >50% of those at NBH-5 in any one organism.

The goal of the biological criteria at Station NBH-4 (Hurricane Barrier) was to identify whether sub-lethal concentrations of water-borne contaminants were discharging into Buzzards Bay as a result of the dredging operations. The toxicity tests selected to assess sub-lethal effects at NBH-4 included the 7-day mysid growth test (USEPA, 1988) and the red alga reproduction test (USEPA, 1988). The decision criteria were sub-lethal effects >20% of the West Island reference station (NBH-5) for any two species, or >50% than at NBH-5 for any single organism. These are the same criteria that were employed effectively during the pilot study.

2.4.2. *Bioaccumulation*

PCB bioaccumulation in blue mussels, *Mytilus edulis*, has been shown to accurately reflect water column PCB concentrations, especially the dissolved fraction (Bergen *et al.*, 1993a). Therefore, blue mussels were again used to monitor for PCB bioavailability at both NBH-2 and NBH-4 during this remedial operation. Ribbed mussels, *Geukensia demissa*, were also used because dredging continued throughout the summer months when water temperatures sometimes exceeded 25 °C at NBH-2.

Blue mussels can become severely stressed when exposed to temperatures >25 °C for long periods. Ribbed mussels have a greater temperature tolerance than blue mussels, and a previous study in NBH demonstrated that they accumulate PCBs in concentrations equivalent to that in blue mussels within a 28-day deployment period (Nelson *et al.*, 1995). This species was used during the summer months when temperatures exceeded 20 °C. The decision criterion for assessing PCB bioaccumulation at NBH-2 and NBH-4 was a statistically significant ($\alpha = 0.05$) increase over pre-operational concentrations.

A detailed description of the mussel deployment and analytical procedures can be found in Bergen *et al.*, (1993a). Briefly, about 25 mussels were placed into polyethylene mesh bags and deployed 1 meter above the bottom at three sites: NBH-2, NBH-4, NBH-5 (Figure 1). Each station consisted of four independent satellite arrays. After 28 days, the mussels were retrieved and frozen. Three samples were analyzed and one was kept frozen as an archive. Prior to analysis, mussels were thawed, shucked, and homogenized. Two grams of homogenate were extracted with acetonitrile and pentane, solvent-exchanged to hexane, and analyzed by gas chromatography for the same PCB congeners quantified in the water samples. Reported results at a station are the means (±S.D.) of the three replicate samples.

3. Results and Discussion

3.1. Net Transport

One Hot Spot remedial goal was to minimize PCB transport to cleaner areas in the lower harbor and Buzzards Bay; therefore, PCB net transport under the Coggeshall Street Bridge was quantified. Based on the data, this goal to limit PCB transport was achieved. Figure 3 shows the daily measured net transport of PCBs (kg/day) at NBH-2. The PCB flux data indicate considerable variability during the period of dredging (mean = 0.2 kg/tidal cycle, S.D. = 0.2); however, this type of variability is expected. NBH is a shallow estuary where weather, especially wind, can have dramatic effects on sediment resuspension. In fact, one of the highest measured water column PCB concentrations during the pilot study occurred during a wind-driven event when no dredging was occurring (Nelson and Hanson, 1991). This finding is consistent with other studies which demonstrated that weather, boat traffic, and natural flow variability can increase resuspension more than dredging operations (Hauge *et al.*, 1998; Whyte and Kirchner, 2000; Ko and Baker, 2003).

The cumulative PCB transport during the dredging operation fell well short of the maximum value "allowable" under the MCT decision criteria. Figure 4 shows the projected maximum cumulative transport, 240 kg, if it were distributed uniformly over the entire dredging period of 260 days (240 kg/260 days). Also shown is the PCB cumulative transport over the same period, both the days when transport was measured directly and estimated. For the entire operation, the mass

