1999 outfall benthic monitoring report

Massachusetts Water Resources Authority

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1999 Outfall Benthic Monitoring Report

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EXECUTIVE SUMMARY

The Outfall Benthic Surveys began in 1992 as part of the Benthic (Sea-Floor) Monitoring component of the MWRA Harbor and Outfall Monitoring (HOM) program. This study is designed to address three main concerns relative to the response of the benthic community to MWRA's relocation of the effluent discharge into Massachusetts Bay: eutrophication, contaminants, and particulate inputs. The Outfall Benthic Surveys provide quantitative measurements of benthic community structure and patterns of contaminant concentrations within sediments of Massachusetts and Cape Cod Bays. The pre-discharge monitoring has provided an extensive understanding of the baseline conditions and changes through time. After effluent discharge into the Bay begins, the focus of the program will change from the collection of baseline data to an evaluation of the effects of the discharge on the Bay ecosystems. Outfall surveys conducted after 2000 will provide the data required for a quantitative assessment of the effects of discharged effluent on sediment chemistry and benthic infauna communities. The objectives of the monitoring program following the initiation of effluent discharge into the Bay are (1) to monitor versus NPDES permit requirements, (2) to test whether or not the discharge-related impacts are within the limits predicted by the SEIS, and (3) to determine if changes in the system exceed Contingency Plan thresholds (MWRA 1997).

The 1999 outfall benthic survey was conducted before effluent discharge began at the new outfall and continued the collection of baseline data from each of the benthic monitoring program's four components: sediment profile images (SPI), geochemical properties, contaminants, and sewage tracers in sediment, benthic infaunal community, and hardbottom community. Sediment profile images (SPI) are collected to monitor the general condition of the soft-bottom benthic habitats in western Massachusetts Bay. In 1999, SPI were collected from 23 western Bay stations. Sediment geochemistry studies, conducted via the collection of sediment grab samples, consist of grain-size analysis, total organic carbon (TOC) content determination, and periodically contaminant concentration analyses. The presence of a sewage tracer, *Clostridium perfringens*, is quantified during these studies. Contaminant sampling and analysis as part of MWRA's baseline monitoring occurred annually from 1992 through 1995. In May 1996 the Outfall Monitoring Task Force determined the sediment contaminant baseline was adequate, and that analyses could stop until discharge resumed. At the time, outfall startup was expected to occur in 1997 or 1998. Given the delayed outfall startup, MWRA decided to supplement the baseline by collecting additional contaminant samples at all stations in August 1999. In addition samples at four stations for the contaminant special study were collected in August of 1999. The presence of a sewage tracer, *Clostridium perfringens*, was also quantified during these studies. Infaunal communities in Massachusetts Bay and Cape Cod Bay are monitored via the collection of samples from 20 Nearfield and 11 Farfield stations. All stations were sampled in 1999. Because of the preponderance of hard substrates in the vicinity of the outfall, semi-quantitative studies of the epifaunal communities associated with them are conducted yearly. In 1999, a remotely-operated vehicle was used to collect still photographs and videotapes from all hard-bottom stations except station T2-5 and Diffuser #44, which were located within a 1000-m zone of the outfall. These stations were not surveyed in 1999 because of work in the outfall tunnel. Summaries of the 1999 results from the components follow.

Sediment Profile Images

In 1999 the SPI study again included a "Quick Look" analysis. This analysis was developed to deliver rapid data turnaround to permit assessment of a benthic trigger, a 50% reduction of the depth of the redox potential discontinuity (RPD). The analysis involved examination of the profile images soon after completion of the survey. The results of the Quick Look analysis, which were reported separately, were found to be highly comparable to a more detailed computer-based analysis. The difference between the two analyses averaged 0.3 cm (SD = 0.35) for the 20 Nearfield stations that had measured RPD layer depths. The RPD depth differed between the two analyses by >1 cm at only one station-replicate

(NF22-2). A comparison of the within-station sensitivity of the Quick Look analysis showed that it had sufficient resolution to evaluate the RPD trigger.

The detailed SPI analysis showed that the average RPD value for 1999 (2.3 cm) was slightly deeper than it was for 1998. Statistical comparison of RPD values for the seven stations that were measured for all for years (1992, 1995, 1997, 1998, 1999) showed strong differences among years. Values for 1992, 1995, and 1999 differed from those for 1997 and 1998. Values for 1992 differed from those for all other years. While pioneering successional Stage I communities prevailed in the Nearfield in 1992 to 1997, stage II communities dominated in 1998 and 1999. The overall 1999 Nearfield average Organism-Sediment Index, which integrates several SPI parameters as a general measure of habitat condition, was statistically the same as those calculated in 1992, 1995, and 1998, but was higher (as was 1998) than the 1997 value. The low 1997 values might have reflected a seasonal change stress as SPI sampling was done in October rather than August. The 1999 SPI data showed that biological processes continued to increase in importance as a structuring mechanism of the Nearfield communities, a trend that likely began in 1995.

Sediment Geochemistry

Generally, the spatial distribution and temporal response of grain-size and total organic carbon (TOC) in 1999 were not substantially different from previous years (1992–1998). Total organic carbon content of the Nearfield sediments continued to be low as none contained > 1.5 % TOC by dry weight. However, *Clostridium perfringens* showed decreasing abundance in 1998 and 1999 from earlier years that suggested a “cleaner effluent” with less particulates is being discharged, possibly as a result of secondary treatment coming on-line in 1997.

The abundance of *Clostridium perfringens* decreased in 1998 and 1999 from earlier years and appeared to decrease with distance from Boston Harbor. Yearly means values of *Clostridium perfringens* (normalized to percent fines) for near-in stations (< 20 km) showed a decrease in abundance in 1998 and 1999 relative to earlier years. In contrast, stations further away from Deer Island Point (> 20 km) were on average relatively constant from 1992–1999. The constancy in results within distance classifications after normalization to fine grained sediments suggests the *Clostridium perfringens* abundance is strongly related to grain size.

Sediment Contaminants

Generally, the spatial distribution and temporal response of contaminant parameters in the 1999 Nearfield and Farfield were not substantially different from earlier years (1992–1998). Concentrations of organic and metal contaminants were generally low and the system was spatially variable. Variability was primarily controlled by grain size and TOC.

Baseline mean values in the Nearfield have been relatively consistent since 1992 and were well below MWRA thresholds. Baseline mean values in the Farfield were also relatively constant since 1992 and were generally less than Nearfield values. The temporal response of the baseline was similar for both Special Contaminant Study stations and the Nearfield, suggesting that the Special Contaminant Study stations are reasonably representative of the Nearfield.

To establish when significant increases above the baseline would be detected, a statistical value was established. The significant increase value was set as the 95th percentile upper confidence limit (based on the “t” distribution) of the mean of the annual means. The significant increase values are well within the range of detection and MWRA thresholds are at least 2.4 times higher than the level of significant increase, suggesting that the ability to detect changes in contaminant concentrations prior to thresholds is high.

Infaunal Communities

Examination of the 1992–1997 infaunal dataset revealed that species diversity in Massachusetts Bay has increased during the course of the monitoring program. Diversity, as measured by log-series alpha and species richness (numbers of species), was significantly higher in 1998 that for the combined 1992–1997 Nearfield data. Infaunal abundance in 1998 was also somewhat higher than for the 1992–1997 period.

Multivariate analysis of the 1998 Nearfield data showed that the infaunal community could be separated into two primary groups of stations. The first group was comprised of samples from stations NF13, NF17, and NF23 and was distinguished by high abundances of the annelids *Polygordius* sp. A and *Spiophanes bombyx*. These species were associated primarily with medium to fine sand sediments. The second group of stations revealed by the multivariate analysis was complex and consisted of samples from the remaining Nearfield (here including stations FF10, FF12, and FF13). Key taxa included the annelids *Prionospio steenstrupi*, *Mediomastus californiensis*, and *Aricidea catherinae*. These taxa were associated with a wide range of sediments, ranging from medium sands to silt. Multivariate analysis of the 1998 Farfield data showed that the infaunal community could be divided into three dissimilar groups. The first group included stations FF01A and FF09, which were characterized by relatively high numbers of the annelid *Prionospio steenstrupi* and the nut clam *Nucula delphinodonta*. The second cluster group consisted of stations located along the eastern portions of the Bay from off Cape Ann to the north and in Cape Cod Bay to the south. This group was characterized by a variety of taxa including the annelids *Euchone incolor*, *Mediomastus californiensis*, *Aricidea quadrilobata*, and *Anobothrus gracilis*. The final cluster was comprised only of samples from station FF06 in Cape Cod Bay. Key taxa here were the annelids *Aricidea catherinae* and *Tharyx acutus* and the amphipod *Leptocheirus pinguis*.

Hard-bottom Communities

Classification analysis of the 1998 hard-bottom data showed that the community could be separated into three main groups of stations. The first group consisted primarily of moderate to high-relief drumlin top areas that had variable sediment drape. The encrusting coralline alga *Lithothamnion* was a common inhabitant of many areas that comprised this group. Other key taxa in Cluster 1 were the upright algae *Asparagopsis hamifera* and *Rhodymenia palmata*. Cluster 2 consisted of drumlin top and flank areas that had light to moderately-light sediment drape. *Lithothamnion* was the dominant taxon in this group. Cluster 3 consisted mainly of drumlin flank areas that had low to moderately-low relief and moderately-heavy sediment drape. Areas in this group were characterized by low abundances of algae and fish and had low to moderate abundances of invertebrates. The sea star *Asterias* was the most common taxon here. The hard-bottom communities near the outfall have been studied consistently for the past four years. During this time the communities, although spatially variable, have shown reasonable temporal stability.

1. INTRODUCTION

The Outfall Benthic Surveys began in 1992 as part of the Benthic (Sea-Floor) Monitoring component of the MWRA Harbor and Outfall Monitoring (HOM) program. This study is designed to address three main concerns relative to the response of the benthic community to MWRA's relocation of the effluent discharge into Massachusetts Bay: eutrophication, contaminants, and particulate inputs. The Outfall Benthic Surveys provide quantitative measurements of benthic community structure and patterns of contaminant concentrations within sediments of Massachusetts and Cape Cod Bays. The pre-discharge monitoring has provided an extensive understanding of the baseline conditions and changes through time. After effluent discharge into the Bay begins, the focus of the program will change from the collection of baseline data to an evaluation of the effects of the discharge on the Bay ecosystems. Outfall surveys conducted after 2000 will provide the data required for a quantitative assessment of the effects of discharged effluent on sediment chemistry and benthic infauna communities. The objectives of the monitoring program following the initiation of effluent discharge into the Bay are (1) to monitor versus NPDES permit requirements, (2) to test whether or not the discharge-related impacts are within the limits predicted by the SEIS, and (3) to determine if changes in the system exceed Contingency Plan thresholds (MWRA 1997).

The 1999 outfall benthic survey was conducted before effluent discharge began at the new outfall and continued the collection of baseline data from each of the benthic monitoring program's four components: sediment profile images (SPI), geochemical properties, contaminants, and sewage tracers in sediment, benthic infaunal community, and hardbottom community. The results and analyses of the sediment profile images collected from 23 western Bay stations are presented in Section 3. Sediment geochemistry studies, conducted via the collection of sediment grab samples, consist of grain-size analysis, total organic carbon (TOC) content determination, and periodically contaminant concentration analyses. Contaminant sampling and analysis as part of MWRA's baseline monitoring occurred annually from 1992 through 1995. In May 1996 the Outfall Monitoring Task Force determined the sediment contaminant baseline was adequate, and that analyses could stop until discharge resumed. At the time, outfall startup was expected to occur in 1997 or 1998. Given the delayed outfall startup, MWRA decided to supplement the baseline by collecting additional contaminant samples at all stations in August 1999. In addition samples at four stations for the contaminant special study were collected in August of 1999. The presence of a sewage tracer, *Clostridium perfringens*, was also quantified during these studies. These studies are presented in Section 4. Infaunal communities in Massachusetts Bay and Cape Cod Bay are monitored via the collection of samples from 20 Nearfield and 11 Farfield stations. All stations were visited in 1999. Analyses of the infaunal communities are described in Section 5 and include an evaluation of infaunal communities in relation to the suite of sediment geochemical parameters measured. Because of the preponderance of hard substrates in the vicinity of the outfall, semi-quantitative studies of the epifaunal communities associated with them are conducted yearly. In 1999, a remotely-operated vehicle was used to collect still photographs and videotapes from all hard-bottom stations except station T2-5 and Diffuser #44, which were located within a 1000-m zone of the outfall. These stations were not surveyed in 1999 because of work in the outfall tunnel. Analyses of the hard-bottom survey data constitute Section 6. This report also includes a programmatic evaluation of each of the components. This evaluation is presented in Section 7.

The raw data for all of these studies are available from MWRA.

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2. FIELD OPERATIONS

By Jeanine D. Boyle

2.1 Sampling Design

2.1.1 Soft-Bottom

Sediment Samples—The Nearfield benthic surveys, conducted annually in August, are designed to provide spatial coverage and local detail of faunal communities inhabiting depositional environments within about 8 km of the diffuser. Samples for sediment chemistry and benthic infauna were collected at 20 Nearfield stations (Figure 2-1). The target locations for the Nearfield stations are listed in the CW/QAPP (Kropp and Boyle 1998). The actual locations of each grab sample collected are listed in Appendix A-1.

Farfield benthic surveys, also conducted annually in August each year, are designed to contribute reference and early-warning data on soft-bottom habitats in Massachusetts and Cape Cod Bays. Grab samples were collected at 11 stations in Massachusetts and Cape Cod Bays (Figure 2-2) for infaunal and chemical analyses. The target locations for the Farfield stations are listed in the CW/QAPP (Kropp and Boyle 1998). The actual locations of each grab sample collected are listed in Appendix A-1.

The Nearfield Contaminant Special Study Surveys are designed to examine the possible short-term impacts of the new outfall discharge on sedimentary contaminant concentrations and their interrelationships with possible sedimentary organic carbon changes in depositional environments near the effluent outfall. In August 1999, samples were collected from the four Contaminant Special Study Stations, in conjunction with the August Nearfield/Farfield Survey. The Nearfield Contaminant Special Study stations include; NF08, NF22, NF24, and FF10. The historical (*i.e.*, pre-1998) criteria used to select these four locations were:

- Historically, stations (except FF10) were comprised of fine grained material (>50% sand/silt);
- Stations were in relatively stable areas (except for FF10, grain size composition >50% sand/silt over the period monitored);
- Stations (except FF10) had high total organic carbon (TOC) content, relative to other locations nearby (at least 1% TOC);
- Stations were within the zone of increased particulate organic carbon deposition predicted by the Bay Eutrophication Model (BEM, Hydroqual and Normandeau, 1995); and
- Selection of these stations complements and expands on stations (NF12, NF17) periodically sampled by the USGS.

Stations FF10, NF08, and NF24 lie on a line extending to the northwest from the west end of the diffuser and along with NF12, separately sampled by the USGS, provide a spatial gradient extending from the diffuser (Figure 2-1). This gradient extends towards the predicted high deposition area. Station NF22 lies to the southwest of the west end of the diffuser and is along the projected long-term effluent transport path from the diffuser. Station FF10 extends the area of impact sampled under the contaminant special studies task and represents a Farfield location near the center of the high deposition location predicted by the BEM model and is a sandier location.

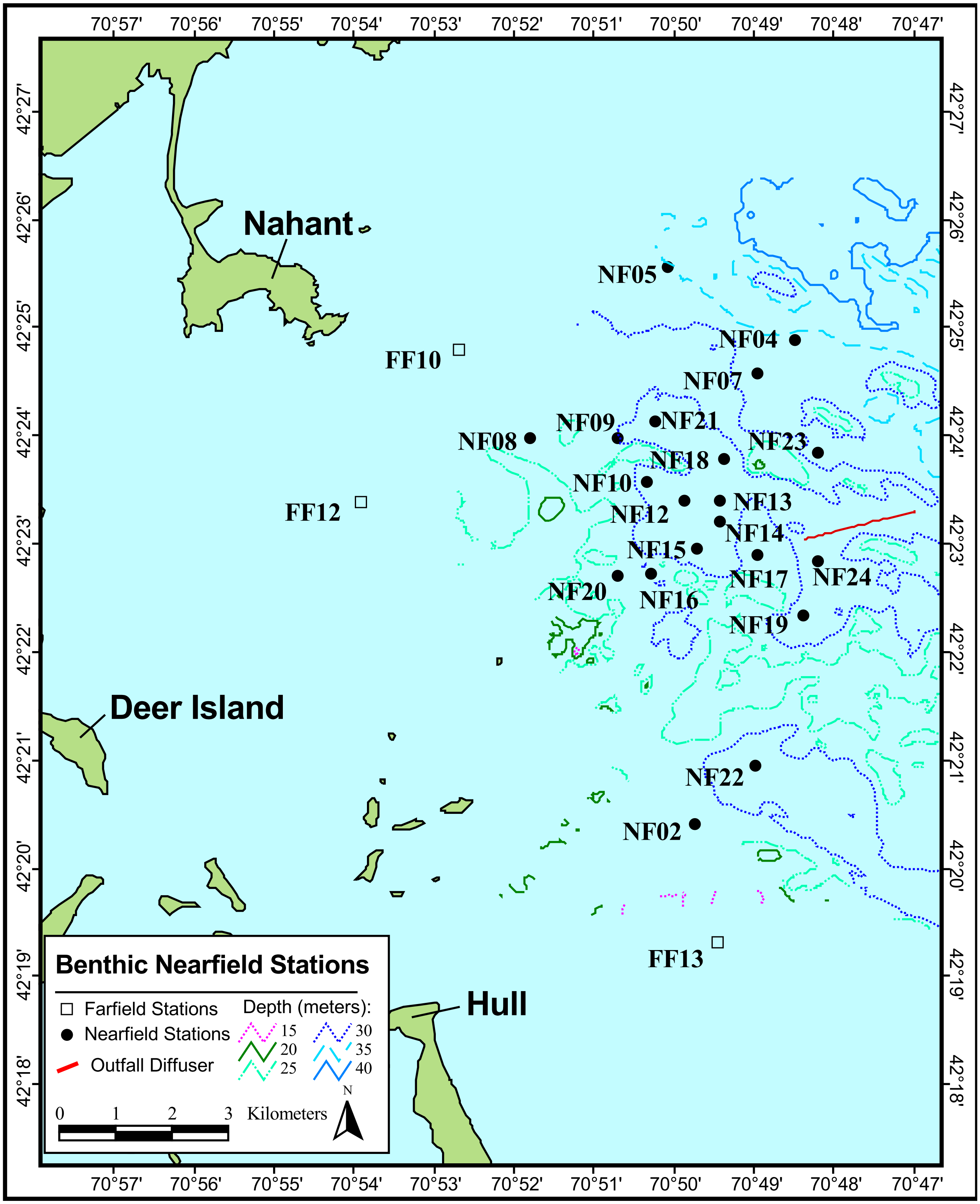


Figure 2-1. Locations of Nearfield and selected Farfield grab stations sampled in August 1999.