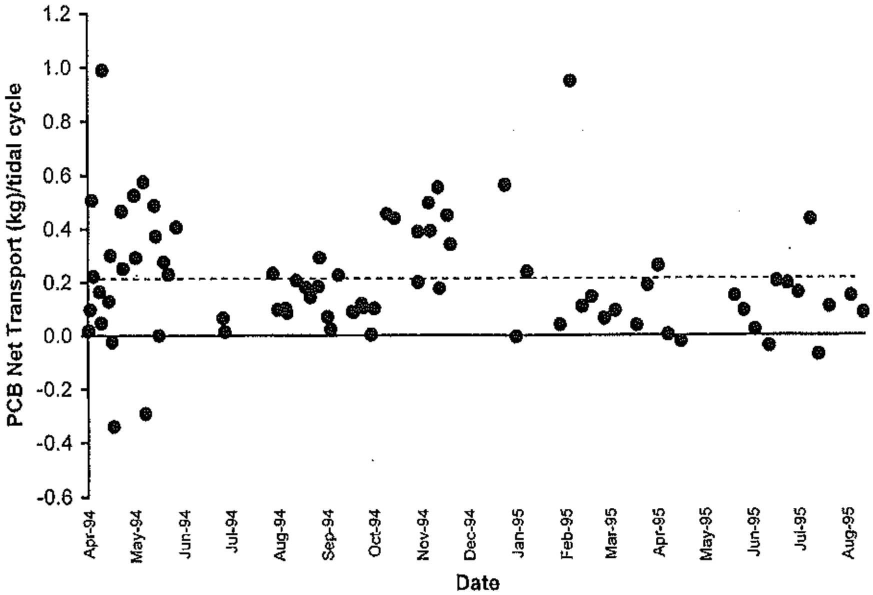

Figure 3. Measured net transport of PCBs under the Coggeshall St. Bridge (NBH-2). Values represent kg/tidal cycle on dredging days. Dashed line represents the mean net PCB transport for the entire Hot Spot remediation (0.2 ± 0.2 S.D.). Positive values indicate net transport out of the upper harbor.

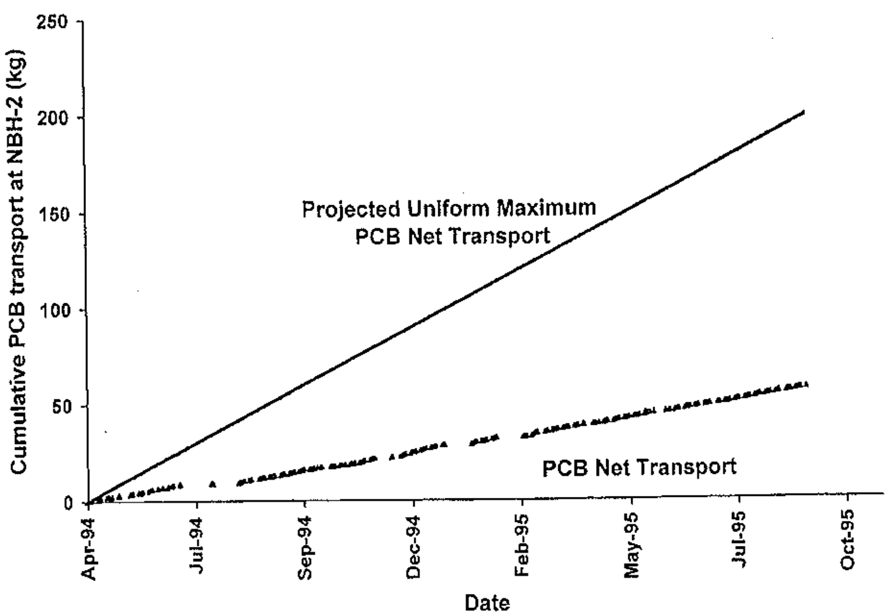

Figure 4. Comparison of PCB net transport, both measured and estimated, during the Hot Spot remediation on the 264 dredging days. Also shown is the projected uniform maximum cumulative transport allowed in the decision criterion.

of PCBs transported under the bridge at NBH-2 was about 57 kg, approximately 24% of the maximum 240 kg allowed for the PCB MCT criterion. It should be noted also that the original MCT limit of 240 kg was to be above baseline PCB transport. In reality, the 57 kg of PCBs transported during the project included background transport, therefore, the criterion for net transport was not violated during the remediation and there was very little transport that could be attributable directly to the dredging operation. For comparison, a mass balance study on the Fox River, WI, found that 14.5 kg of PCB was mobilized during 106 days of dredging in a less contaminated area (i.e., average sediment concentration of 53 ppm PCB). This represented 9% of the amount that would have normally been transported annually out of the contaminated area, while permanently removing 650 kg from the river (Steuer, 2000).

Based on these data, the measured mass of PCBs transported out of the upper harbor during the Hot Spot dredging was below the decision criterion level that was estimated to not require additional remediation in the lower harbor; however, this value was admittedly subjective. Subsequent sediment data collections in NBH indicate that this criterion was also very effective. As part of a long-term monitoring plan in NBH (Nelson *et al.*, 1996), sediment PCB concentrations were measured at stations throughout NBH before (1993) and after (1995) the Hot Spot dredging. The data indicate a mean ($N = 23$ locations) PCB sediment concentration of 8 ppm in 1993 and 7 ppm in 1995 for the lower harbor. These data highlight several points: 1) the original assumptions and "best professional judgement" approach used for calculating the MCT value were valid, 2) the field design and measurements were rigorous enough to accurately quantify net transport, and 3) the MCT criterion value of 240 kg was not only met from an operational perspective, but was also effective in meeting the objective of no additional remediation in the lower harbor.

3.2. Toxicity Tests

3.2.1. *Sea Urchin Sperm Cell Test*

During the dredging project, 86 sperm cell tests were performed on water collected at NBH-2 and mortality was never 10% more than that measured at station NBH-5, the reference site (Table II). At station NBH-4 the maximum difference between station NBH-4 and NBH-5 was 12%. Therefore, the mortality was below both the 20% of response at NBH-5 for any two species or 50% for any single species and the decision criterion was not violated.

3.2.2. *Mysid Test*

Seven week-long tests were conducted with mysids, with one instance at station NBH-2 demonstrating a negative impact relative to mysid survival (100% mortality occurred during the week of 12/12/94) (Table II). This observation was assessed in the context of the other mysid data collected during the same period. In contrast to NBH-2, there were 100 and 95% survival, respectively, for stations NBH-1

TABLE II
Synthesis of toxicity test results relative to biological decision criteria

	Acute effects (NBH-2)			Sub-lethal effects (NBH-4)	
Station location	Sperm cell survival	Mysid survival	*Champia* survival	Mysid growth	*Champia* reproduction
NBH-2	0 (86)	1 (7)	1 (83)		
NBH-4	0 (85)	0 (7)	0 (82)	0 (7)	5 (66)

Note. The biological criteria at NBH-2 were mortality >20% of NBH-5 for any two species, or >50% for any single species. At NBH-4, the criteria were sub-lethal effects >20% of NBH-5 for any two species, or >50% for any single species. Values indicate the number of times criteria were exceeded for each test, along with the total number of tests conducted, in parentheses, during the Hot Spot monitoring program.

and NBH-7, which were closer to the dredging operation. Furthermore, no effects were observed in the other test species during this time period, so the significant mortality was not attributed to the dredging operation; rather, it may have been due to some other factor such as processing or handling. Explanation of this type of contradictory observation was the rationale for including the extra non-decision criteria stations (i.e., NBH-1, NBH-7) in the monitoring plan. Relative to the sub-lethal mysid growth criteria established at NBH-4, no negative effects were observed on any occasion and dredging was determined to not have any chronic effects at this location.

3.2.3. *Champia Test*

Water column samples collected on 85 days were assessed for *Champia* survival at NBH-2 (Table II). On only one occasion (9/7/94) was mortality >50% that of NBH-5. Comparison of this particular test response with results from other upper harbor locations on the same day, indicated survival was 100% at station NBH-1 which was closer to the dredging operation and 50% at NBH-7, which was near the CDF. In addition, no corresponding negative effects were observed in the sea urchin acute test at station NBH-2 on this day. The exact reason for this mortality is hard to pinpoint, but the fact that *Champia* survival was high at the station closest to the dredging, the sea urchin tests showed no effects, and *Champia* survival was 100% the next time it was measured at NBH-2, indicating that whatever the cause it was transient in nature and limited to this species. Other anomalous results with this species were observed during the course of the testing and are discussed later.

Champia reproduction, measured as cystocarp production, was one of two tests used to assess sub-lethal effects at NBH-4; however, interpretation of the results was often problematic. For example, 18 of the 84 testing days showed no reproduction (<1 cystocarp) at NBH-5, the reference site in Buzzards Bay; therefore, the decision criterion was only evaluated on 66 days. On 5 of those 66 days, cystocarp production at NBH-4 was <50% that at NBH-5, the criterion value. While indicative of a potential problem, the results also indicate that on 4 of those days, cystocarp production was similarly low at all of the other stations. In addition, on the other occasion, while reproduction was low at NBH-4, it was not different from the reference station (NBH-5) or any of the upper harbor stations (NBH-1, NBH-7, or NBH-2) closer to the dredging operation. The fact that sub-lethal effects were observed in only five out of 66 tests (~8%) at NBH-4, while no reproduction was observed at the reference site (NBH-5) on 18 of 84 days (~21%), indicates that sole reliance on this test to assess sub-lethal effects due to the remedial dredging operation was difficult. Furthermore, when assessed in the context of the other chronic test (i.e., mysid growth), there was no overlap between effects.