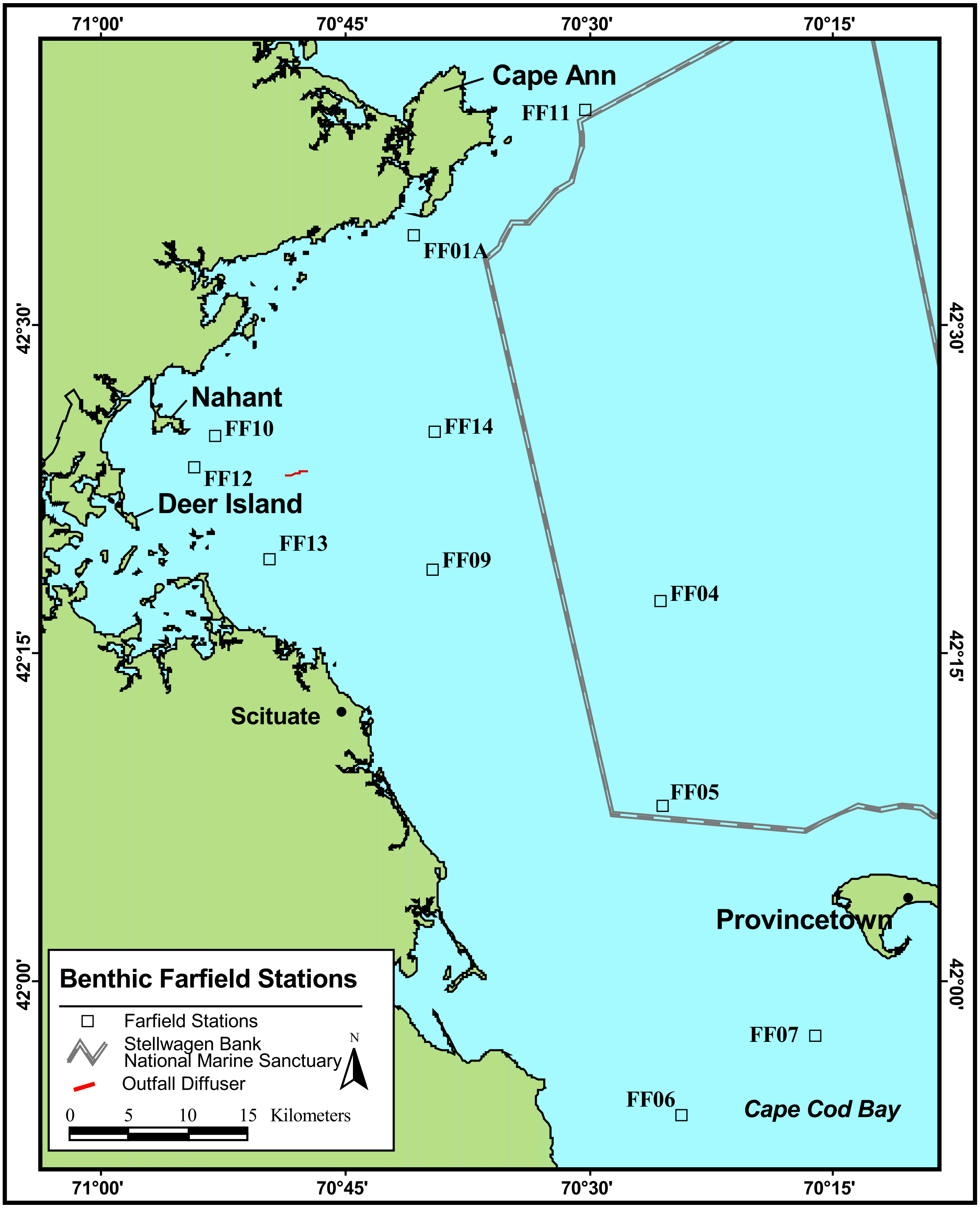


Figure 2-2. Locations of Farfield grab stations sampled in August 1999.

The actual locations of all grab samples collected on the contaminant special study survey are listed in Appendix A-1.

Sediment Profile Images—The Nearfield Sediment Profile Image surveys are conducted in August of each year at 20 Nearfield and 3 Farfield stations (Figure 2-1) to give an area-wide, qualitative/ semi-quantitative assessment of sediment quality and benthic community status that can be integrated with the results of the more localized, quantitative surveys to determine sedimentary conditions near the outfall. Furthermore, these surveys provide rapid comparison of benthic conditions to the benthic triggering thresholds. Traditional sediment profile imagery (35-mm slides) allows a faster evaluation of the benthos to be made than can be accomplished through traditional faunal analyses. A more rapid analysis of the SPI data was accomplished by fitting the profile camera prism with a digital video camera arranged to view the same sediment profile as the 35-mm film camera. The target locations for the SPI sampling are the same as those for the grab sampling effort. The actual locations of all sediment profile images collected are listed in Appendix A-2.

2.1.2 Hard-Bottom

Because of the relative rarity of depositional habitats in the Nearfield and in the vicinity of the diffusers, a continuing study of hard-bottom habitats has been implemented to supplement the soft-bottom studies. The Nearfield hard-bottom surveys are conducted in June of each year. Video tape footage and 35-mm slides were taken at 19 waypoints along six transects and at two additional discrete waypoint (T9-1 and T10-1). In preparation for the diffuser uncapping, the outfall area was designated a no-anchor zone in April 1999 and two historical waypoints, Diffuser 44 and T2-5, were not sampled this year (Figure 2-3). Actual coordinates for hard-bottom stations sampled in June 1999 are listed in Appendix A-3.

2.2 Surveys/Samples Collected

The dates of the outfall benthic surveys and the numbers of samples collected on them are listed in Table 2-1.

Table 2-1. Survey dates and numbers of samples collected on benthic surveys in 1999.

Survey	ID	Date(s)	Samples Collected								
			Inf	TOC	Gs	Cp	C	Tm	SPI	35	V
Nearfield Benthic	BN991	10, 11, 12, 13 Aug 1999	26	28	28	28	28	28	–	–	–
Farfield Benthic	BF991	11, 13 Aug 1999	33	23	23	23	23	23	–	–	–
SPI	BR991	24, 25, 26 Aug 1999	–	–	–	–			76	–	76
Hard-bottom	BH991	22, 23, 24 Jun 1999	–	–	–	–			–	756	42
Nearfield Contaminant[a]	BC992	10, 12, 13 Aug 1999	–	12	12	12	12	12	–	–	–

[a] Six samples collected during surveys BF/BN991 were used to supplement the six collected during survey BC992.

Key:

Inf, Infauna
Gs, grain size
C, contaminant
35, 35-mm slides (hard-bottom)
Tm, trace metals

TOC, total organic carbon
Cp, *Clostridium perfringens*
SPI, sediment profile images (slides)
V, video segments (hard-bottom)

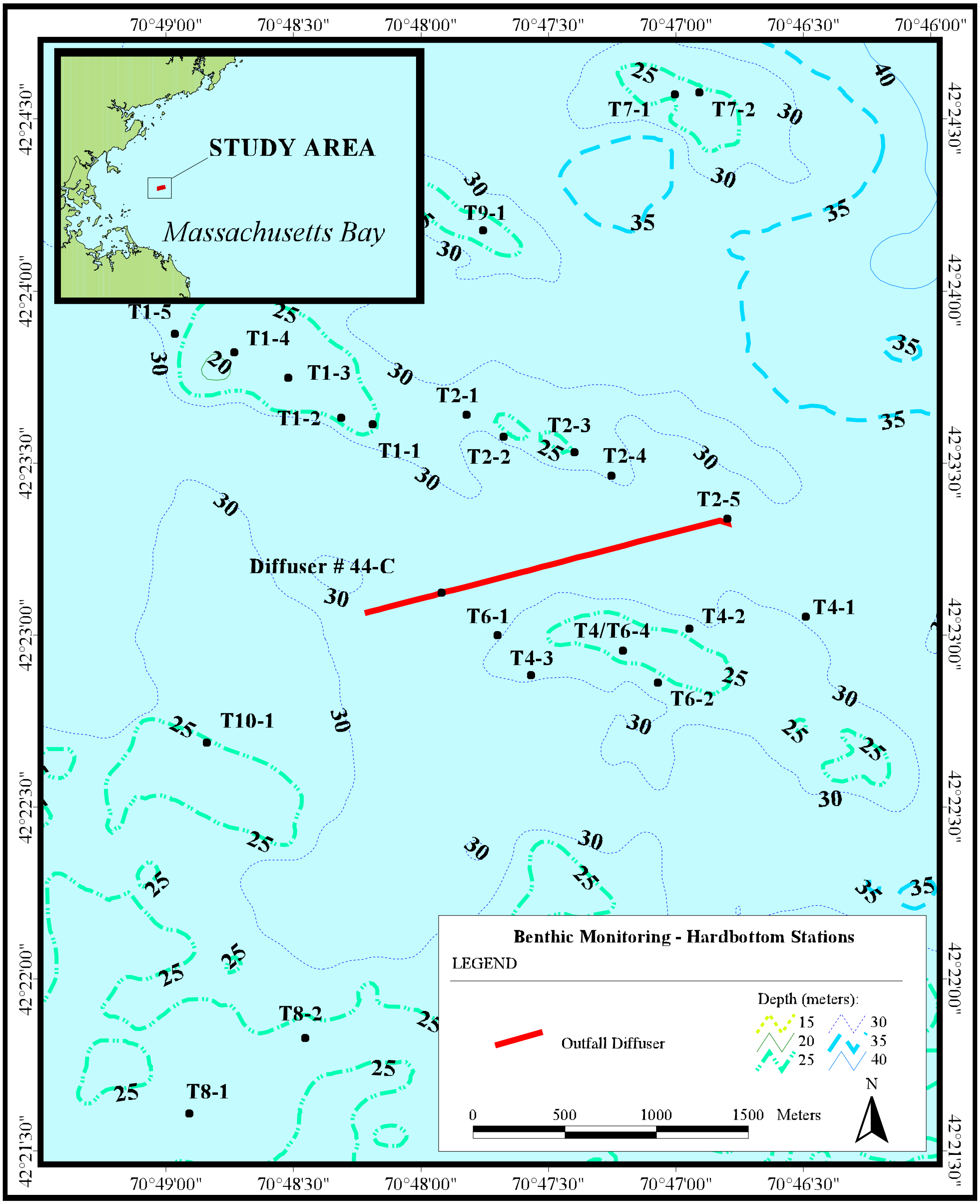


Figure 2-3. Locations of hard-bottom stations sampled in June 1999. Diffuser 44 and T2-5 were not sampled in 1999 because of the no-anchor zone established around the diffusers.

2.3 Field Methods Overview

The following is a brief overview of the methods and protocols used on the benthic surveys. More detailed descriptions of the methods are contained in the CW/QAPP (Kropp and Boyle 1998).

2.3.1 Vessel/ Navigation

Vessel positioning during benthic sample operations was accomplished with the BOSS Navigation system. This system consists of a Northstar differential global positioning system (DGPS) interfaced to the on-board BOSS computer. Data were recorded and reduced using NAVSAM data acquisition software. The GPS receiver has six dedicated channels and is capable of locking into six satellites at one time. The system was calibrated with coordinates obtained from USGS navigation charts at the beginning and end of each survey day.

At each sampling station, the vessel was positioned as close to target coordinates as possible. The NAVSAM navigation and sampling software collected and stored navigation data, time, and station depth every 2 seconds throughout the sampling event, and assigned a unique ID to each sample when the sampling instrument hit bottom. The display on the BOSS computer screen was set to show a radius of 30 m around the target station coordinates (6, 5-m rings) for all MWRA benthic surveys. A station radius of up to 30 m is considered acceptable for sediment sampling in Massachusetts Bay.

2.3.2 Grab Sampling

Nearfield/Farfield Benthic Surveys—At all 11 Farfield stations and 3 Nearfield stations (NF12, NF17, and NF24), a 0.04-m^2 modified van Veen grab sampler was used to collect 3 replicate samples for infaunal analysis and 2 replicate samples for *Clostridium perfringens*, sediment grain size, TOC, and contaminant analyses. At each of the remaining 17 Nearfield stations, 1 grab sample for infaunal analysis and one grab sample for *C. perfringens*, sediment grain size, TOC, and contaminant analyses were collected. Infaunal samples were sieved onboard the survey vessel over a 300-μm-mesh sieve and fixed in buffered formalin. The “chemistry” sample was skimmed off the top 2 cm of the grab by using a Kynar-coated scoop, and was homogenized in a clean glass bowl before being distributed to appropriate storage containers. The TOC samples were frozen, whereas the *C. perfringens* and grain size samples were placed on ice in coolers.

Sediment sampling at stations FF04 and FF05 in the Stellwagen Bank National Marine Sanctuary was conducted under Permit #SBNMS-D6-98.

Nearfield Contaminant Special Study—During the August Nearfield/Farfield benthic survey, additional sediment was collected from stations NF08, NF22, NF24, and FF10 to bring the total number of “chemistry” replicates (TOC, grain size, *Clostridium,* and contaminants) at those stations to three. Samples were collected from the top 2 cm of the Kynar-coated grab and processed as described above.

2.3.3 SPI

At each station, a Hulcher Model Minnie sediment profile camera fitted with a digital video camera, to allow for real-time viewing of the sediment profiles, was deployed three times. The profile camera was set to take two pictures, using Fujichrome 100P slide film, on each deployment at 2 and 12 seconds after bottom contact. In the event that sediments were soft the two-picture sequence would ensure that the sediment-water interface would be photographed before the prism window over penetrated. The combination of video and film cameras ensured accurate and reliable collection of sediment profile images. Any replicates that appeared to be disturbed during deployment were retaken. The videotape ran during each drop and was narrated in real time by the Senior Scientist, Dr. Robert Diaz, as the photos were taken. The narration included the station, time, approximate prism penetration depth, and a brief description of the substrate. In addition, the Oxidation-Reduction Potential Discontinuity was estimated by Dr. Diaz at each Nearfield station. These measurements were recorded in Dr. Diaz's log, and the Battelle Survey logbook. Each touch down of the camera was marked as an event on the NAVSAM©. The video image was recorded for use as part of the Quick Look analysis.

2.3.4 Hard-Bottom

The June 1999 hard-bottom survey of the Nearfield examined 19 waypoints distributed along 6 transects (T1, T2, T4, T6, T7, and T8), plus 2 additional waypoints (T9-1 and T10-1). A MiniRover MK II ROV equipped with a Benthos low-light, high-resolution video camera, a Benthos Model 3782 35-mm minicamera with strobe, 150 W halogen lamps, a compass, and a depth gauge was deployed from the survey vessel to obtain the necessary video and slides. The ROV was guided as close to the bottom as possible so that the clarity of the video and photographs was maximized. Approximately 20 minutes of video footage per waypoint were recorded along a randomly-selected heading. Along this route, still photographs were taken as selected by the Senior Scientist, Dr. Barbara Hecker, until an entire (36 exposure) roll of 35-mm film was exposed at each waypoint.

The date, time, and ROV depth were recorded on the videotapes and appeared on the video monitor during the recording. These data were not recorded on each photograph taken at the waypoints. These were recorded in a notebook and later transferred to the still slides. The start of and stop of each video tape, the start of each roll of film, and the capture of each 35-mm image were recorded as "events" on the NAVSAM© system. The time displayed on the video monitor (and recorded on the tape) was synchronized with the NAVSAM© clock. When a still photograph was taken, the event also was marked verbally on the video tape. The NAVSAM© produced labels that were attached to each video cartridge and each film canister. All slides were developed onboard to monitor camera proficiency. Slides were labeled manually at the lab after mounting. All slides were scanned into electronic images and copied onto a CD for archival.

3. 1999 SEDIMENT PROFILE CAMERA RECONNAISSANCE OF NEARFIELD BENTHIC HABITATS

by Robert J. Diaz

3.1 Materials and Methods

3.1.1 Quick Look Analysis

The Quick Look analysis was developed in 1998 to meet the needs of rapid data turn around for assessment of benthic triggers, one of which is an area wide 50% reduction in the average depth of the redox potential discontinuity (RPD) layer (MWRA 1997). The exposed film was developed 26 August, the last day of field operations, and the Quick Look analysis completed 30 August (Diaz 1999). See Kropp *et al*. (2000) for details on the Quick Look analysis.

3.1.2 Image Analysis

The sediment profile images were first analyzed visually by projecting the images and recording all features seen into a preformatted standardized spreadsheet file. The images were then digitized using a Nikon 2000 scanner and analyzed using the Adobe PhotoShop and NTIS Image programs. Data from each image were sequentially saved to a spreadsheet file for later analysis. Details of how these data were obtained can be found in Diaz and Schaffner (1988), Rhoads and Germano (1986), and Kropp *et al*. (2000).

3.2 Results and Discussion

3.2.1 Quick Look vs. Detailed Analyses

Overall there was a high degree of correspondence between the Quick Look and detailed analyses (Table 3-1). For example, the correlation between the two analyses for the apparent color RPD layer depth, one of the benthic trigger parameters (MWRA 1997), was 0.81 ($p < 0.001$) with the Quick Look analysis tending to be higher relative to the detailed analysis (paired t-test, $p = 0.01$). The difference between the two analyses averaged 0.3 cm (SD = 0.35) for the 20 Nearfield stations that had measured RPD layer depths (Table 3-2). At three clean sandy sediments stations (NF04, NF13 and NF17) the RPD layer was deeper than prism penetration. The RPD depth differed between the two analyses by >1 cm at only one station-replicate (NF22-2) (Table 3-1). About two-thirds of the replicate images with measured RPD depths had deeper values in the Quick Look analysis. Overestimation of RPD depth in the Quick Look analysis was related to the 0.5 cm resolution of the Quick Look and the overall light color and low contrast of sediment at many stations. Both of these problems were accounted for in the computer image analysis.

To test the sensitivity of the Quick Look analysis for estimating RPD depths, the station Quick Look value was expressed as a percentage of the computer analysis value (Table 3-2). For the 20 stations with measured RPD depths, only one station exceeded a difference of 50% (NF24). This indicated that the Quick Look analysis had sufficient resolution to estimate changes in RPD depths given the 50% change criteria.

Table 3-1. Comparison of August 1999 Nearfield apparent color RPDs from the Quick Look and detailed computer analyses of SPI images. Quick Look analysis was completed two days after fieldwork. Detailed analysis was completed 30 days after fieldwork. Delta is the difference between the two analyses. Negative sign indicates detailed analysis produced a deeper RPD layer depth estimate.

Station	Replicate	Quick Look RPD(cm)	Detailed RPD(cm)	Delta(cm)
FF10	1	IND*	IND	IND
FF10	2	3	2.2	0.8
FF10	3	2.5	2.2	0.3
FF12	1	2	1.3	0.7
FF12	2	2.5	1.7	0.8
FF12	3	2.5	1.9	0.6
FF13	1	IND	IND	IND
FF13	2	IND	IND	IND
FF13	3	1	1.0	0.0
FF13	4	2	1.2	0.8
FF13	5	3	2.4	0.6
NF02	1	IND	IND	IND
NF02	2	IND	IND	IND
NF02	3	IND	IND	IND
NF02	4	2	2.1	–0.1
NF04	1	>3*	>3.2	>–0.2
NF04	2	>4	>3.1	0.9
NF04	3	>4	>4.2	–0.2
NF05	1	2.5	2.3	0.2
NF05	2	2.5	2.2	0.3
NF05	3	3	3.5	–0.5
NF07	1	1.5	1.6	–0.1
NF07	2	1.5	2.1	–0.6
NF07	3	1	1.0	0.0
NF08	1	2	1.9	0.1
NF08	2	2	1.5	0.5
NF08	3	2	1.7	0.3
NF09	1	2	2.3	–0.3
NF09	2	2	1.4	0.6
NF09	3	2.5	2.0	0.5
NF10	1	2.5	1.6	0.9
NF10	2	2	2.5	–0.5
NF10	3	2	1.6	0.4
NF12	1	2.5	1.8	0.7
NF12	2	2	1.3	0.7
NF12	3	3	2.5	0.5
NF13	1	>3	>2.8	>0.2
NF13	2	>3	>2.8	0.2
NF13	3	>3	>2.5	0.5
NF14	1	4	4.6	–0.6

Station	Replicate	Quick Look RPD(cm)	Detailed RPD(cm)	Delta(cm)
NF14	2	3	3.0	0.0
NF14	3	2	2.1	–0.1
NF15	1	2.5	2.3	0.2
NF15	2	3	2.5	0.5
NF15	3	2.5	2.1	0.4
NF16	1	3	2.2	0.8
NF16	2	2	1.2	0.8
NF16	3	2.5	1.9	0.6
NF17	1	>4	>3.4	>0.6
NF17	2	>5	>5.2	–0.2
NF17	3	>3	>3.3	–0.3
NF18	1	3	2.6	0.4
NF18	2	2.5	2.5	0.0
NF18	3	3.5	2.9	0.6
NF19	1	1.5	1.5	0.0
NF19	2	1.5	1.6	–0.1
NF19	3	1	1.3	–0.3
NF20	1	3	3.4	–0.4
NF20	2	2	2.0	0.0
NF20	3	3	2.9	0.1
NF21	1	3	2.3	0.7
NF21	2	2.5	2.0	0.5
NF21	3	1.5	0.9	0.6
NF22	1	2.5	1.9	0.6
NF22	2	3.5	2.4	1.1
NF22	3	2.5	1.9	0.6
NF23	1	>4	>3.7	>0.3
NF23	2	>3	>2.7	0.3
NF23	3	4	4.4	–0.4
NF23	4	>3	>2.6	0.4
NF24	1	2	1.1	0.9
NF24	2	2	1.6	0.4
NF24	3	IND	IND	IND
NF24	4	IND	IND	IND

* IND = RPD was indeterminate.
\> = RPD layer depth was greater than prism penetration

Table 3-2. Difference between Quick Look (QL) and detailed (D) computer analyses of the apparent color RPD layer depth from Nearfield stations, August 1999. Delta is the difference between QL and D. Negative sign indicates detailed analysis produced a deeper RPD layer depth estimate. Only images that had identifiable RPD layers were included.

Station	QL (cm)	D (cm)	Delta (cm)	Percent Difference
FF10	2.8	2.2	0.6	26.5
FF12	2.3	1.6	0.7	44.7
FF13	2.0	1.5	0.5	31.7
NF02	2.0	2.1	–0.1	–4.9
NF04	>3.7*	>3.5	–	–
NF05	2.7	2.7	0.0	–0.6
NF07	1.3	1.6	–0.2	–14.1
NF08	2.0	1.7	0.3	16.8
NF09	2.2	1.9	0.3	15.0
NF10	2.2	1.9	0.3	15.5
NF12	2.5	1.9	0.6	33.9
NF13	>3.0*	>2.7	–	–
NF14	3.0	3.3	–0.3	–8.0
NF15	2.7	2.3	0.4	17.4
NF16	2.5	1.8	0.7	42.1
NF17	>4.0*	>4.0	–	–
NF18	3.0	2.6	0.4	14.0
NF19	1.3	1.5	–0.1	–9.1
NF20	2.7	2.8	–0.1	–3.4
NF21	2.3	1.7	0.6	36.0
NF22	2.8	2.1	0.7	35.8
NF23	3.5	3.3	0.2	4.7
NF24	2.0	1.3	0.7	50.5
Grand Ave.	2.4	2.1	0.3	14.8
SD	0.5	0.6	0.3	–

* Not included in average, prism penetration too shallow to see RPD.

3.2.2 1999 Nearfield Image Data

At least three replicate sediment profile film images and taped video were collected at each of 23 Nearfield stations (Figure 2-1). A complete listing of sediment profile image (SPI) data can be found in Appendix B-1. Appendix B-2 provides a summary of within station variability for quantitative measurements; prism penetration, surface relief, RPD, OSI, and number of infauna, burrows, and voids. A station summary of SPI data is contained in Table 3-3.

Physical processes and sediments—Grain size ranged from cobbles and pebbles (FF13) to mixed sandy-silt-clay sediments (NF10) (Table 3-3, see Appendix 3-3 for image plates). Heterogeneous sediments, defined as those having more than two textural end-members (silt, sand, gravel, pebble, or cobble), occurred at nine stations. Homogeneous sandy sediments occurred at four stations (FF12, NF04, NF13, and NF17) and nine stations had homogeneous fine sediments (Table 3-3). Sediment layering, fine-sand layer over silty-clay, occurred at one station (NF05). The modal grain size descriptors were silty-fine-sand and fine-sand-silt-clay both with four stations. Within station variation of sediment type was high at the heterogeneous stations with individual replicates ranging from silty-fine-sand to pebbles (NF24) and low at fine sediment stations where all replicates had the same sediment type. Grain size for all three replicates was the same at 14 of the 23 stations (Appendix 3-1). The stations with the most spatial heterogeneity in sediment type were: FF10, FF13, NF02, NF23, and NF24 where each of the replicates had a different sediment type.

All nine stations with pebble or cobble sediments, indicative of high kinetic energy or transport bottoms, also had a fine sediment component. Pure sands and gravels, also indicative of higher bottom energy, were seen at four stations scattered over the study area (Figure 3-1). Bedforms typically associated with higher energy sandy bottoms were seen at two stations (NF04 and NF23). The lack of bedforms may be related to the lack of large storms over the winter of 1998–1999 that would have reshaped bottom sediments. Benthic organisms would tend to destroy physical structures such as bedforms during quiescent periods. Homogeneous finer sediments, fine-sand-silt-clay and silt-clay, were concentrated to the northwest of the diffused but also occurred to the south (Figure 3-1). Finest sediments that appeared to have been composed only of silts and clays (modal Phi > 6) occurred at four stations NF07, NF08, NF21 and NF22.

The correspondence between the SPI image and grab sediment analysis was good given the divergent approach with which the two methods sampled the sediments (Table 3-4). Both methods indicated the sediments were heterogeneous in some areas and homogeneous in other areas. The SPI images, which were from three replicates, were able to sample a larger area than the single grab sample and provided *in situ* information across the width and depth of the image. Therefore, the images provided better estimates of spatial and end member variability of the sediments, particularly for coarse sediments. The grab samples and grain-size analysis provided better estimates of fine sediment end members (Section 4). To compare the two methods the grab data were converted to a Wentworth classification as described in Folk (1974) and the shell, pebble, and cobble removed from the SPI data (Table 3-4). The very coarse end members were removed because the grab would not sample them.

Prism penetration and sediment grain size were closely related with lowest penetration at hard sand-gravel-pebble-shell bottoms (NF02). The range of average station penetration was 0.5 (NF02) to 21.6 cm (NF08) and reflected the dichotomy of benthic habitats, where habitats in the Nearfield area had either coarser heterogeneous or finer homogenous sediments (Table 3-3). Mixed and fine sediments, fine-sand-silt-clay and silt-clay, had highest penetration (NF08 and NF12).

In physically dominated sandy and coarse habitats surface relief (bed roughness) ranged from 0.9 to 6.8 cm and was caused by pebble/rocks or bedforms (NF02 or NF23). In muddy habitats surface relief was lower and ranged from 0.7 to 2.6 cm and was typically irregular surfaces, caused by biogenic activity of benthic organisms (NF16). Biological surface roughness ranged from feeding mounds (NF22) and tubes (NF09) to colonies of hydroids (FF10)

Apparent Color RPD Depth—Benthic habitat quality has long been associated with RPD layer depth, in particular relative to organic enrichment and successional stage (Pearson and Rosenberg 1978). As organic loading increases the RPD layer becomes shallower in response to increased sediment oxygen demand and the elimination of deep bioturbating fauna. Conversely, as successional stage advances the RPD layer depth increases. Based on this close association between organic loading, successional stage, and habitat quality RPD makes a good monitoring parameter. However, factors other than organic

Table 3-3. Station summary of SPI parameters for the August 1999 survey of the Nearfield area. Data from all replicates were averaged for quantitative parameters and summed for qualitative parameters (for example, the presence of tubes in one replicate resulted in a + for the station).

					Surface Features			**Subsurface Features**							
Stat	**Pen. (cm)**	**SR (cm)**	**RPD (cm)**	**Sediment Type**	**Surface Features**	**Amp**	**StkA**	**Tubes**	**Layers**	**Wrm**	**Bur**	**Oxic Voids**	**Anaer Voids**	**Succ Stage**	**OSI**
FF10	4.1	4.1	2.2	RK to SIFS	BIO/PHY	–	–	+	–	4.0	1.5	0.0	0.0	II	6.0
FF12	4.6	0.5	1.6	FS	BIO/PHY	–	–	+	–	8.0	6.7	0.0	0.0	II/III	6.7
FF13	1.7	2.9	1.5	RK to FSSI	BIO/PHY	–	–	+	–	3.3	1.7	0.0	0.0	II	5.7
NF02	0.5	6.8	2.1	RK to FSSI	PHY, SH	–	–	+	–	.	.	.	.	.	.
NF04	3.5	0.9	>3.5	FS, GR	BIO/PHY, SH	–	–	+	–	0.3	0.0	0.0	0.0	II	8.3
NF05	5.3	1.1	2.7	FS/SICL	BIO	+	+	+	GS	4.0	4.3	0.0	0.0	II	7.0
NF07	13.9	1.0	1.6	SIFS	BIO	–	+	MAT	–	7.0	9.3	1.3	0.3	II/III	6.3
NF08	21.6	0.7	1.7	SIFS	BIO	–	–	MAT	CL	7.3	6.7	0.0	0.3	II	5.7
NF09	11.6	1.7	1.9	FSSI	BIO	–	+	MAT	–	8.3	5.3	2.7	0.0	III	8.0
NF10	12.2	1.1	1.9	FSSICL	BIO	–	–	MAT	–	10.3	8.0	2.3	0.3	III	8.3
NF12	21.0	1.7	1.9	FSSICL	BIO	–	–	MAT	–	8.0	5.7	4.7	0.3	III	8.0
NF13	2.7	1.3	>2.7	FSMS	BIO/PHY, SH	–	–	+	–	0.0	0.0	0.0	0.0	II	7.0
NF14	5.7	1.2	3.3	PB to SIFS	BIO/PHY, SH	–	–	+	–	1.0	1.0	0.0	0.0	II/III	8.0
NF15	4.7	1.3	2.3	PB to FSSI	BIO/PHY, SH	–	–	+	–	1.7	2.0	0.3	0.0	II	6.7
NF16	16.2	2.6	1.8	FSSICL	BIO	–	–	MAT	–	8.7	5.3	1.7	1.0	II/III	7.0
NF17	4.0	1.3	>4.0	GR to FSMS	PHY,SH	–	–	+	–	0.0	0.0	0.0	0.0	II	8.5
NF18	8.9	2.5	2.6	PB to SIFS	BIO/PHY	–	–	+	–	2.3	2.7	1.7	0.0	II	6.7
NF19	3.3	1.1	1.5	FSSICL	BIO/PHY, SH	–	–	+	–	4.0	6.3	0.0	0.0	II	5.3
NF20	6.0	2.2	2.8	PB to SIFS	BIO/PHY	–	–	MAT	–	2.0	1.3	0.0	0.0	II	7.0
NF21	17.4	1.2	1.7	SIFS	BIO	–	–	MAT	–	7.0	8.3	2.7	1.0	II/III	7.7
NF22	13.2	1.5	2.1	SIFS	BIO	–	–	MAT	–	8.3	5.3	1.7	0.3	II/III	7.7
NF23	4.1	2.3	>3.4	PB to FSSICL	BIO/PHY, SH	–	–	+	–	0.5	0.0	0.0	0.0	I/II	7.0
NF24	5.4	3.0	1.3	PB to FSSICL	BIO/PHY	–	–	+	–	10.5	7.5	2.0	1.0	II/III	6.0

> At least one replicate had an RPD layer deeper than the prism penetration.

Table 3–3. Station summary of SPI parameters for the August 1999 survey of the Nearfield area.

Key:

Stat. = Station
Pen = Average prism penetration depth
SR = Average surface relief across the 15 cm width of the prism face plate
RPD = Average depth of the apparent color RPD
Sediment Type:
  FS = Fine-sand
  FSMS = Fine-Medium-sand
  FSSICL = Fine-sand-silt-clay
  FS/SICL = Sand layer over silty
  GR = Gravel
  PB = Pebble
  RK = Rock
  SH = Shell
  SIFS = Silty Fine-sand
Surface Features = Predominant sediment surface structuring process: BIO = Biogenic, PHY = Physical
Amp = *Ampelisca* tubes
StkA = Stick amphipod biogenic structures, likely the genus *Dyopedos*
Tube = Worm tubes: MAT = tubes dense enough to form a mat over surface
Layers = Sediment layering: GS = Grain size layering, CL = Color layering
Wrm = Subsurface infaunal worms, average number per image
Burr = Infaunal burrows, average number per image
Oxic Voids = Water filled inclusions in sediment, active biogenic features, average number per image
Anaer Voids = Water filled inclusions in sediment, relic biogenic features, average number per image
SS = Estimated successional stage
OSI = Organism Sediment Index

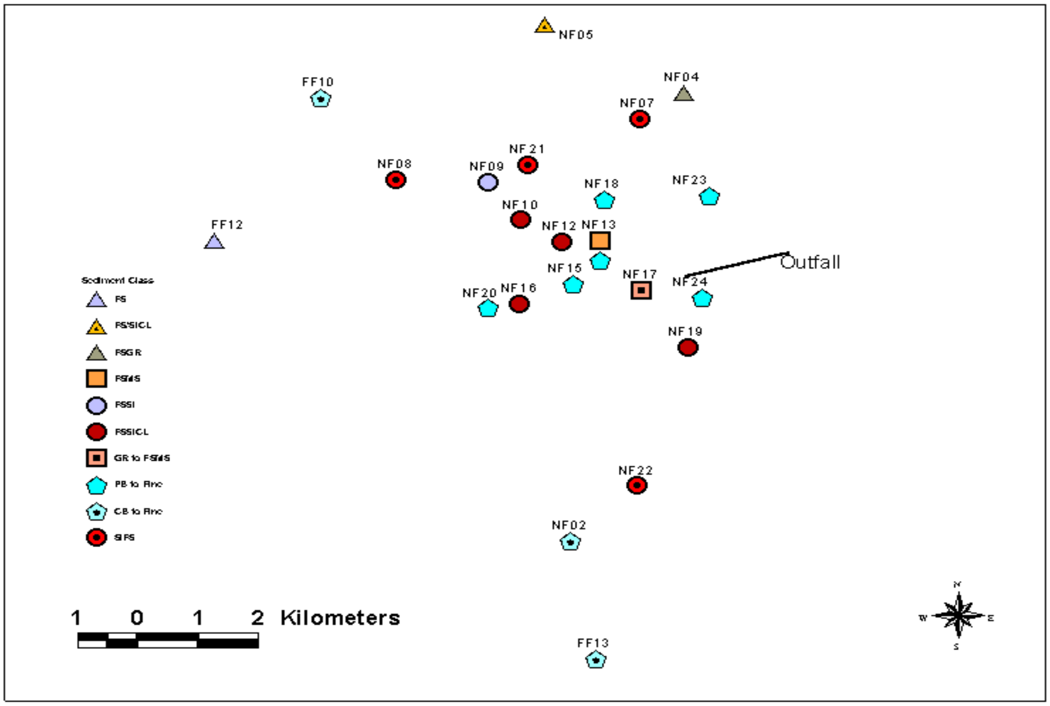


Figure 3-1. Distribution of estimated sediment types at Nearfield stations based on SPI, August 1999.

loading and successional stage can cause RPD layer depth to fluctuate. Seasonality, grain size, pore water flow, water quality (particularly dissolved oxygen), and intensity of bioturbation are all known to contribute to small scale spatial and temporal variation in RPD layer depth (Rhoads and Boyer 1982, Jones and Jago 1993, Diaz and Rosenberg 1995, Aller and Aller 1998).

Average apparent color RPD layer depth at the 23 stations ranged from 1.3 to > 4.0 cm (Table 3-3). The average RPD layer depth for all stations was 2.3 cm (0.73 SD, 0.15 SE) with the inclusion of stations that had shallow penetration, at least as minimal estimates of RPD depth. If the three shallow penetration sand stations were removed the average RPD layer depth was 2.0 cm (0.52 SD, 0.12 SE). The deepest RPD layers occurred in the vicinity of the outfall to the west and north (Figure 3-2). Porous sandy/gravelly sediments had the deepest apparent color RPD layer depths (NF17). In mixed sediments with high levels of biogenic activity (NF22) RPD layers also tended to be deeper. The shallowest average RPD layer occurred at station NF24. For an individual replicate the shallowest RPD was 0.9 cm at NF21-3 and the deepest measured RPD was 4.6 cm at NF14-3. The RPD layer was > 5.2 cm, the prism penetration depth, at station NF17-3 (Appendix 3-1). Biogenic activity deepened the penetration of oxic sediments at most stations with the deeper maximum RPD depths associated with oxidized sediments around burrow structures. Sediments that appeared to be oxic, lite-brown to reddish in color, extended > 10 cm below the sediment-water-interface at three stations (NF10, NF12, and NF21).

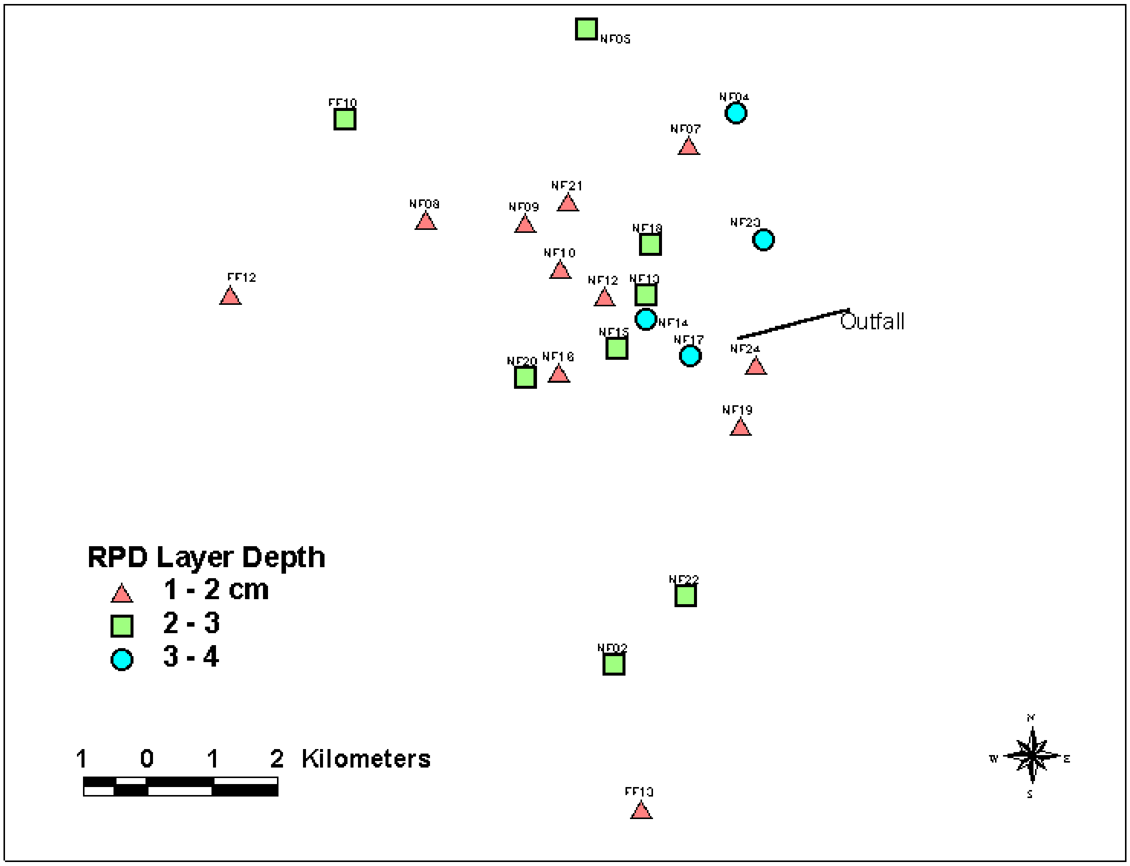


Figure 3-2. Distribution of estimated apparent color RPD layer depth, based on SPI, at Nearfield stations August 1999.

Within station variation in RPD layer depth was greater than the overall study area variation. To determine the degree of variation among the three replicates two statistics were evaluated. The coefficient of variation (CV) and a statistic derived from the range divided by the median, both statistics were expressed as a percentage (Appendix 3-2). These statistics provide estimates of variability independent of the mean and median, being parametric and nonparametric, respectively. Both were used because of the small sample size (three) at each station. For the 16 stations that had RPD measurements for all three replicate images the range was about 8 to 49% for the CV and 15 to 117% for the nonparametric statistic. None of the stations exceeded a CV of 50% while eight exceeded 50% for the nonparametric statistic. Higher variability in RPD layer depth at a station was related to two factors; small sample size and small-scale patchiness in sediment type and bioturbating fauna (Table 3-4; Sections 4 and 5). Station NF18 was representative of low RPD depth variation and FF13 representation of a high variation station (Appendix 3-2).

Comparison to RPD Threshold—The variance of the average station RPD layer was analyzed to determine the sensitivity of SPI for estimating a 50% change in the apparent color RPD over the study area. The MWRA (1997) has set this amount of change in the depth of the RPD layer as a critical trigger level for assessing outfall effects. Only 16 stations with RPD measurements for all three replicates were used in this analysis. At seven stations the RPD depth of at lease one replicates images could not be determined. To detect a 50% change in RPD layer depth over the study area from one year to the next with a 95% confidence interval and 90% power would require approximately eight stations. This assumed a *t*-test would be used to assess the significance of the difference between the current year average relative to the previous year and that the variance of the 1999 data was representative of the population of RPD depths (Zar 1999, pages 132-133). Ten stations would give a 95% confidence interval and power and 16 stations would increase the power to 99%.

Table 3-4. Comparison of sediment grain-size determined by SPI and grab analyses for 1999 Nearfield stations. Only sediment fractions from gravel to silt-clay are compared. Coarser sediments were sampled by SPI but not by grab. Percent gravel is based on total sample weight. Percentages of sand, silt, and clay are based only on the weight of those fractions.