Of all the toxicity tests used in this monitoring program, *Champia* reproduction is the most sensitive to two classes of anthropogenic stressors (metals and organics) as well as natural stressors (e.g., nutrients, temperature) (Schimmel *et al.*, 1989). In addition, another study with this test species was conducted to assess small-scale (i.e., within a station) and large-scale (i.e., between station) variability (Thursby *et al.*, 2000). The results indicated that there was as much variability at a station over tide and depth as there was among stations. Furthermore, there was no consistent relationship between *Champia* reproduction and *Arbacia* fertilization, another test used in this monitoring program. Therefore, while this test provides a comprehensive assessment of overall water quality due to many factors, the contradictory and variable results make it more difficult to interpret relative to this specific contaminated sediment dredging operation.

In the case of NBH, an industrial harbor subject to numerous historical and present environmental insults (e.g., largest fishing fleet in New England, elevated hydrocarbons and nutrient levels, etc.) (Pesch and Garber, 2001), a "broad spectrum" toxicity test such as *Champia* reproduction may not be adequate to assess remedial effects in and of itself. The approach taken during this monitoring program was to use multiple toxicity tests to raise a "red flag" when appropriate; however, each occurrence was assessed in the context of all other available information. The rationale for this approach was that any single organism's response during toxicity testing can be variable, as was the case especially with *Champia* reproduction, but multiple "hits" with different species may indicate a real problem. Based on this approach, the overall interpretation of the toxicity testing data indicates little or no effect that can be directly attributable to the remedial dredging. On those instances where acute or chronic effects were observed at either stations NBH-2 or NBH-4, no confirmatory evidence at locations closer to the actual dredging operation was found. These results were similar to those obtained during the pilot study in NBH, where no toxicity criteria violations occurred (Nelson and Hansen, 1991). One question that may arise from these two studies is the overall sensitivity of the selected species. However, biological effects were observed in the immediate vicinity of the pilot study dredging operation using the same toxicity tests (Nelson and Hansen, 1991), indicating that their use was appropriate to assess the Hot Spot dredging as well.

TABLE III
Mean (standard deviation) PCB concentrations (μg/g dry weight) in mussels deployed at monitoring stations for 28 days

	PCB Concentration (ppm)		
Station	Pre-operational	Operational	Post-operational
NBH-2	15 (4.4)	14 (4.1)	17 (4.4)
NBH-4	3.8 (0.89)	4.1 (0.76)	5.2 (1.3)
NBH-5	0.61 (0.18)	0.40 (0.07)	0.41 (0.14)

Note. Pre-operational samples were collected between July 1987 and December 1993 ($n = 9$); Operational samples were collected between May 1994 and September 1995 ($n = 14$); Post-operational samples were collected between September 1995 and October 2000 ($n = 12$).

3.3. Mussel Bioaccumulation

The mean and standard deviation of PCB bioaccumulation in deployed mussels are summarized in Table III for the three operational phases (pre-operational, operational, post-operational). The decision criterion at stations NBH-2 and NBH-4, no statistical increase ($\alpha = 0.05$) in mussel PCB tissue concentration relative to pre-operational concentrations, was not violated. The mean and standard deviation for each individual deployment at station NBH-2, closest to the dredging, are shown in Figure 5. These data exhibit typical seasonal variability in accumulation that is present at all stations, as well as in the indigenous ribbed mussel (*Geukensia demissus*) population (Bergen *et al.*, 2001). Seasonal variability is most likely due to the reproductive cycle in mussels where lipid-rich gametes increase during the year (along with lipophilic organic contaminants such as PCBs) and then decrease dramatically during spawning.

In addition, these data indicate that during the period from 1987 to 2000, no decrease in PCB water column concentrations was evident. To date, 12 post-operational deployments have been conducted and an ANOVA (Snedecor and Cochran, 1967) among all operational phases and stations indicate no change in PCB bioaccumulation within a station; however, the differences among stations persist over the past 13 years. This observation does not indicate that mussel bioaccumulation is an insensitive indicator, it varies by an order of magnitude over relatively short distances; rather, it persists because the exposure regime has not changed over that time frame. The Hot Spot remediation was undertaken as a mass removal operation in a small area and, even though the overall PCB mass removed was significant, it was not intended to and did not reduce the overall surficial sediment PCB concentrations (i.e., exposure) in the upper harbor (i.e., Hot Spot was only 5 of ~200 acres in the upper harbor). Significant PCB exposure reduction should occur during full-scale upper harbor remediation, scheduled to begin in 2004. Because