SPI Data				Grab Data				
Station	Coarsest	Coarse to Fine*	Coarse to Fine	Mean Phi	Gravel %	Sand %	Silt %	Clay %
FF10	RK, PB, SH	GR, FSMS, SIFS	GR, FS, SI	3.0	21.1	75.6	19.0	5.5
FF12		FS	FSSI	3.8	5.0	73.4	18.2	8.4
FF13	RK, PB	GR, FS, FSSI	FSSICL	4.9	2.7	43.8	37.1	19.1
NF02	RK, PB	GR, FSSI	MS	1.8	1.4	95.1	2.5	2.3
NF04		GR, FS	FS	2.6	0.1	94.8	3.0	2.2
NF05		FS/SICL	FS, SI	3.2	1.0	82.8	14.7	2.5
NF07		SIFS	FSSI	3.9	1.8	66.0	23.8	10.1
NF08		SIFS	SIFS	5.5	2.0	26.9	60.9	12.3
NF09		FSSI	FSSI	4.0	0.4	61.4	27.4	11.1
NF10		FSSICL	FSSI	4.5	0.2	58.8	34.4	6.8
NF12		FSSICL	SICL	5.8	0.0	26.5	55.2	18.4
NF13		FSMS	FS	2.4	0.1	94.5	2.3	3.2
NF14	PB, SH	SIFS	GR, MS	1.9	13.1	88.2	9.7	2.2
NF15	PB, SH	GR, FS, FSSI	FS	2.5	4.0	88.0	11.6	0.4
NF16		FSSICL	FSSI	3.6	1.2	67.3	26.3	6.4
NF17		GR, MS, FSMS	FS	2.2	0.1	98.8	0.7	0.6
NF18	PB, SH	GR, SIFS	GR, CS, SI	0.6	51.2	78.1	18.2	3.7
NF19		FSSICL	FS	3.1	2.3	84.1	9.7	6.1
NF20	PB	SIFS	GR, FS, SI	2.8	11.4	74.9	16.6	8.5
NF21		SIFS	SIFS	5.3	0.0	39.4	50.3	10.3
NF22		SIFS	FSSI	4.3	4.0	55.0	33.5	11.6
NF23	PB, SH	GR, FSMS, FS, FSSICL	GR, MS	1.4	21.1	98.0	1.0	1.0
NF24	PB	FSSI, FSSICL, SIFS	FSSICL	5.2	0.2	37.5	47.7	14.8

* Composite of all sediment classes seen in the three replicate images.

Biogenic Activity—The sediment surface at about half the stations was dominated by a combination of biogenic and physical structures. The biology associated with activities of successional stage II and III fauna and physical associated with currents that lead to heterogeneous coarse/pebble/cobble sediments (Table 3-3). Biogenic surface features dominated at about 40% of the stations. The surface biogenic structures observed included biogenic whips or sticks made by amphipods (NF07), likely in the genus *Dyopedos* (Mattson and Cedhagen 1989). *Dyopedos monacanthus* occurred at seven grab stations in 1999 including NF07 (Section 5). Other biogenic features were small and large worm tubes (NF09), epibenthic organisms (NF15), burrow openings (NF14), feeding pits (NF), biogenic mounds (NF) and shells (NF16). Station NF02 was the only station with no evidence of biogenic activity in all three replicates.

Subsurface biogenic structures and actives were associated with infaunal organisms and included active oxic burrows (NF07), water filled oxic voids (NF12), and water filled anoxic voids (NF21). Free-burrowing infaunal worms occurred at all but three stations. At station NF24 the average number of worms was about 10 per image with a maximum of 15 worms at NF22-1 (Appendix 3-1 and 3-2).

Successional Stage and Organism Sediment Index—The modal successional stage was estimated to be Stage II and occurred at 50% of the stations. About 32% of the stations appeared to have combined traits of Stage II and III communities. The high degree of biogenic sediment reworking observed in many images was consistent with Stage II and III successional designation. Station NF23 had the lowest overall successional stage designation (Stage I/II) with little indication of subsurface biogenic activity other than a few worms (Table 3-3). Lower successional stage stations clustered around the western end of the outfall (Figure 3-3).

The average Organism Sediment Index (OSI) at the Nearfield stations was 7.0 (0.94 SD, 0.20 SE) and in the range just above levels indicative of communities under moderate stress. Rhoads and Germano (1986) developed the OSI for assessing stress in estuarine and coastal embayments and found that OSI values < 6 were associated with benthic communities under some form of moderate stress while higher values were associated with well-developed communities. Only three stations had OSI values < 6 (FF13, NF08, and NF19). Analysis of benthic community and other SPI data point to a lessening of physical stress over the Nearfield stations in 1998 relative to the last few years (Kropp *et al*. 2000). The OSI values were evenly spread from about 6 to 8, with an overall range of 5.3 (NF19) to 8.5 (NF17) (Figure 3-4, Table 3-3).

3.3 Summary of 1999 SPI Data

While the distribution of sediment textures at benthic habitats in the Nearfield study area appeared to be dominated by physical processes, surface features were dominated by biogenic activity. Even station NF02, which appeared completely dominated by physical processes, had an abundance of epifaunal organisms. Feeding mounds and tubes were the dominant surface biogenic structures and occurred at all but one station. Subsurface biogenic structures and organisms were also common and widely distributed. The predominance of biological activity at most stations was indicative of a well-developed fauna that was characterized as being intermediate to advanced in successional stage (Stage II to II/III). The organism sediment index also indicated that biological processes were dominating in areas that previously had been dominated by physical processes. Overall, it appeared that biological processes were more prominent in 1999 relative to the last few years.

Coarse sand/pebble/cobble sediments over much of the study area were heterogeneous and exhibited large within station variability from cobble to silty-sand. Finer silts and clays areas were more homogeneous. The sampling design, with 23 stations in the Nearfield area, provided more than sufficient statistical power for a *t*-test with a 95% confidence interval and 80% power to detect a 50% change in mean

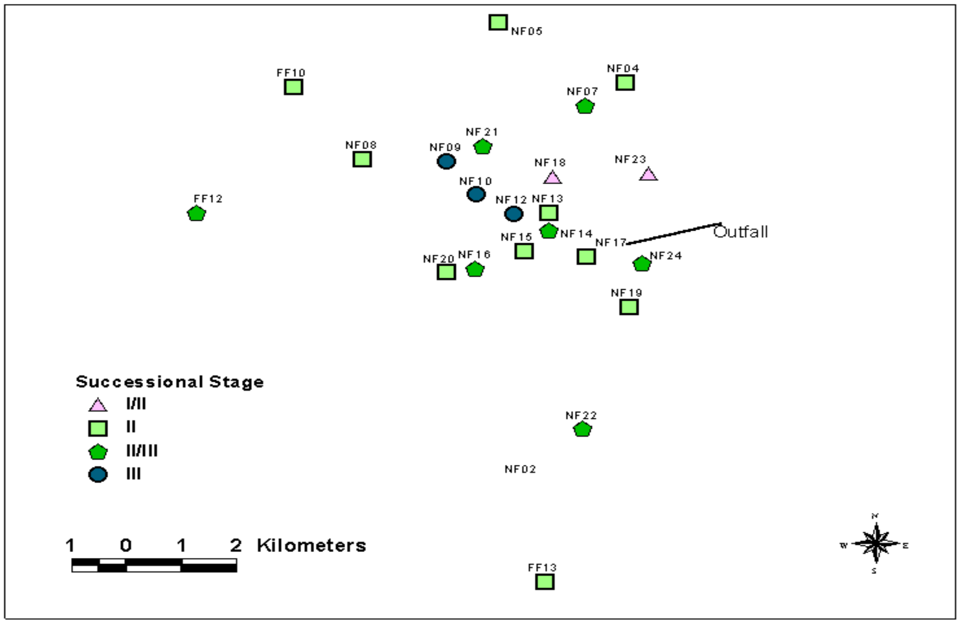


Figure 3-3. Distribution of estimated successional stage at Nearfield stations based on SPI, August 1999.

RPD layer depth over the entire study area from one year to the next. Based on the variation in the 1999 data, as few as three replicates at eight stations would yield a test with a 95% confidence interval and 90% power. With 16 stations power would increase to 99%.

3.4 Long-term Trends in Nearfield SPI Data

Sediment profile images have now been collected five times at Nearfield stations. The first SPI data was collected in 1992 (Blake *et al.* 1993) and again in 1995 (Hilbig *et al.* 1997), then annually from 1997 (Blake *et al.* 1998, Kropp *et al.* 2000).

Approximately 16 of the 23 Nearfield stations were primarily silty (4 to 5 Phi) to very-fine-sand (3 to 4 Phi). Nine of these finer-sediment stations, for example NF07 and NF22, were consistent through time with little or no variation in sediment type (Table 3-5). Grain size variation between the estimated major fine sediment descriptors (VFS, FSSI, SIFS, and FSSICL) was not more than one or two Phi units. The coarser-sediment stations NF13, NF17 and FF12 also exhibited little variation through time. Six fine sediment stations, for example NF14 and NF18, exhibited a coarsening trend with time that started in 1998 while only one station (NF19) appeared to be getting finer with the addition of the 1999 data. Four stations were consistently heterogeneous through time with sediments ranging from fines to cobbles depending on the year. Station NF02 was particularly variable, alternating between finer and coarser sediments from 1992 to 1999. Within a year station NF20 consistently had the most heterogeneous sediments (Table 3-5).

Assessment of the depth of the apparent color RPD through time was complicated by shallow prism penetration and/or coarse pebble/cobble sediments at 10 stations where at least one replicate image for one year had insufficient penetration to estimate the RPD. Six stations were also not sampled all five years. This leaves seven stations with a complete set of RPD measurement for all years. Yearly averages for estimated RPD layer depths were calculated for all stations with measured values and also for only the seven stations (NF05, NF07, NF08, NF09, NF10, NF12, and NF18) that had measured RPD for all five years.

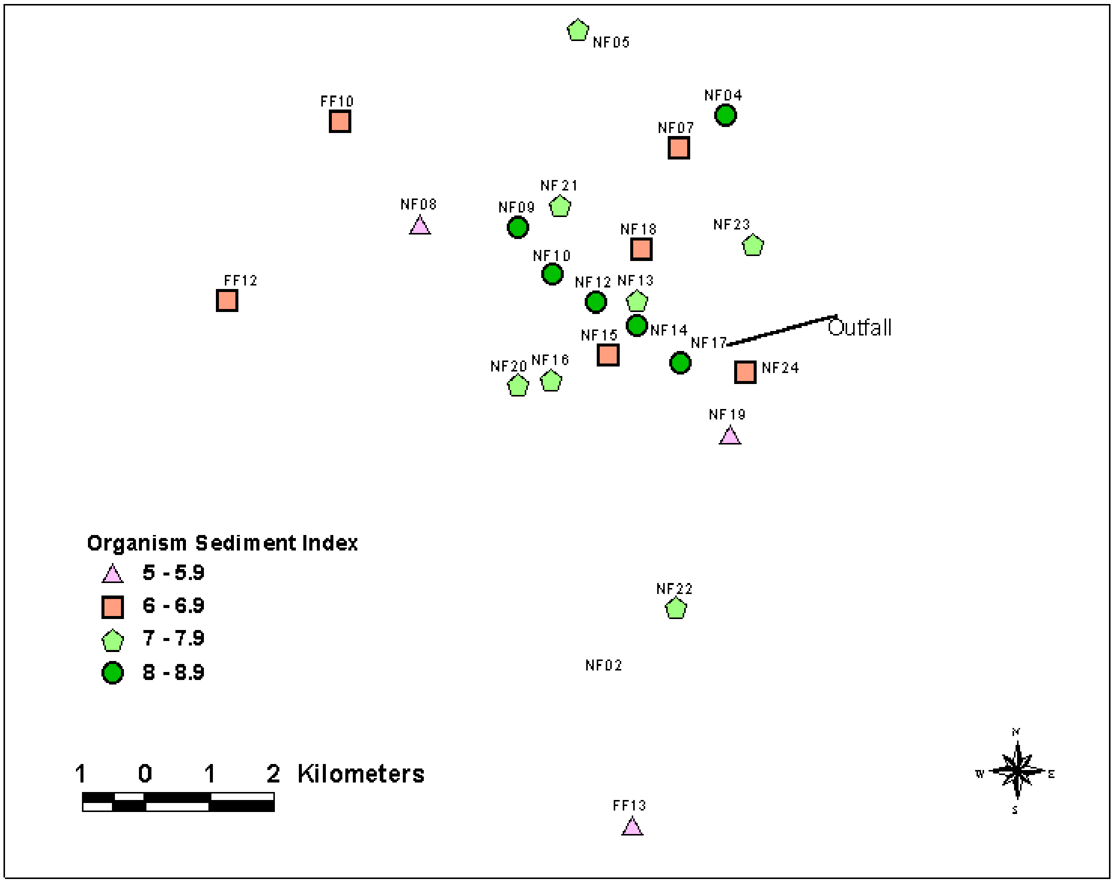


Figure 3-4. Distribution of the Organism Sediment Index (OSI), based on SPI, at Nearfield stations August 1999.

RPD	1992	1995	1997	1998	1999
All stations	2.6 (0.30)	2.5 (0.15)	1.7 (0.15)	1.6 (0.13)	2.0 (0.12)
Stations sampled every year	3.1 (0.45)	2.3 (0.20)	1.6 (0.08)	1.6 (0.16)	2.0 (0.16

These summaries point to a shallowing of the average RPD layer depth from 1992 to 1997–1998 and a possible deepening in 1999. However, while analysis of variance of data from the seven stations that had measured RPD's for all years (Table 3-6) indicated that there were strong differences between years (log transformation, df = 4, $F = 6.75$, $p = 0.0005$), there were no statistically distinct sets of years (Figure 3-5). For example, 1992, 1995, and 1999 were significantly different than 1997 and 1998, and 1992 was different than all other years. The shallowing trend in RPD from 1992 to 1995–1998 and the1999 deepening was likely linked to the interaction of physical and biological process at work in structuring bottom communities. Blake *et al.* (1998) and Kropp *et al.* (2000) concluded that bottom instability (waves and currents) leads to a patchy mosaic of successional Stage I pioneering communities, which are associated with shallower RPD measurements. Stage I communities dominated the Nearfield area from 1992 to 1997, with Stage II communities dominating in 1998 and 1999 (Table 3-7). It seemed that factors responsible for the depth of the RPD layer were acting at the regional scale in the Nearfield. There was no significant difference in mean RPD depth trends among the seven stations with year as a covariate (analysis of covariance, log transformation) (Figure 3-6).

Table 3-5 Historical description of sediment types, as determined from SPI, at Nearfield Stations, 1992–1999.

Station	1992	1995	1997	1998	1999
NF02	VFS	CS	SIFS	PB to GR	CB to FSSI
NF04	FS	FS	VFS	FS	GR to FS
NF05	FS	VFS	VFS	VFS	FS/SICL
NF07	VFS	VFS	VFS	VFS	SIFS
NF08	VFS	SIFS	VFS	VFS	SIFS
NF09	VFS	VFS	VFS	VFS	FSSI
NF10	VFS	VFS	VFS	VFS	FSSICL
NF12	VFS	SI	SIFS	SIFS	FSSICL
NF13	FS	FS to VFS	FS	PB to SIFS	FSMS
NF14	FS	VFS	VFS	PB to VFS	PB to SIFS
NF15	FS	VFS	VFS	GR to FS	PB to FSSI
NF16	VFS	SIFS	VFS	SIFS	FSSICL
NF17	FS	FS	FS	FS	GR to FSMS
NF18	VFS	VFS	VFS	GR to VFS	PB to SIFS
NF19	.*	CS to VFS	VFS	FSSICL	FSSICL
NF20	VFS	CS to VFS	GR to FSMS	GR to SICL	PB to SIFS
NF21	.	SIFS	VFS	SIFS	SIFS
NF22	.	SIFS	SIFS	SIFS	SIFS
NF23	.	CS to VFS	FS	FS	PB to FSSICL
NF24	.	SI	SIFS	FSSICL	PB to FSSICL
FF10	VFS	.	VFS	VFS	CB to SIFS
FF12	.	.	VFS	FS	FS
FF13	.	.	SIFS	SIFS	CB to FSSI

*Station not sampled.
CB = Cobble
CS = Coarse-sand, possibly gravel
FS = Fine-sand
FSSICL = Fine-sand-silt-clay
GR = Gravel
IND = Parameter indeterminate.
MS = Medium-sand
PB = Pebbles
SI = Silt
SICL = Silt-clay
SIFS = Silty-fine-sand
VFS = Very-fine-sand

In 1995 the first signs of amphipod tubes, characteristic of stage II community development, were seen in the Nearfield SPI images (Stations NF05, NF04, NF16, NF21, Hilbig *et al.* 1997). In 1998 and 1999, however, the wide spread occurrence of Stage II communities did not appear to lead to deeper RPD layers, nor did the increased occurrence of Stage III communities. There appeared to be an increase in the amount of surface and subsurface biogenic activity in 1998 that continued into 1999, relative to the other years, which accounted for the increase in the prevalence of Stage II and III successional stage communities. Most of the biogenic activity was related to burrowing organisms that created feeding mounds and pits in the sediment surface and small surface-tube-building worms, which were very abundant in 1999. There was also no increase in Stage II amphipods in the infaunal data from 1992 to 1999, with ampeliscid amphipods occurring in low numbers all years.

Table 3-6. Comparison of apparent color RPD depth (cm), as determined by SPI, Nearfield Stations, 1992–1999.

Station	1992	1995	1997	1998	1999
NF02	0.9	>2.7	2.7	IND	2.1
NF04	IND	>3.8	>1.4	>1.8	>3.5
NF05	4.1	1.8	1.4	1.3	2.7
NF07	2.9	1.6	1.7	0.8	1.6
NF08	2.1	2.8	1.8	1.8	1.7
NF09	1.7	2.7	1.8	1.9	1.9
NF10	4.1	2.9	1.3	1.7	1.9
NF12	4.8	2.3	1.6	2	1.9
NF13	2.2	>3.9	>1.9	>3.3	>2.7
NF14	2.6	>4.2	>3.1	0.8	3.3
NF15	2	3.3	>1.7	>2.2	2.3
NF16	2.3	>3.7	1.1	1.7	1.8
NF17	IND	>5.7	>2.1	>2.1	>4.0
NF18	2.3	1.8	1.4	1.7	2.6
NF19	.	2.2	>1.4	0.5	1.5
NF20	3.6	1.8	IND	1.9	2.8
NF21	.	2.9	2	1.3	1.7
NF22	.	2.8	0.7	1.9	2.1
NF23	.	3.3	>2.0	>2.9	>3.4
NF24	.	2.8	2.4	1.2	1.3
FF10	1.5	.	>3.0	2.3	2.2
FF12	.	.	>1.5	2.2	1.6
FF13	.	.	2.1	2.2	1.5

> Indicates that RPD layer in at least one replicate images, was deeper than prism penetration.

The Organism Sediment Index of Rhoads and Germano (1986) indicated that on average, for some the years, benthic communities in the Nearfield were subjected to some form of stress (OSI values < 6). Physical processes were the most likely source of stress since water and sediment quality within the Nearfield were always good (see Section 4). The average (SE) yearly OSI values were:

OSI	1992	1995	1997	1998	1999
All stations	6.8 (0.47)	6.1 (0.39)	4.8 (0.34)	6.4 (0.25)	7.0 (0.20)
Stations sampled every year	7.0 (0.52)	6.2 (0.53)	4.7 (0.44)	6.4 (0.28)	7.3 (0.25)

The lower values for 1997 may be related to the additional stress of seasonal change as some of the stations were sampled in October while those in the other years (and some 1997 stations) were sampled in August. Analysis of variance of data from all stations or just those 12 with OSI values for all years (Table 3-8) produced the same results and indicated there were strong differences between years in average OSI (for the latter analysis of only 12 stations, df = 4, $F = 5.87$, $p = 0.0005$). But similar to the RPD analysis, there were no statistically distinct sets of years (Figure 3-7). Yearly average OSI's were the same for 1992, 1995, 1998, and 1999, the last of which were significantly higher than 1997. 1995 and 1997 were also the same and significantly lower than 1992, 1998, and 1999. OSI values averaged by station indicated that there were no differences between stations (ANOVA, df = 11, $F = 1.27$, $p = 0.27$) (Figure 3-8).

Table 3-7. Estimated successional stage, as determined by SPI, at Nearfield stations, 1992–1999.

Station	1992	1995	1997	1998	1999
NF02	I	I	I-II on III	IND	IND
NF04	I	I-II	I-II	II	II
NF05	I	I-II	I on III	II-III	II
NF07	I-III	I	I	II-III	II-III
NF08	I-III	I	I-II	II-III	II
NF09	I-III	I on III	I	II-III	III
NF10	I	I-I on III	I-II	II-III	III
NF12	II-III	I-I on III	I-II on III	II-III	III
NF13	I	I	I	II	II
NF14	I	I	I	II-III	II-III
NF15	I	I	I	II-III	II
NF16	I	II-I on III	I	II-III	II-III
NF17	I	I	I	II	II
NF18	I	I	I-II on III	I-II	II
NF19	.*	I	I-II	I-II	II
NF20	I	I	I	II-III	II
NF21	.	II-I on III	I	II-III	II-III
NF22	.	I on III	I-II on III	II-III	II-III
NF23	.	I	I	II	I-II
NF24	.	I	I-I on III	II-III	II-III
FF10	I-III	.	I	II-III	II
FF12	.	.	I	II-III	II-III
FF13	.	.	I-II	II-III	II

* Station not sampled.
IND Parameter indeterminate.
I Stage I pioneering community
II Stage II intermediate community
III Stage III equilibrium community
I on III Stage I community at surface over Stage III community
II on III Stage II community at surface over Stage III community

Based on the sediment profile image data, the general physical and biological conditions at the Nearfield stations reflect the physically dynamic nature of the processes that dominate the area. The 1998 and 1999 data indicated an increasing trend in the importance of biological processes that may have started in 1995.

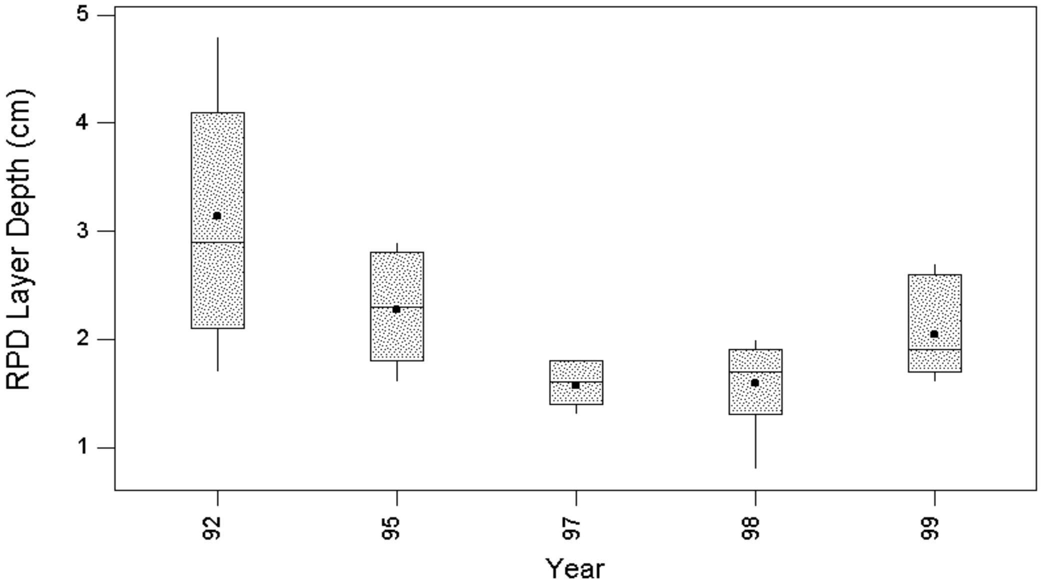


Figure 3-5. Box plot of apparent color RPD layer depth (cm) by year for the seven Nearfield stations that had no missing values from 1992 to 1999. Bar is median, dot is mean, box is interquartile range, and whiskers are total range of the station data.

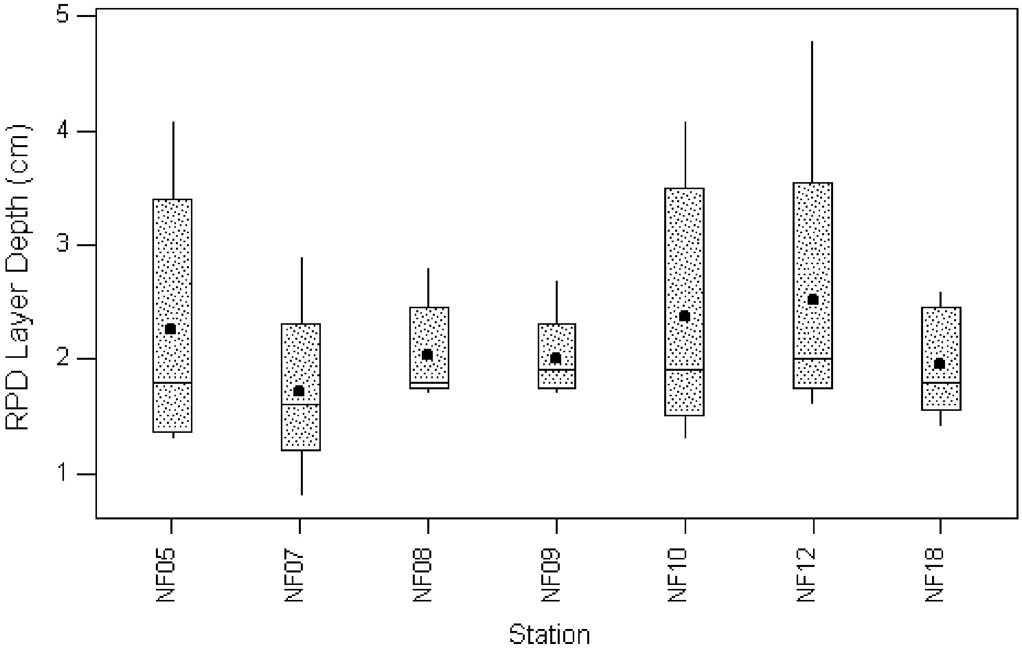


Figure 3-6. Box plot of apparent color RPD layer depth (cm) by station for the seven Nearfield stations that had no missing values from 1992 to 1999. Bar is median, dot is mean, box is interquartile range, and whiskers are total range of the yearly data for each station.

Based on the sediment profile image data, the general physical and biological conditions at the Nearfield stations reflect the physically dynamic nature of the processes that dominate the area. The 1998 and 1999 data indicated an increasing trend in the importance of biological processes that may have started in 1995.

Table 3-8. Organism Sediment Index, as determined by SPI, at Nearfield stations, 1992–1999.

Station	1992	1995	1997	1998	1999
NF02	4.0	5.0	7.5	IND	IND
NF04	IND	7.7	3.7	6.5	8.3
NF05	8.5	4.7	7.3	5.7	7.0
NF07	7.6	3.3	3.7	5.3	6.3
NF08	7.0	5.3	4.3	6.3	5.7
NF09	6.7	9.0	4.0	7.3	8.0
NF10	8.3	6.3	3.7	6.7	8.3
NF12	9.7	7.0	7.7	7.3	8.0
NF13	4.0	7.0	4.0	8.0	7.0
NF14	9.0	6.7	5.7	5.0	8.0
NF15	5.7	5.7	4.0	6.7	6.7
NF16	5.5	9.3	2.7	6.7	7.0
NF17	8.0	7.0	4.0	6.3	8.5
NF18	4.6	3.7	5.0	5.0	6.7
NF19	.	4.0	4.0	3.5	5.3
NF20	8.0	3.5	IND	6.5	7.0
NF21	.	7.0	2.0	6.3	7.7
NF22	.	7.7	6.3	6.7	7.7
NF23	.	6.0	4.0	7.7	7.0
NF24	.	5.3	7.3	4.7	6.0
FF10	5.5	.	5.5	7.3	6.0
FF12	.	.	3.7	7.7	6.7
FF13	.	.	6.0	8.0	5.7

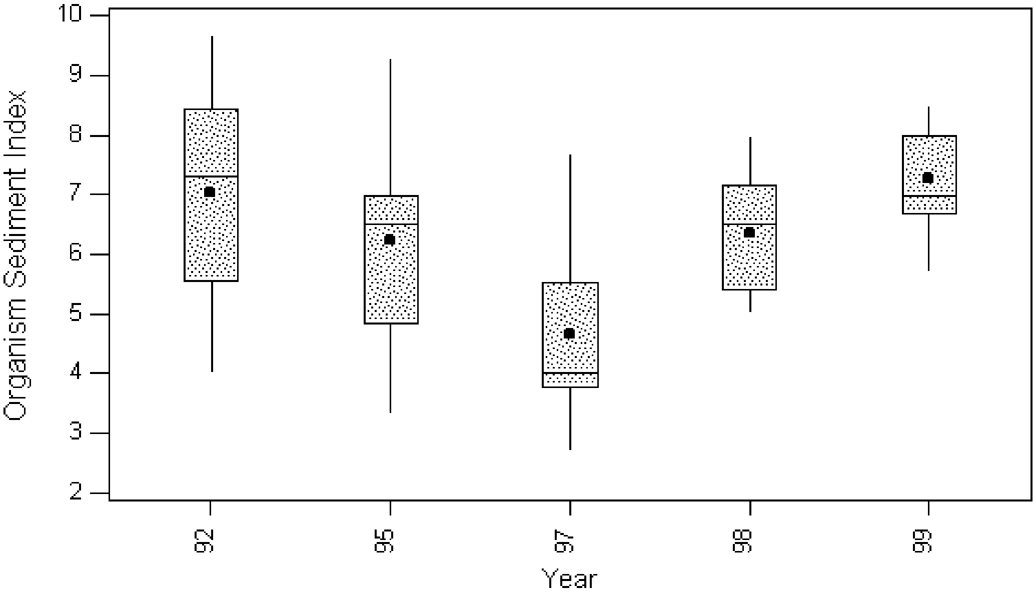


Figure 3-7. Boxplot of the Organism Sediment Index by year for seven Nearfield stations that had no missing values from 1992 to 1999. Bar is median, dot is mean, box is interquartile range, and whiskers are total range of station data.

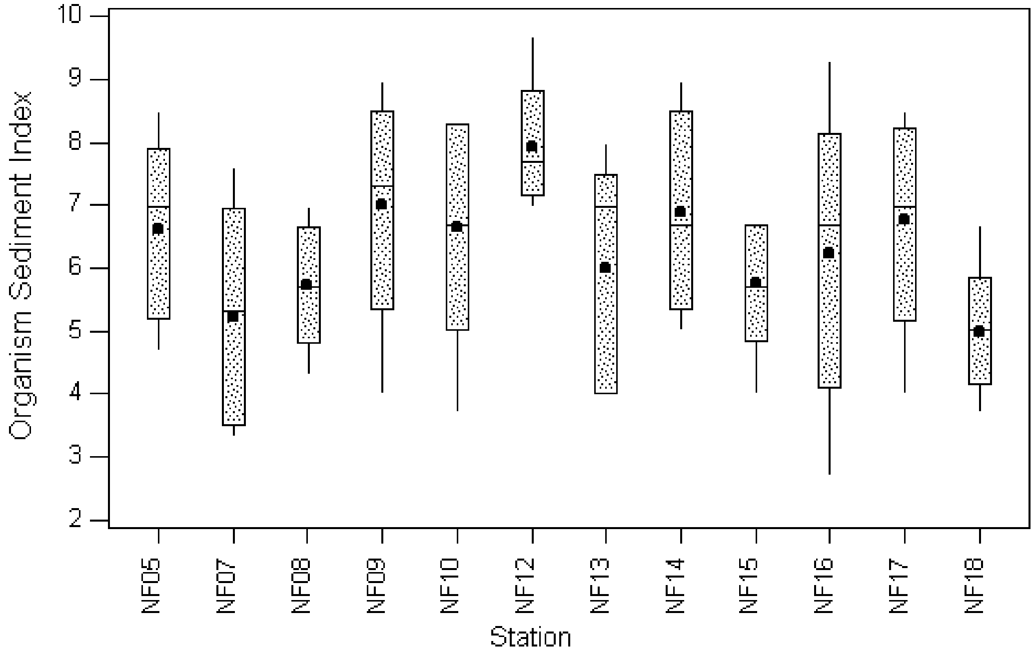


Figure 3-8. Box plot of the Organism Sediment Index by station for the twelve Nearfield stations that had no missing values from 1992 to 1999. Bar is median, dot is mean, box is interquartile range, and whiskers are total range of the station data.

4. ANALYTICAL CHEMISTRY

by Deirdre T. Dahlen and Carlton D. Hunt

with acknowledgement to Dr. Scott A. Stout (Battelle) for his support with the PCA

4.1 Methods

4.1.1 Grain Size, Total Organic Carbon, and *Clostridium perfringens*

Laboratory procedures followed those outlined in the Benthic Monitoring CW/QAPP (Kropp and Boyle 1998). Summaries of the procedures are provided below.

Grain Size—Samples were analyzed for grain size by a sequence of wet sieving and dry sieving. Methodologies followed Folk (1974). The sand/gravel fraction was separated from the mud fraction. This sand/gravel fraction was transferred to a 200-mL beaker, decanted, and dried overnight at 95 ºC. The dried sand/gravel fraction was mixed by hand to disaggregate the material, and then dry-sieved on stacked −1-, 0-, 1-, 2-, 3-, and 4-phi sieves. Each size class was weighed to the nearest 0.1 mg on a top-loading balance. Particles smaller than 4 phi were analyzed using the pipette method. Data were presented in weight percent by size class. In addition, the gravel:sand:silt:clay ratio and a numerical approximation of mean size and sorting (standard deviation) were calculated. Grain size determinations were made by GeoPlan Associates.

Total Organic Carbon—A portion of the sample to be analyzed for TOC content was dried at 70ºC for 24–36 hours and ground to a fine powder. The sample was treated with 10 % HCl to remove inorganic carbon and dried at 70 ºC for 24 hours. Between 10 and 500 mg of dry, finely ground, and homogenized sample were weighed to the nearest 0.1 mg and placed in a crucible that had been precombusted for 4 hours at 500 ºC. A Coulometric Carbon Analyzer was used to determine the TOC content of the samples. TOC determinations were performed by Applied Marine Sciences, Inc. according to SOP 9703.

***Clostridium perfringens*—**Sediment extraction methods for determination of *Clostridium perfringens* spores followed those developed by Emerson and Cabelli (1982), as modified by Saad (1992). The filters for enumeration of *Clostridium perfringens* spores were incubated anaerobically at 44.5 ºC for 24 hours. Following incubation, the filter was exposed to ammonium hydroxide for 15–30 seconds. Yellowish colonies that turn red to dark pink upon exposure were counted as *C. perfringens*. Data are reported here as colony-forming units (cfu) per gram dry weight of sediment. This analysis was performed by MTH Environmental Associates.

4.1.2 Contaminants

Analyses of sediments for organic constituents and metals were performed following methods outlined in Table 4-1. Samples were analyzed for the parameters listed in Table 4-2, including linear alkyl benzenes (LABs), polycyclic aromatic hydrocarbons (PAH), polychlorinated biphenyls (PCBs), chlorinated pesticides, and metals. Analytical methods followed general NS&T methodologies (Peven *et al*. 1993a, Peven *et al*. 1993b). More detailed information is provided in the CW/QAPP (Kropp and Boyle 1998).

Table 4-1. Parameters and methods of analysis for organic constituents and metals.

Parameter	Unit of Measurement	Method	Reference
Linear Alkylbenzenes	ng/g	GC/MS	Battelle SOP 5-157
Polycyclic Aromatic Hydrocarbons	ng/g	GC/MS	Battelle SOP 5-157
Polychlorinated Biphenyls/ Pesticides	ng/g	GC/ECD	Battelle SOP 5-128
Major Metals (Al, Fe)	% Dry Weight	EDXRF	KLM Technical Procedure 7-40.48
Trace Metals (Cr, Ni, Pb, Zn, Cu)	μg/g	EDXRF	KLM Technical Procedure 7-40.48
Trace Metals (Ag, Cd, and Hg)	μg/g	ICP-MS (Ag, Cd) CVAA (Hg) GFAA (as required)	Battelle SOP MSL-I-022 Battelle SOP MSL-I-016 Battelle SOP MSL-I-029

4.1.3 Statistical Analysis, Data Terms, and Data Treatments

Statistical Analysis—numerical analyses techniques to evaluate sediment chemical data included correlation and principal component analyses.

Correlation analysis was performed on sediment grain size, TOC, *Clostridium perfringens*, and contaminant data to examine the correlation between these parameters. Probability values were taken from Rohlf and Sokal (1969).

Principal component analysis (PCA) was employed to evaluate sediment grain size, TOC, *Clostridium perfringens* and contaminant data. All data were normalized prior to PCA analysis to remove effects of magnitude and give all parameters equal weight. Such analyses are an effective means of comparing the chemical data from many samples (Gabriel 1971, Boon *et al*. 1984, Wold *et al*. 1987, Oygard *et al*. 1988, Stout 1991, de Boer *et al*. 1993, Kannan *et al*. 1998). PCA has the additional advantage of being able to convey the complex chemical differences or similarities among many samples in a visual manner that is more easily understood.

PCA was performed by using Ein*Sight (Version 4.0; Infometrix, Inc., Seattle, WA).

PCA was used to visualize the intersample and intervariable relationships among the sediment chemical data. PCA yields a distribution of samples (*e.g.*, sediment samples) in *n*-dimensional space, where *n* is the number of variables (*e.g.*, PAH). The Euclidean distances between sample points on these factor score plots are representative of the variance captured in each PC. In simpler terms, samples that cluster together are chemically similar and outliers are chemically distinct. A factor loading is calculated for each variable (*e.g.*, PAH) contributing to each PC. A crossplot of the factor loadings for the first few PCs reveals the individual variables responsible for the variance in each PC.

Table 4-2. Sediment chemistry analytical parameters.

Parameter	Parameter	Parameter
Polycyclic Aromatic Hydrocarbons	**Polychlorinated Biphenyls**	Metals
Naphthalene	Cl2(8)	Al Aluminum
C_1-Naphthalenes	Cl3(18)	Cd Cadmium
C_2-Naphthalenes	Cl3(28)	Cr Chromium
C_3-Naphthalenes	Cl4(44)	Cu Copper
Acenaphthylene	Cl4(52)	Fe Iron
Acenaphthene	Cl4(66)	Pb Lead
Biphenyl	Cl4(77)	Hg Mercury
Dibenzofuran	Cl5(101)	Ni Nickel
Fluorene	Cl5(105)	Ag Silver
C_1-Fluorenes	Cl5(118)	Zn Zinc
C_2-Fluorenes	Cl5(126)	
C_3-Fluorenes	Cl6(128)	**Physical Sediment Parameters/Sewage Tracers**
Dibenzothiophene	Cl6(138)	Grain Size
C_1-Dibenzothiophenes	Cl6(153)	Gravel
C_2-Dibenzothiophenes	Cl7(170)	Sand
C_3-Dibenzothiophenes	Cl7(180)	Silt
Phenanthrene	Cl7(187)	Clay
Anthracene	Cl8(195)	phi<-1
C_1-Phenanthrenes/Anthracenes	Cl9(206)	−1<phi<0
C_2-Phenanthrenes/Anthracenes	Cl10(209)	0<phi<1
C_3-Phenanthrenes/Anthracenes		1<phi<2
C_4-Phenanthrenes/Anthracenes	Chlorinated Pesticides	2<phi<3
Fluoranthene	Aldrin	3<phi<4
Pyrene	Dieldrin	4<phi<8
C_1-Fluoranthenes/Pyrenes	Endrin	phi>8
Benz(a)anthracene	Hexachlorobenzene	Total Organic Carbon
Chrysene	Lindane	Clostridium perfringens
C_1-Chrysenes	Mirex	Linear Alkyl Benzenes
C_2-Chrysenes	2,4-DDD	Phenyl decanes (C_{10})
C_3-Chrysenes	2,4-DDE	Phenyl undecanes (C_{11})
C_4-Chrysenes	2,4-DDT	Phenyl dodecanes (C_{12})
Benzo(b)fluoranthene	4,4-DDD	Phenyl tridecanes (C_{13})
Benzo(k)fluoranthene	4,4-DDE	Phenyl tetradecanes (C_{14})
Benzo(e)pyrene	4,4-DDT	
Benzo(a)pyrene	DDMU	
Perylene	Cis-chlordane	
Indeno(1,2,3-c,d)pyrene	Heptachlor	
Dibenzo(a,h)anthracene	Heptachlorepoxide	
Benzo(g,h,I)perylene	Trans nonachlor	
Benzothiazole		

Data Terms—In the discussion of Nearfield results, the term Nearfield refers to all Nearfield stations plus Farfield stations FF10, FF12, and FF13. These Farfield stations were included in the Nearfield analyses because of the potential for transport of carbon from the Massachusetts Bay outfall (see the Bays Eutrophication Model, Fitzpatrick *et al*. 2000). Similarly, the term Farfield refers to all Farfield stations, excluding FF10, FF12, and FF13.

Data Treatments—In the discussion of bulk sediment and contaminant data, the following terms are used.

- Percent Fines – sum of percent silt and clay
- Total PAH – sum of all PAH compounds listed in Table 4-2, excluding Benzothiozole
- Total PCB – sum of all PCB congeners listed in Table 4-2
- Total Pesticide – sum of Aldrin, Dieldrin, Endrin, Hexachlorobenzene, Lindane, and Mirex
- Total DDT – sum of the six DDT, DDE, and DDD compounds listed in Table 4-2
- Total Chlordane – sum of Cis-chlordane, Heptaclor, Heptachlorepoxide, and Trans nonachlor
- Total LAB – sum of C_{10} – C_{14} LABs listed in Table 4-2

To determine these total values in sediment in cases where an individual analyte was not detected, a value of 0.0 was assigned to that analyte.