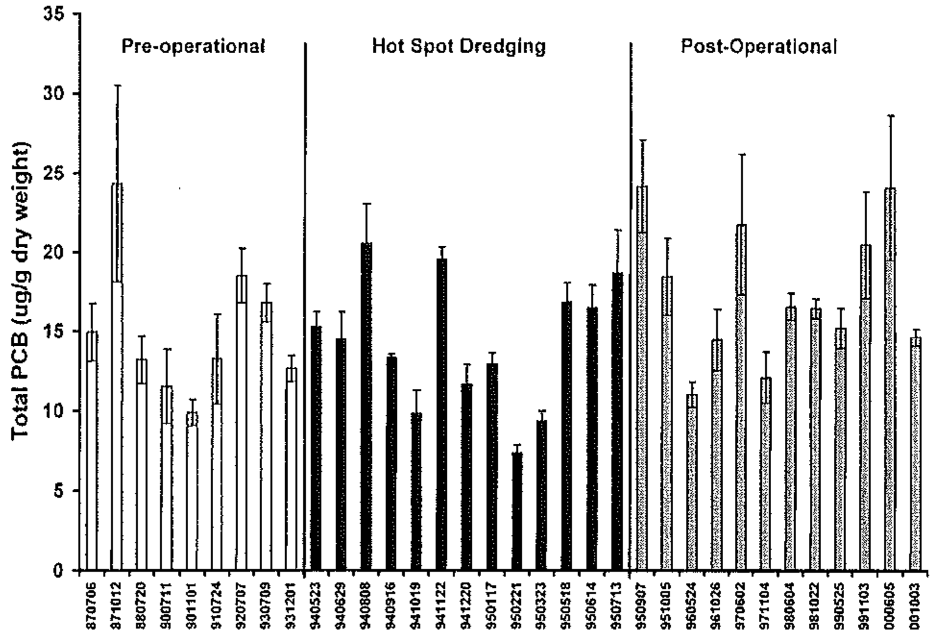

Figure 5. Total PCB (μg/g dry weight) for individual 28-day deployments of blue mussels (*Mytilus edulis*) and (*Geukensia demissa*) at station NBH-2 (Coggeshall St. Bridge). Results are shown for the pre-operational (1987–1993), operational (1994–September 1995), and post-operational (September 1995–2000) phases of the NBH Hot Spot remediation.

mussel PCB bioaccumulation was monitored to signal increases in water column PCB concentration if dredging caused increased resuspension and bioavailability, and none was observed, this decision criterion was not violated. The current mussel bioaccumulation data set will continue to be augmented twice yearly at these three stations to provide an integrated assessment of water column PCB concentrations as part of the NBH Long-term Monitoring Plan (Nelson *et al.*, 1996). When full-scale remediation of the upper harbor is completed, this dataset will be one of the primary indicators used to assess the overall effectiveness of remedial activities relative to sediment and water column PCB concentrations and subsequent bioavailability.

4. Conclusions

The monitoring data collected during the Hot Spot dredging indicated that the two remedial operation objectives were met; the net transport of PCBs resuspended during dredging did not result in the need for additional remediation in cleaner areas of the lower harbor and toxicity and bioaccumulation were limited. In general, the results of the biological testing indicate minimal, if any, acute and chronic impacts directly attributable to dredging, although there were sporadic, and sometimes contradictory occurrences.

Remedial dredging at Superfund sites like New Bedford Harbor (NBH) involves the potential for causing detrimental environmental effects due to resuspension and/or release of toxic contaminants. These effects can be mitigated by: 1) implementing an effective monitoring program to rapidly assess potential impacts, 2) modifying operational procedures where necessary to minimize effects, and 3) using the site-specific information gathered (e.g., general approaches) and "lessons learned" for future dredging operations, both at that location and others. The monitoring program described here utilized PCB net transport, water column toxicity, and bioaccumulation to quantify the impacts of the Hot Spot remedial dredging in NBH. The data indicate that the dredging operation did not result in increased PCB transport to cleaner areas of the harbor, had little or no effect on water column toxicity, and did not result in significant increases in mussel PCB bioaccumulation. Collectively, these monitoring results indicate that the site-specific criteria developed to limit negative impacts were effective and that the remedial dredging operation was completed within the acceptable limits agreed to by USEPA, CENEA, and the Commonwealth of Massachusetts.

In summary, the approach described here resulted in permanently removing 14 000 cubic yards of contaminated sediment with PCB concentrations in excess of 4000 μg/g without causing significant additional environmental impacts, thereby demonstrating that severely contaminated estuarine sediments can be remediated safely. Furthermore, while the individual decision criteria were specific to this NBH dredging operation, the approach used was built on "lessons learned" during a previous pilot study and the full-scale remediation in NBH will benefit from insights gained during this operation. This overall monitoring approach was found to be effective in NBH and is recommended for use at other contaminated sediment sites as well.

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