Mean parameter (*e.g*., total PAH) values were determined for three categories:

- Station Mean – Average of all station replicates; laboratory replicates were averaged to determine a single value prior to calculation of station means. Station means were determined for each parameter within a given sampling year. Station mean values were used in the PCA to determine if the spatial distribution of contaminants in the 1999 Nearfield and Farfield were substantially different than for previous years.
- Nearfield Baseline Mean – Average of all Nearfield stations including FF10, FF12, and FF13; each field sample replicate was treated as an individual sample. Nearfield baseline mean values were determined for each parameter within a given sampling year and were used to assess temporal trends in the Nearfield from 1992–1999.
- Farfield Baseline Mean – Average of all Farfield stations, excluding FF10, FF12, and FF13; each field sample replicate was treated as an individual sample. Farfield baseline mean values were determined for each parameter within a given sampling year and were used to assess temporal trends in the Farfield from 1992–1999.

Yearly “mean values” and 95 % confidence intervals were determined for *Clostridium perfringens* to evaluate the spatio/temporal distribution of *Clostridium perfringens* at all Nearfield and Farfield stations from 1992–1999. Yearly mean values were determined as a function of distance from Deer Island Point, as follows:

- < 20 km – Average of all stations that are within 20 km of Deer Island Point. Stations included all Nearfield stations plus Farfield stations FF10, FF12, and FF13.
- 20 km and < 40 km – Average of all stations that are more than 20 km, but less than 40 km of Deer Island Point. Stations included FF01A, FF09, and FF14.

- 40 km – Average of all stations that are more than 40 km from Deer Island Point. Stations included FF04, FF05, FF06, FF07, and FF11.

Sediment grain size results were evaluated by using ternary plots to visually display the distribution of sand, silt and clay in sediment collected from Nearfield and Farfield stations.

Results from sediment grain size, total organic carbon (TOC), *Clostridium perfringens*, and contaminant analyses were compared from all stations by using histogram plots.

The numerical approximate mean phi, referred to simply as mean phi in the text, was calculated by weighting each class fraction measured and summing the weighted fractions (Table 4-3).

Table 4-3. An example of numerical approximate mean phi determination.

phi Class	Weight Factor[1]	% Fraction Measured (station FF01A)	Weighted Fraction[2]
phi<-1	−1.5	0.06	−0.0009
−1<phi<0	−0.5	1.62	−0.0081
0<phi<1	0.5	10.54	0.0527
1<phi<2	1.5	14.56	0.218
2<phi<3	2.5	8.02	0.200
3<phi<4	3.5	54.09	1.893
4<phi<8	6	10.2	0.612
phi>8	9	0.9	0.081
Sum of weighted fractions Numerical approximate mean phi[3]			3.05

[1] Weight Factor represents middle of the phi class range
[2] Weighted Fraction = (Weight Factor)*(%Fraction Measure/100)
[3] Numerical approximate mean phi = Sum of weighted fractions

4.2 Results and Discussion

Bulk sediment and contaminant results for all Nearfield and Farfield samples were evaluated separately to examine spatial and temporal characteristics. Nearfield and Farfield station mean values are reported in Appendix C (bulk sediment — Appendix C-1; organic contaminants — Appendix C-2; metal contaminants — Appendix C-3). All sediment results are discussed in terms of dry weight using station, Nearfield baseline, and Farfield baseline mean values.

4.2.1 Nearfield Chemistry 1992–1999

Spatial Characteristics—PCA was performed on a multi-year/multi-parameter data set to determine if the spatial distribution of bulk sediment and contaminant parameters in 1999 was substantially different from 1992–1998 patterns. Physical and chemical data from all Nearfield stations plus FF10, FF12, and FF13 were included in the PCA. The physical and chemical parameters included in the data set were sand, silt, clay, TOC, *Clostridium perfringens*, total PAH, total PCB, total DDT, total LAB, and metals (Al, Cd, Cr, Cu, Fe, Pb, Hg, Ni, Ag, Zn). PCA can only be performed on a common set of parameters. Because contaminant data were not available for 1996 and 1997, these sampling years were excluded from the PCA. In addition, only NF08, NF22, NF24, and FF10 were sampled in 1998. Only these stations from 1998 were included in the PCA.

The factor score cross plot generated by PCA showed some clustering of stations (Figure 4-1a, b). The accompanying factor loading cross plot revealed that the primary controlling variables included 1) total PAH, 2) *Clostridium perfringens*, and 3) metals and sand (Figure 4-1c). Approximately 67% of the variability in these data were accommodated by the first and second principal components. The silt content variable plotted closer to the middle of the factor loading cross plot and had less influence on the data set (Figure 4-1b). Many Nearfield stations from across all sampling years clustered in quadrants Q1 and Q3 of the cross plot (Figure 4-1a). The primary variables controlling this cluster of Nearfield stations included total PAH and *Clostridium perfringens*. Stations included in quadrant Q3 generally contained higher concentrations of total PAH and lower abundance of *Clostridium perfringens* relative to stations that clustered quadrant Q1. Nearfield stations NF02, NF04, NF13, NF17, NF19, and NF23 clustered in quadrants Q2 and Q4 of the cross plot (Figure 4-1a, b). The primary variables controlling this cluster of stations included sand, metals, and *Clostridium perfringens*. Nearfield stations included in this cluster were comprised of very sandy sediments (>90 % sand) that contained low concentrations of metals, *Clostridium perfringens*, and organics relative to other Nearfield stations. Figure 4-1 shows that each cluster group includes a mix of Nearfield stations across all sampling years, indicating that the spatial distribution of bulk sediment and contaminant parameters in 1999 was not substantially different from 1992–1998.

While the primary objective of the PCA was to determine if the spatial distribution of bulk sediment and contaminant parameters in 1999 was substantially different from earlier years, the PCA results also revealed that sediment grain size, sand content in particular, is a key controlling variable in the Nearfield. In particular, sandy sites had much lower concentrations of organic contaminants. These results are supported by evaluations made in previous reports (Kropp *et al*. 2000) which showed that sediment types, that is, sandy versus silty, are major factors influencing concentrations of contaminants in the Nearfield.

Temporal Characteristics—Nearfield baseline mean values and 95 % confidence intervals were determined for bulk sediment properties, *Clostridium perfringens*, and contaminant parameters as described in Section 4.1.3. With the exception of *Clostridium perfringens*, the temporal response of the baseline for bulk sediment and contaminant parameters showed relatively constant means without substantial variability (Figure 4-2). The 95 % confidence intervals generally overlapped across all sampling years, supporting the conclusions above that the spatial distribution of contaminants was not substantially different over time. The Nearfield baseline mean values for *Clostridium perfringens* showed lower abundance and less variability in 1998 and 1999 relative to earlier years (Figure 4-2). Trends in *Clostridium perfringens* are discussed in greater detail in Section 4.2.3.

4.2.2 Farfield Chemistry 1992–1999

Spatial Characteristics—PCA was performed on a multi-year/multi-parameter data set to determine if the spatial distribution of bulk sediment and contaminant parameters in the 1999 Farfield were substantially different from 1992–1998. Physical and chemical data from all Farfield stations excluding FF10, FF12, and FF13 were included in the PCA. The physical and chemical parameters included in the data set were sand, silt, clay, TOC, *Clostridium perfringens*, total PAH, total PCB, total DDT, total LAB, and metals (Al, Cd, Cr, Cu, Fe, Pb, Hg, Ni, Ag, Zn). Data from 1996, 1997, and 1998 were excluded from the PCA because a complete data set with all common parameters (*i.e*., contaminants) was not available.

The factor score cross plot showed a general spread of Farfield stations (Figure 4-3a) as opposed to the more distinctive clustering observed for the Nearfield (Figure 4-1a). Farfield stations clustered somewhat along the Factor 2 zero axis (Figure 4-3a). Primary controlling variables included total PAH and metals for Factor 1 and total PCB, total DDT, and sand for Factor 2 (Figure 4-3b). Approximately 67% of the

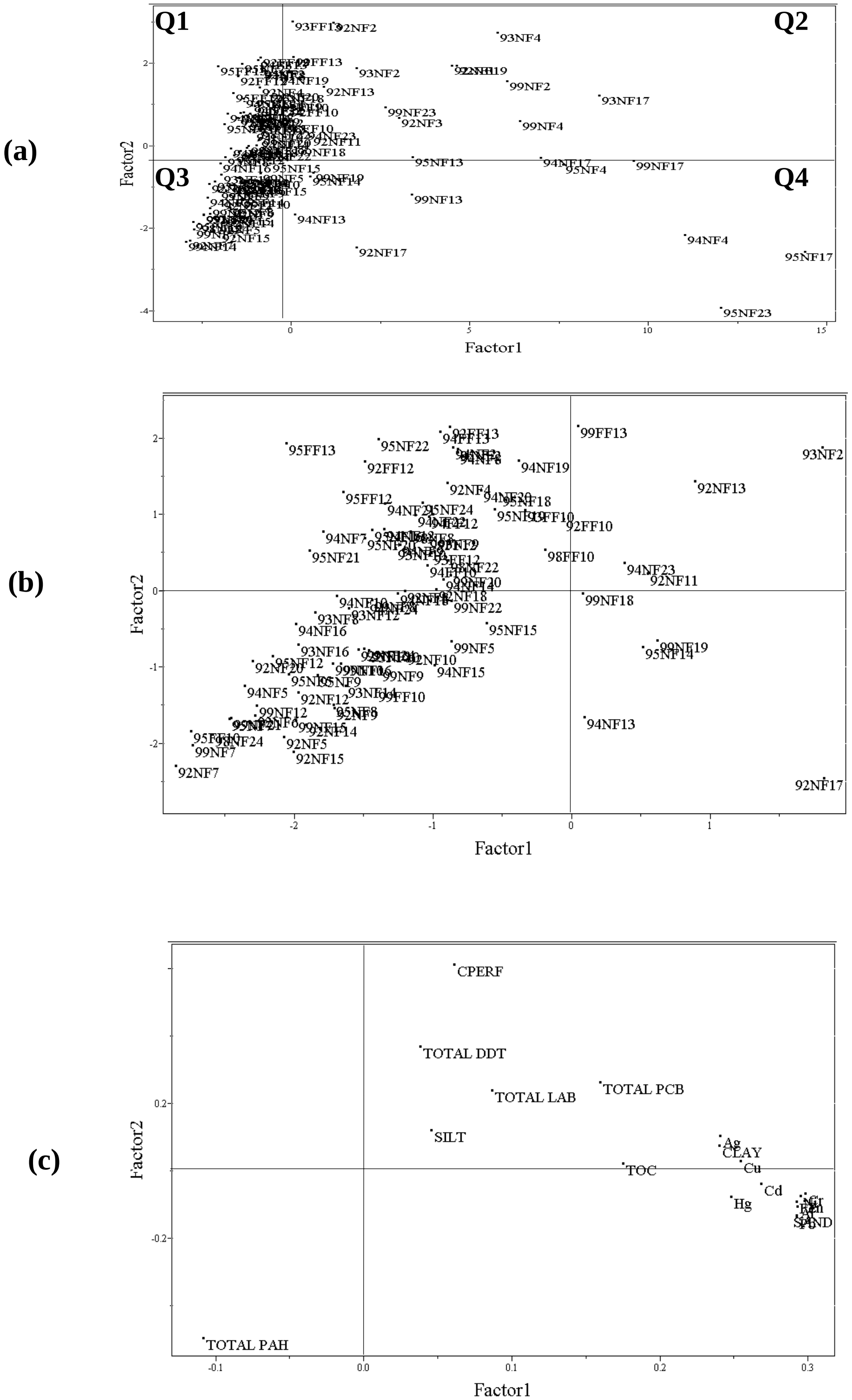


Figure 4-1. Results from the principle component analysis of the Nearfield from 1992 to 1999: (a) factor score plot showing distribution of stations, (b) close-up view of stations clustering in quadrants Q1 and Q3, and (c) factor loading plots with principal components.

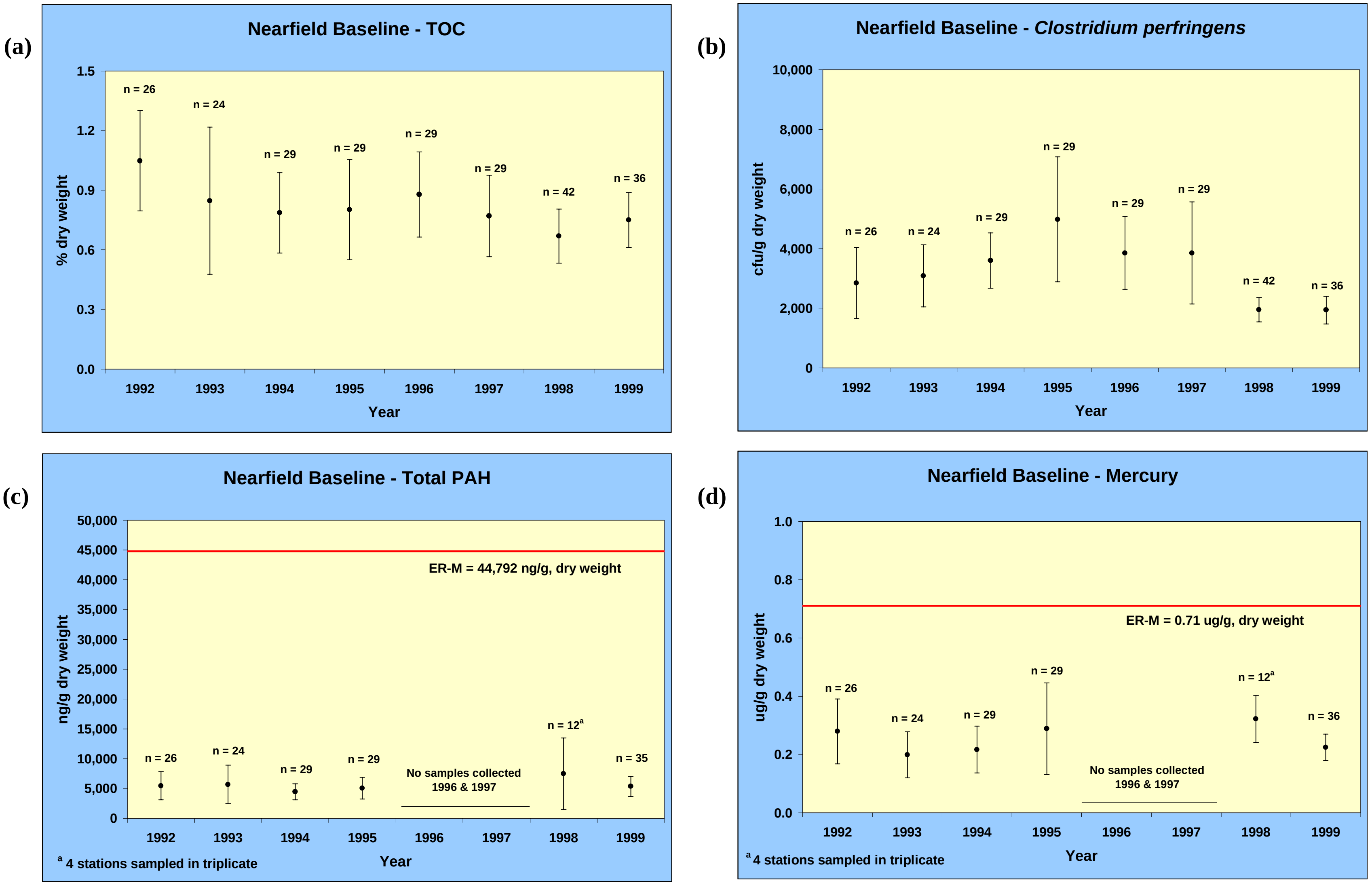


Figure 4-2. Nearfield baseline from 1992–1999 for TOC, *Clostridium perfringens*, total PAH, and mercury. Error bars depict 95% confidence intervals.

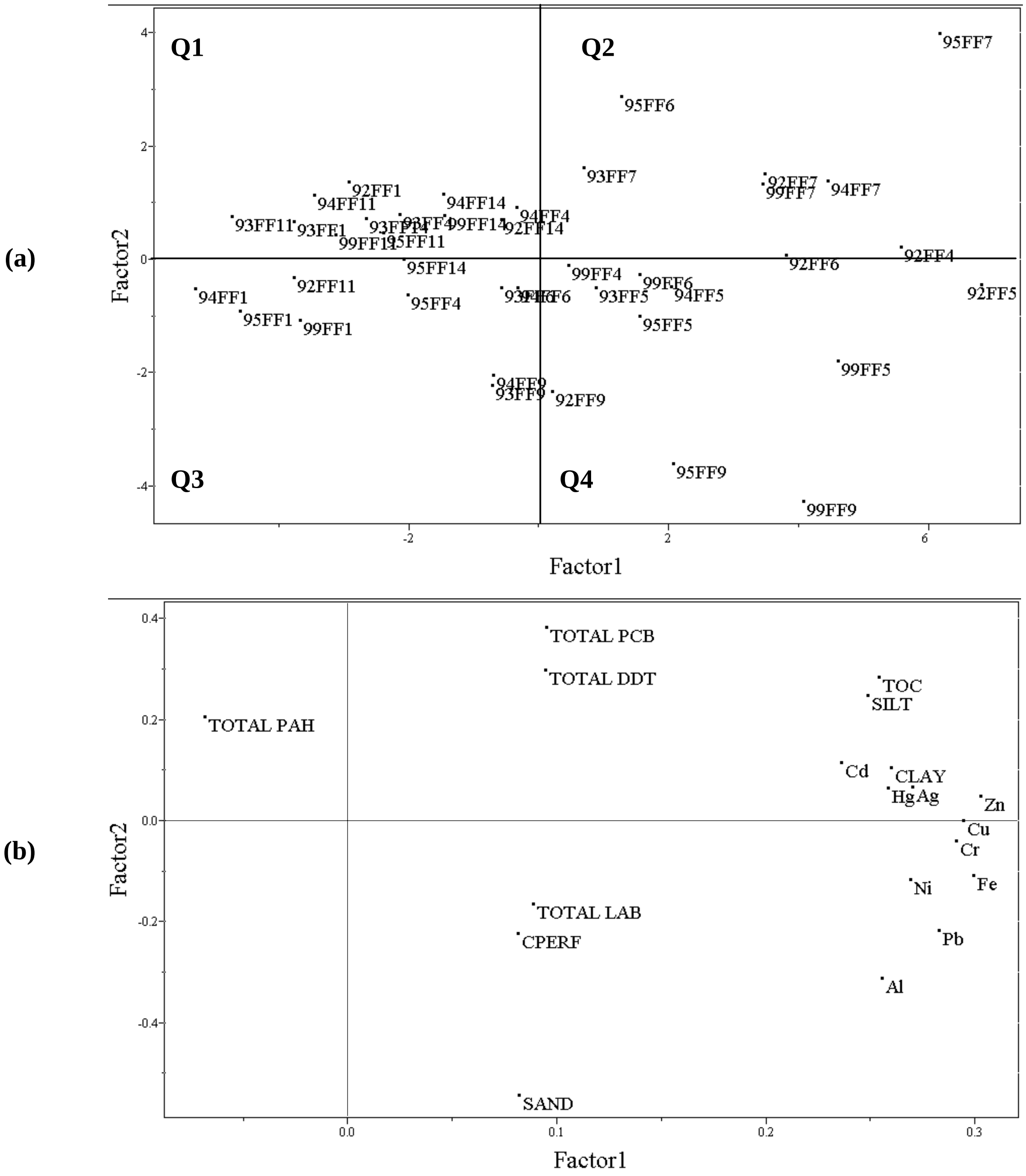


Figure 4-3. Results from the PCA of the Farfield for the period 1992–1999: (a) factor score plots showing distribution of stations, and (b) factor loading plots with principal components. (The original station FF01 – near the MBDS – was sampled only in 1992 and 1993; FF01a – off Gloucester – was sampled from 1994 to 1999)

variability in these data were accommodated by the first and second principal components. Total LAB and *Clostridium perfringens* variables plotted closer to the middle of the factor loading cross plot and had less influence on the data set (Figure 4-3b). The spread in Farfield stations, without any distinct clustering of stations by year, suggests that the spatial distribution of bulk sediment properties and contaminant parameters in the 1999 Farfield was not substantially different from 1992–1998.

However, perhaps the most striking aspect of the PCA is that Factor 1 almost perfectly separates the deepwater Farfield data into groups of northern and southern stations (Figure 4-3a). Northern Stellwagen Basin stations including station FF11 off Cape Anne and the original station FF01 (near the MBDS, sampled only in 1992 and 1993), as well as station FF14, generally clustered in quadrants Q1 and Q3 of the cross plot (Figure 4-3a), with negative Factor 1 loadings. Stations clustering in quadrants Q1, and Q3 to a lesser extent, contained higher concentrations of organic contaminants (*i.e.*, total PAH, total PCB, and total DDT) and were less sandy compared to other Farfield stations.

With few exceptions, all southern Stellwagen Basin and Cape Cod Bay stations (FF04 – FF07) for all years, as well as station FF09 (located between the Nearfield and Stellwagen Basin) clustered in quadrants Q2 and Q4 of the cross plot (Figure 4-3a), with near zero or positive Factor 1 loadings. Station FF07 (Cape Cod Bay) for all years clustered in quadrant Q2 of the cross plot (Figure 4-3a) and was characterized by higher concentrations of total DDT and total PCB with less sand content. Stations FF09 (located between the Nearfield and Stellwagen Basin) and FF05 (Stellwagen Basin) clustered in quadrant Q4 of the cross plot (Figure 4-3a) and were more sandy with lower concentrations of total PAH, total PCB, and total DDT relative to other Farfield stations.

Temporal Characteristics—Farfield baseline mean values and 95 % confidence intervals were determined for bulk sediment properties, *Clostridium perfringens*, and contaminant parameters as described in Section 4.1.3. Farfield baseline mean values for organic and some metal (Hg, Cu, Ag) contaminants were consistently less than Nearfield baseline mean values. Farfield baseline mean values for Pb, Cr, and Zn were fairly similar to Nearfield baseline mean values. In contrast, Farfield baseline mean values for Ni were generally 20–50 % higher than Nearfield baseline mean values.

With few exceptions (gravel, *Clostridium perfringens*), the temporal response of the baseline for bulk sediment and contaminant parameters showed fairly constant means without substantial variability (Figure 4-4). The 95 % confidence intervals generally overlapped across all sampling years, supporting the conclusions above that the spatial distribution of contaminants was not substantially different between sampling years. The Farfield baseline mean values for *Clostridium perfringens* were more variable across sampling years (Figure 4-4). Farfield baseline means in 1995–1997 were generally higher compared to yearly mean values determined in 1992–1994 and 1998–1999. Farfield baseline means decreased in abundance in 1998 and 1999 relative to 1995–1997. Trends in *Clostridium perfringens* are discussed in greater detail in Section 4.2.3.

4.2.3 Spatio/Temporal Response of *Clostridium perfringens* 1992–1999

The spatio/temporal distribution of *Clostridium perfringens* at all Nearfield and Farfield stations from 1992–1999 was evaluated to determine if the gradient in *Clostridium perfringens* observed by USGS (Parmenter and Bothner 1993) is consistent or has changed as harbor cleanup has proceeded. The USGS study observed decreasing spore density (normalized to percent fines) in bottom sediments with distance from Boston Harbor.

The gradient in *Clostridium perfringens* densities (raw and normalized to percent fines) with distance from Boston Harbor (defined as the Deer Island Light) was evaluated for the period 1992–1999. Each sampling year showed trends consistent with USGS findings and indicated that *Clostridium perfringens* densities decreased with distance from Boston Harbor. *Clostridium perfringens* showed a trend toward decreasing abundance in 1998 and 1999 from earlier years (Figure 4-5). There is a wide range in abundance of *Clostridium perfringens* for stations within 20 km of Deer Island Point (Figure 4-5). In contrast, stations further away from Deer Island Point consistently have lower spore densities (Figure 4-5). Variability in abundance of *Clostridium perfringens* at stations further from Deer Island Point decreased when results were normalized to percent fines, indicating that grain size is likely a major controlling factor (Figure 4-6).

Clostridium perfringens results were re-evaluated based on three distance classifications including a near-in group (< 20 km), mid-distance group (> 20 km but < 40 km) and far-distance group (> 40 km) from Deer Island Point. Yearly means (raw and normalized to percent fines) and 95 % confidence intervals were determined for the three distance classifications. Yearly means values of *Clostridium perfringens* (normalized to percent fines) for near-in stations (< 20 km) showed a decrease in abundance in 1998 and 1999 relative to earlier years (Figure 4-7). In contrast, stations further away from Deer Island Point (> 20 km) were on average relatively constant from 1992–1999 (Figure 4-7). The constancy in results within distance classifications after normalization to fine grained sediments suggests the *Clostridium perfringens* is preferentially attached to fine-grained particles and is transported with fine sediments. The decreasing abundance observed in 1998 and 1999 for near-in stations (< 20 km) does not appear to be method related, as the yearly means for all distance categories did not decrease equally. Instead, the trend toward decreasing abundance was most notable for stations within 20 km of Deer Island Point.

MTH Environmental Associates, the laboratory that performed the *C. perfringens* analyses was contacted to help address the following questions:

- *Have the methods used to determine spore densities changed from earlier years?*
- *What is the likely inter-laboratory variability and what level of differences would be considered "real?"*

MTH verified that the methods used to determine spore densities have not changed from earlier years. MTH indicated that there have been no studies looking at the issue of inter-laboratory variability with regard to *C. perfringens* levels in marine sediments. However, based on MTH's experience with marine sediments, observed decreases in abundance of 30% or more do suggest "real differences" in the system provided that samples have been collected and analyzed consistently over time. Further, this observation would be strengthened should trends in other effluent markers (*e.g.,* total LAB) show similar decreases over time. Trends in other effluent markers will be examined in the 2000 Outfall report.

C. perfringens abundance in 1998 and 1999 for near-in stations (<20 km) did decrease by more than 30% from abundances measured in earlier years. Further, Harbor wide concentrations of *C. perfringens* also showed decreasing abundance in August 1998 and 1999 compared to 1996-1997 values (Kropp *et al*. 2000). Thus, the decreasing abundance of *Clostridium perfringens* suggests that the removal of particulates initiated in 1997 by the secondary treatment may be causing the observed changes in 1998 and 1999. This is further supported by the decrease in total suspended solids (TSS) in the Deer Island effluent observed in 1998 (Werme and Hunt 2000).

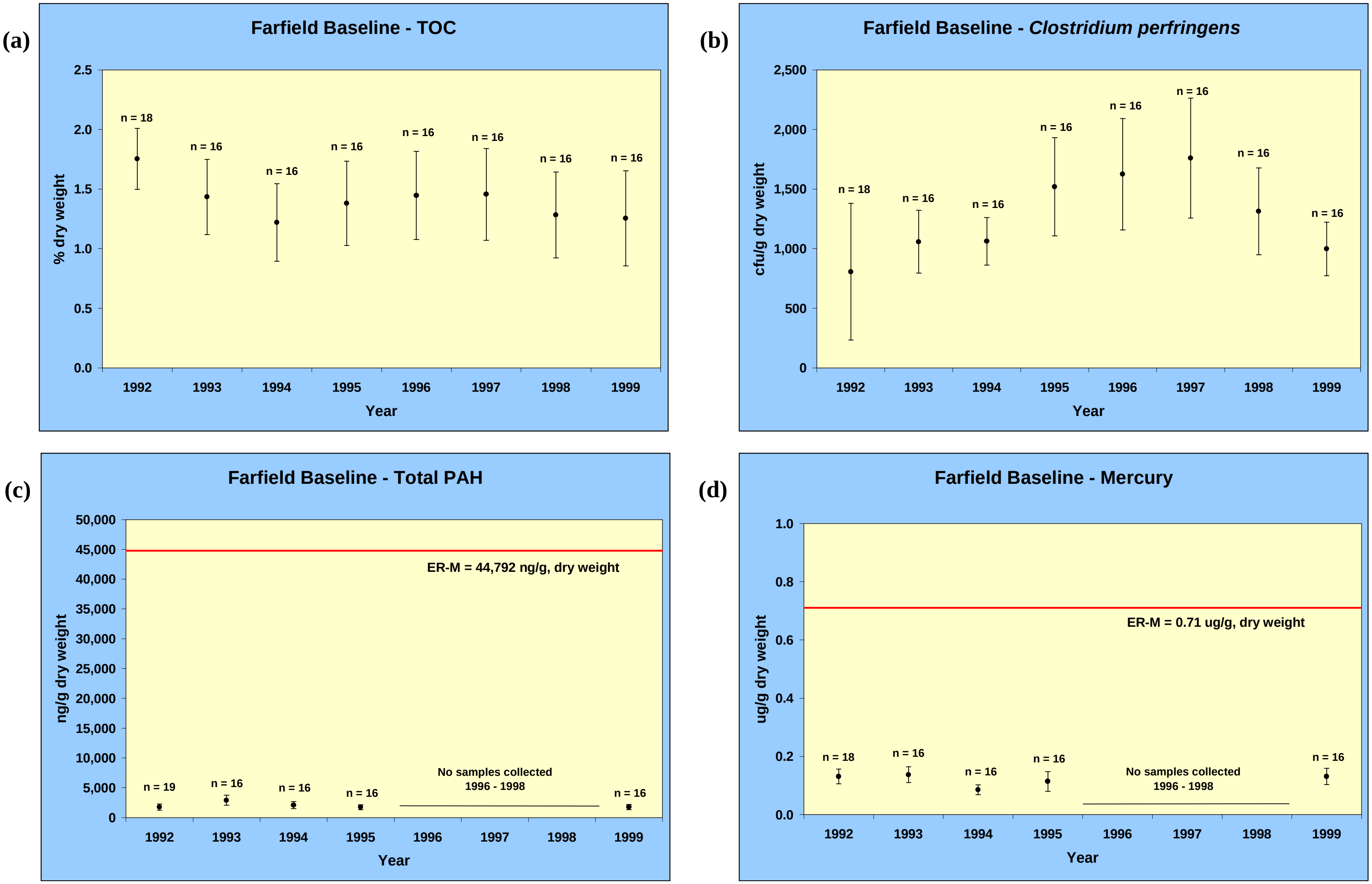


Figure 4-4. Farfield baseline for the period 1992–1999 for TOC, *Clostridium perfringens*, total PAH, and mercury. Error bars depict 95% confidence intervals.

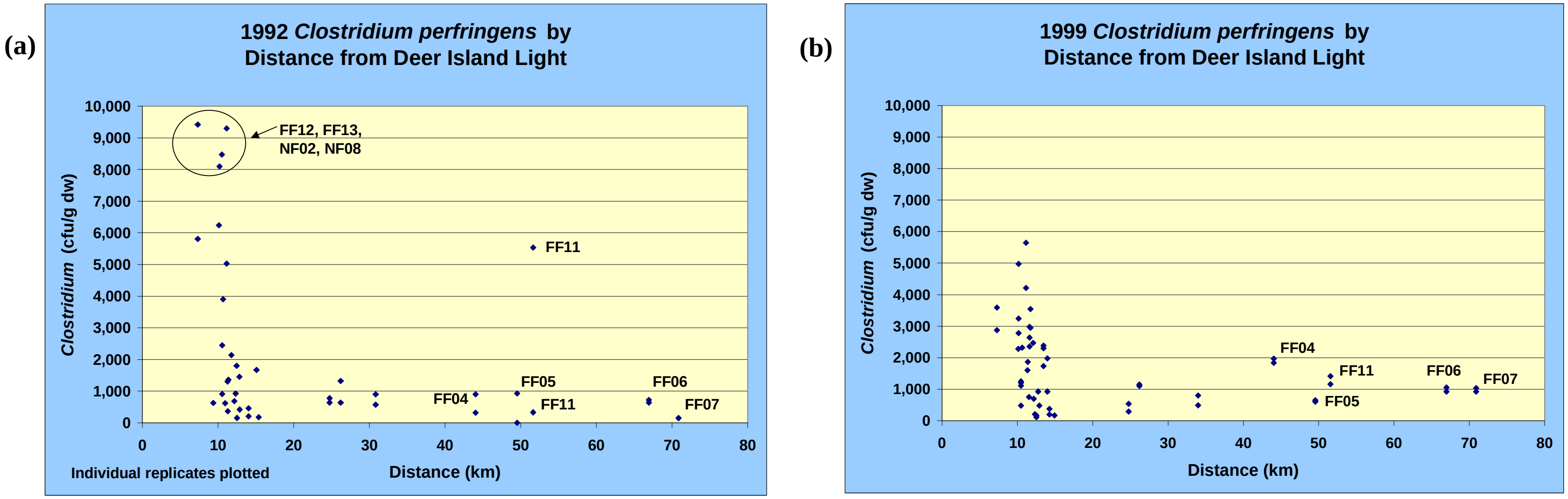


Figure 4-5. Distribution of *Clostridium perfringens* (raw) with distance from Deer Island Light in 1992 and 1999.

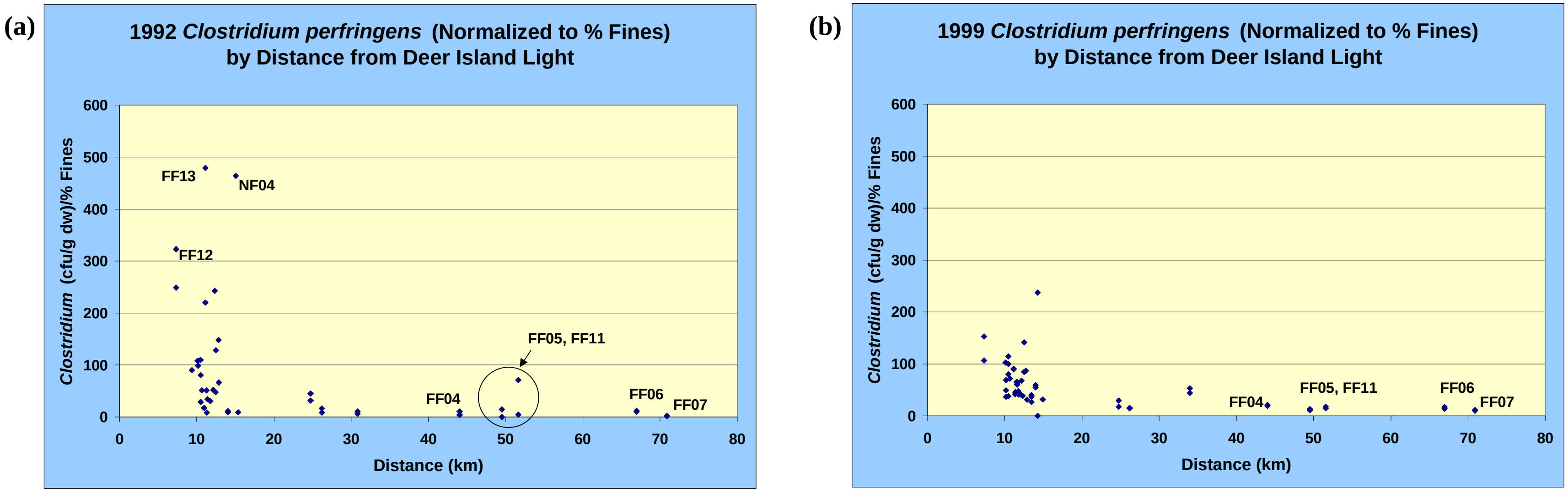


Figure 4-6. Distribution of *Clostridium perfringens* (normalized to percent fines) with distance from Deer Island Light in 1992 and 1999.

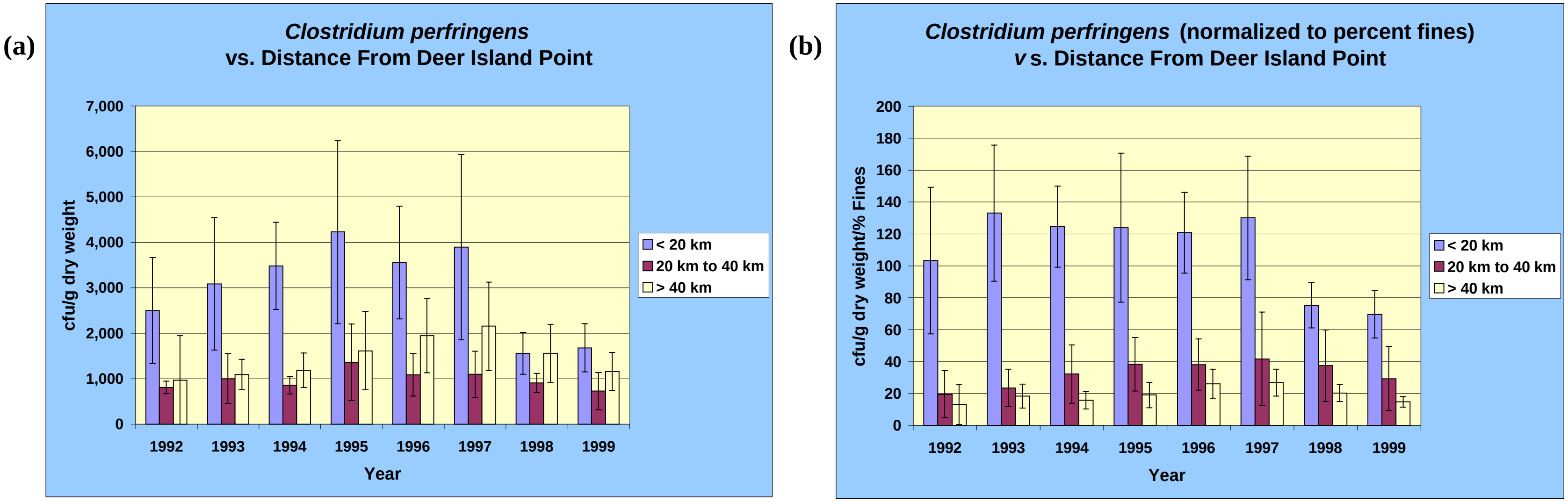


Figure 4-7. Yearly mean concentrations of *Clostridium perfringens* (raw and normalized to percent fines) by distance classification from Deer Island Light (1992–1999).

4.2.4 Chemistry Interrelationships

The correspondence within bulk sediment properties and against contaminants was evaluated for all Nearfield and Farfield stations by using correlation analysis.

Nearfield—Station mean values for Nearfield stations were used in the correlation analysis and the results are presented in Table 4-4. Grain size correlated strongly with TOC across all years ($r = 0.787$, $n = 108$, $p < 0.01$). Bulk sediment properties also correlated well with organic and metal contaminants across all years (Table 4-4, Figure 4-8). With few exceptions (total LAB, Cu, Pb), the correspondence between contaminants and bulk sediment properties was equally strong whether the correlation was performed against percent fines or TOC. The correlation coefficients for total LAB, Cu, and Pb were stronger (25–35 %) when the correlation was performed against TOC as compared to grain size. The evaluation confirms that the contaminant variability in the Nearfield is dominated by grain size and TOC.

Table 4-4. Correspondence within bulk sediment properties and against contaminants in the Nearfield, 1992–1999.

Parameter	Correspondence with Percent Fines			Correspondence with TOC		
	r	***n***	***p***	***r***	***n***	***p***
Percent Fines	1.000	108	<0.01	0.787	108	<0.01
TOC	0.787	108	<0.01	1.000	108	<0.01
Clostridium perfringens	0.641	108	<0.01	0.634	108	<0.01
Total PAH	0.657	108	<0.01	0.716	108	<0.01
Total PCB	0.690	108	<0.01	0.816	108	<0.01
Total DDT	0.725	108	<0.01	0.768	108	<0.01
Total LAB	0.506	108	<0.01	0.723	108	<0.01
Al	0.617	108	<0.01	0.537	108	<0.01
Cd	0.689	108	<0.01	0.807	108	<0.01
Cr	0.824	108	<0.01	0.889	108	<0.01
Cu	0.702	108	<0.01	0.892	108	<0.01
Fe	0.657	108	<0.01	0.684	108	<0.01
Pb	0.703	108	<0.01	0.894	108	<0.01
Hg	0.709	108	<0.01	0.812	108	<0.01
Ni	0.805	108	<0.01	0.760	108	<0.01
Ag	0.692	108	<0.01	0.822	108	<0.01
Zn	0.782	108	<0.01	0.885	108	<0.01

Farfield—Station mean values for Farfield stations were used in the correlation analysis and the results are presented in Table 4-5. Grain size and TOC were strongly correlated ($r = 0.896$, $n = 40$, $p < 0.01$). Although the relationships were high, the correspondence between bulk sediment properties and organic contaminants in the Farfield was generally not as strong as the correspondence observed in the Nearfield. This may suggest perhaps that the primary controlling variables in the Farfield are other than how depositional a station is. With few exceptions, the correspondence between bulk sediment and metals contaminants in the Farfield and Nearfield were more comparable.

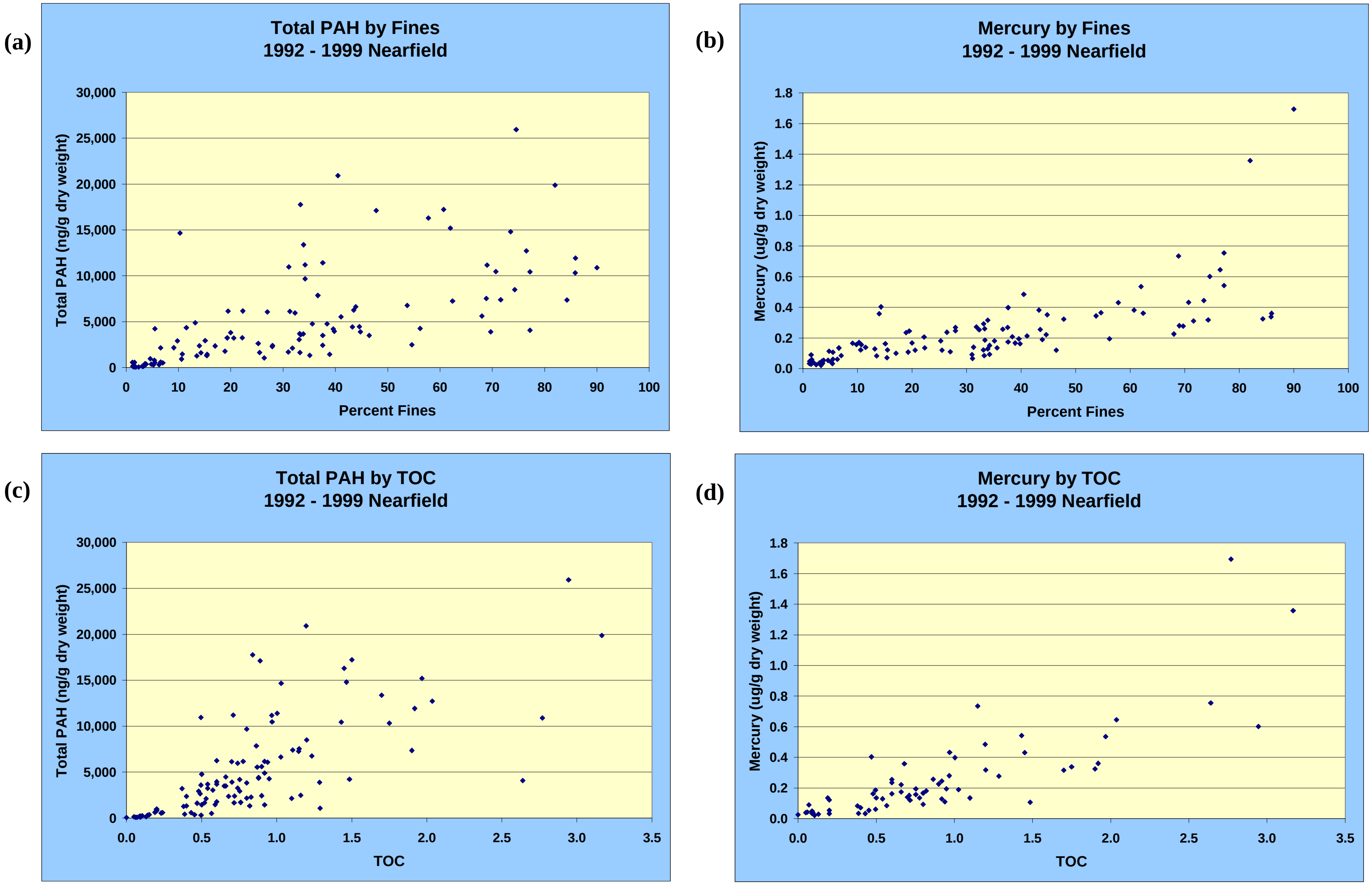


Figure 4-8. Correspondence between bulk sediment properties and representative contaminants (total PAH, mercury) in the Nearfield for the period 1992–1999.

Table 4-5. Correlation coefficients within bulk sediment properties and against contaminants in the Farfield 1992–1999 (excluding FF10, FF12, FF13).

Parameter	Correspondence against Percent Fines			Correspondence against TOC		
	r	***n***	***p***	***r***	***n***	***p***
Percent Fines	1.000	40	<0.01	0.896	40	<0.01
TOC	0.896	40	<0.01	1.000	40	<0.01
Clostridium perfringens	0.410	40	<0.05	0.331	40	<0.05
Total PAH	0.387	40	<0.05	0.434	40	<0.01
Total PCB	0.501	40	<0.01	0.439	40	<0.01
Total DDT	0.585	40	<0.01	0.499	40	<0.01
Total LAB	0.083	40	>0.05	0.012	40	>0.05
Al	0.623	40	<0.01	0.697	40	<0.01
Cd	0.574	40	<0.01	0.698	40	<0.01
Cr	0.808	40	<0.01	0.852	40	<0.01
Cu	0.819	40	<0.01	0.877	40	<0.01
Fe	0.805	40	<0.01	0.924	40	<0.01
Pb	0.761	40	<0.01	0.849	40	<0.01
Hg	0.742	40	<0.01	0.760	40	<0.01
Ni	0.762	40	<0.01	0.895	40	<0.01
Ag	0.571	40	<0.01	0.554	40	<0.01
Zn	0.870	40	<0.01	0.951	40	<0.01

4.2.5 Special Contaminant Study 1998–1999

The Special Contaminant Study was initiated in October 1998 with continued sampling in August 1999. Sediment samples were collected in triplicate at NF08, NF22, NF24, and FF10 to address possible short-term transport and impact with a focus on high TOC/depositional areas.

Bulk sediment and contaminant results from the replicate analyses of sediment samples are reported in Table 4-6 and Appendix C. Data are presented as station mean values and standard deviation of the triplicate analyses. All results are reported on a dry weight basis to three significant figures.

Grain Size—Patterns in sediment texture from October 1998 to August 1999 were variable at some stations (NF08, FF10), and more consistent at others (NF22, NF24) (Figure 4-9; Table 4-6). Sediment from NF08 contained considerably more silt and less sand in August 1999 compared to October 1998. Sediment from FF10 contained greater amounts of gravel in August 1999 compared to October 1998. With some exceptions, the relative variability between sample triplicates was fairly consistent between October 1998 and August 1999. The relative variability in silt content between sample triplicates at NF08 was approximately six times less variable in August 1999 compared to October 1998 results (Table 4-6). Sand and clay composition at NF22 was also two to three times more variable in August 1999 compared to October 1998 results, whereas sand, clay, and silt composition at NF24 was three to eight times less variable in August 1999 compared to October 1998 results (Table 4-6).

Table 4-6. Special contaminant study bulk sediment and contaminant parameters determined in October 1998 and August 1999.

Parameter	Units (dry weight)	ER-M[a]	NF08				NF22				NF24				FF10			
			1998		1999		1998		1999		1998		1999		1998		1999	
			Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
Total PAH[b,c]	ng/g	44,792	6760	2350	7400	1480	3900	705	4430	606	17100	20200	7260	805	2120	135	3230	1930
Total PCB[b]	ng/g	180	26.9	7.14	18.7	6.48	11.1	2.68	12.1	3	20.7	9.79	12.6	0.694	5.88	1.87	2.62	0.448
Total DDT[b]	ng/g	46.1	11	10.7	6.32	7.01	2.51	0.443	2.56	0.389	3.96	2.01	6.28	6.77	2.22	1.9	0.587	0.302
Total Chlordane[b]	ng/g	6[d,e]	0.681	0.123	0.378	0.0782	0.266	0.0573	0.238	0.206	0.274	0.266	0.127	0.22	0.103	0.0901	0.0281	0.0487
Total Pesticide[b]	ng/g	NA	0.737	0.24	0.0824	0.0736	0.141	0.122	0.176	0.306	0.227	0.283	ND	NA	0.00617	0.0107	ND	NA
Total LAB[b]	ng/g	NR	290	53.3	128	22.2	184	18.9	91.3	8.27	191	54.8	72.7	15.4	79.2	12.6	25.6	14.2
Dieldrin	ng/g	8	0.329	0.0604	ND	NA	0.129	0.112	0.176	0.306	0.181	0.243	ND	NA	ND	NA	ND	NA
Al	pct	NR	5.86	0.262	5.52	0.387	5.9	0.0208	6.01	0.224	5.74	1.04	5.74	0.371	5.32	0.0208	5.07	0.335
Cd	µg/g	9.6	0.244	0.0599	0.221	0.0363	0.107	0.0198	0.109	0.00613	0.108	0.0687	0.103	0.0188	0.0646	0.064	0.0713	0.0104
Cr	µg/g	370	119	14.8	95.4	20.6	73.4	8.78	74	8.75	95.1	56.2	83	9.14	70.1	8.33	56.9	11.4
Cu	µg/g	270	32.4	3.71	32.4	7.6	21.8	2.68	25.4	2.75	31.2	9.58	32.9	2.42	15.1	2.93	20.6	10.8
Fe	pct	NR	2.78	0.164	2.61	0.166	2.57	0.0839	2.66	0.0814	2.52	0.803	2.73	0.0819	1.83	0.109	2.05	0.311
Pb	µg/g	218	49.6	2.96	50.9	6.22	40	2.9	45.9	1.51	55.4	23.5	68.3	9.76	31.4	1.51	28.5	3.03
Hg	µg/g	0.71	0.344	0.0485	0.311	0.0849	0.351	0.0695	0.381	0.112	0.322	0.179	0.362	0.0889	0.272	0.256	0.107	0.00673
Ni	µg/g	51.6	21.8	1.04	19.1	4.05	19.8	3.1	23.2	2.66	19.9	7.8	24.2	2.7	15	1.7	17.7	9.99
Ag	µg/g	3.7	0.901	0.17	0.918	0.223	0.593	0.101	0.66	0.0961	0.698	0.427	0.488	0.0403	0.302	0.0128	0.269	0.0554
Zn	µg/g	410	81.1	8.04	79.4	15.2	63.4	3.35	65.6	1.01	72.3	28.4	79.1	5.77	43.8	1.97	55.9	12.9
Sand	pct	NR	48.5	13.8	26.3	6.53	51.8	1.28	52.8	3.66	38.7	34.7	37.5	4.28	49	19.8	59.6	18.7
Gravel	pct	NR	1.7	2.94	2.03	3.44	2.5	4.07	3.97	3.6	0.667	0.833	0.167	0.289	1.02	1.36	21.1	17.6
Silt	pct	NR	38.6	13.8	59.6	3.65	34.6	5.18	32.2	3.76	46.1	28.9	47.7	5.88	39	17.3	15	10.3
Clay	pct	NR	11.1	2.85	12	2.85	11.1	0.777	11.1	1.93	14.5	8.38	14.7	2.72	11	3.87	4.33	1.96
Fines[b]	pct	NR	49.8	16.7	71.6	5.19	45.8	5.96	43.3	5.47	60.6	37.2	62.4	4.16	49.9	21.2	19.3	12.3
Mean phi	pct	NR	4.71	0.816	5.48	0.202	4.50	0.479	4.32	0.323	5.05	1.52	5.19	0.103	4.27	0.966	2.27	1.22
TOC	pct	NR	1.31	0.275	1.11	0.285	0.693	0.19	0.88	0.171	1.07	0.51	1.15	0.0577	0.493	0.0907	0.54	0.137
Clostridium	cfu/gdw	NR	4590	361	3660	1150	3230	534	2660	315	2610	1760	2140	354	1630	180	1190	72.1

[a] From Long *et al*. (1995)

[b] Grain size and contaminant groups defined in Section 4.1.3

[c] Total PAH reported was calculated from an extended list of individual PAHs that were not included in the ERM total PAH group (Long 1995)

[d] ERM value is for Total Chlordane

[e] From Long and Morgan (1991)

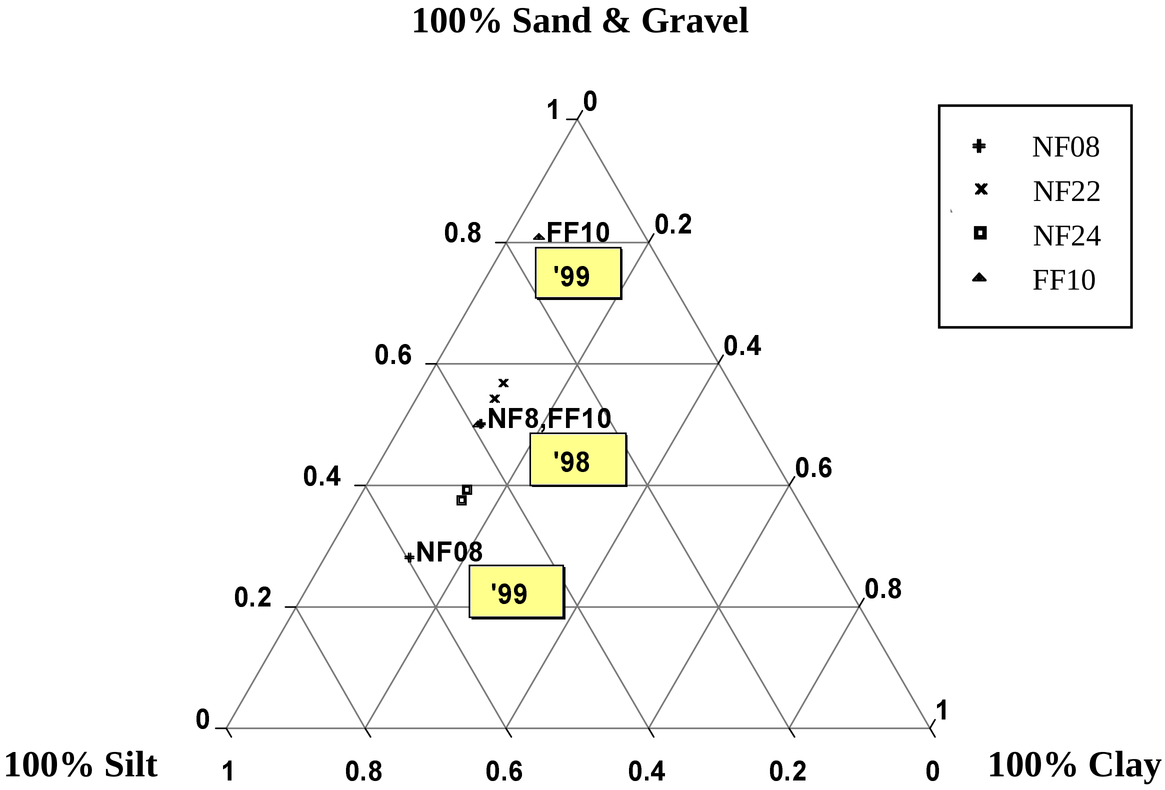


Figure 4-9. Grain size composition at Special Contaminant Study stations in 1998 and 1999.

TOC—Station mean concentrations of TOC for each of the four Contaminannt Special Study stations from October 1998 and August 1999, as well as TOC results for the same stations analyzed as part of the Nearfield in August 1998, are shown in Figure 4-10. With the exception of station NF24, concentrations of TOC were generally consistent from 1998 to 1999 (Figure 4-10). Mean concentration of TOC at station NF24 in October 1998 and August 1999 were approximately two times higher compared to August 1998 levels (Figure 4-10). With the exception of NF24, the relative variability between sample triplicates was fairly consistent from October 1998 to August 1999 (Table 4-6). Relative variability between sample triplicates at NF24 was approximately 10× less in August 1999 compared to October 1998 results (Table 4-6).

***Clostridium perfringens*—**Station mean abundances of *Clostridium perfringens* for each of the four Contaminant Special Study stations from October 1998 and August 1999, as well as spore density results for the same stations analyzed as part of the Nearfield in August 1998, are shown in Figure 4-11. With the exception of station NF24, patterns in *Clostridium perfringens* densities were consistent from October 1998 to August 1999. However, overall densities were 20 to 40 % lower in August 1999 compared to October 1998 levels (Figure 4-11). With the exception of station NF24, *Clostridium perfringens* densities were 5 to 25% lower in August 1999 compared to August 1998 levels (Figure 4-11). *Clostridium perfingens* densities at station NF24 were approximately 35% lower in August 1998 compared to

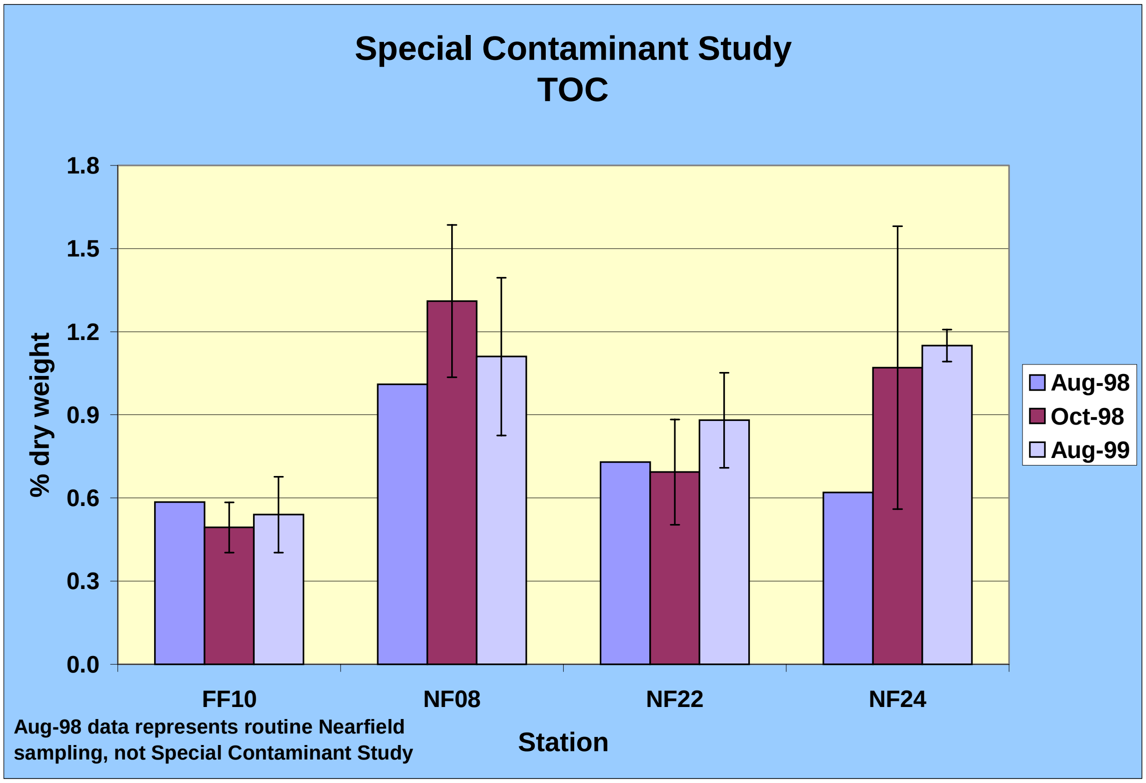


Figure 4-10. TOC content at Special Contaminant Study stations in August 1998, October 1998 and August 1999.

August 1999 levels (Figure 4-11). With the exception of NF08, precision between sample triplicates was tighter in August 1999 compared to October 1998 (Table 4-6, Figure 4-11). The relative variability between sample triplicates at NF08 was approximately four times greater in August 1999 compared to October 1998.

Contaminants—With the exception of NF24, station mean values for total PAH were generally consistent between October 1998 and August 1999 (Figure 4-12). Concentrations of total PAH at NF24 in August 1999 decreased by more than 50 % from October 1998 levels. However, one of the replicates from NF24 had anomalously high PAH content in October 1998 and had this replicate been excluded then the station mean values for total PAH would be fairly constant from October 1998 to August 1999. With the exception of NF22, station mean values for total PCB were consistently 30 to 40 % lower in August 1999 compared to October 1998 values (Figure 4-12). Concentrations of total DDT decreased in August 1999 at FF10 and NF08, increased at NF24 and remained fairly constant at NF22. Station mean values for total LAB decreased by more than 50 % at all stations in August 1999 compared to October 1998 values. With few exceptions, station mean values for metals were consistent between October 1998 and August 1999 (Table 4-6, Figure 4-12).

Relative variability between sample triplicates was fairly consistent from October 1998 to August 1999 at some stations (NF08, NF22), and less consistent at others (FF10, NF24). Relative variability between sample triplicates for total PAH, total LAB, and most metals (excluding Cd, Hg) was higher in August 1999 at FF10, and lower at NF24 for total PAH, total PCB, and metals (Table 4-6).

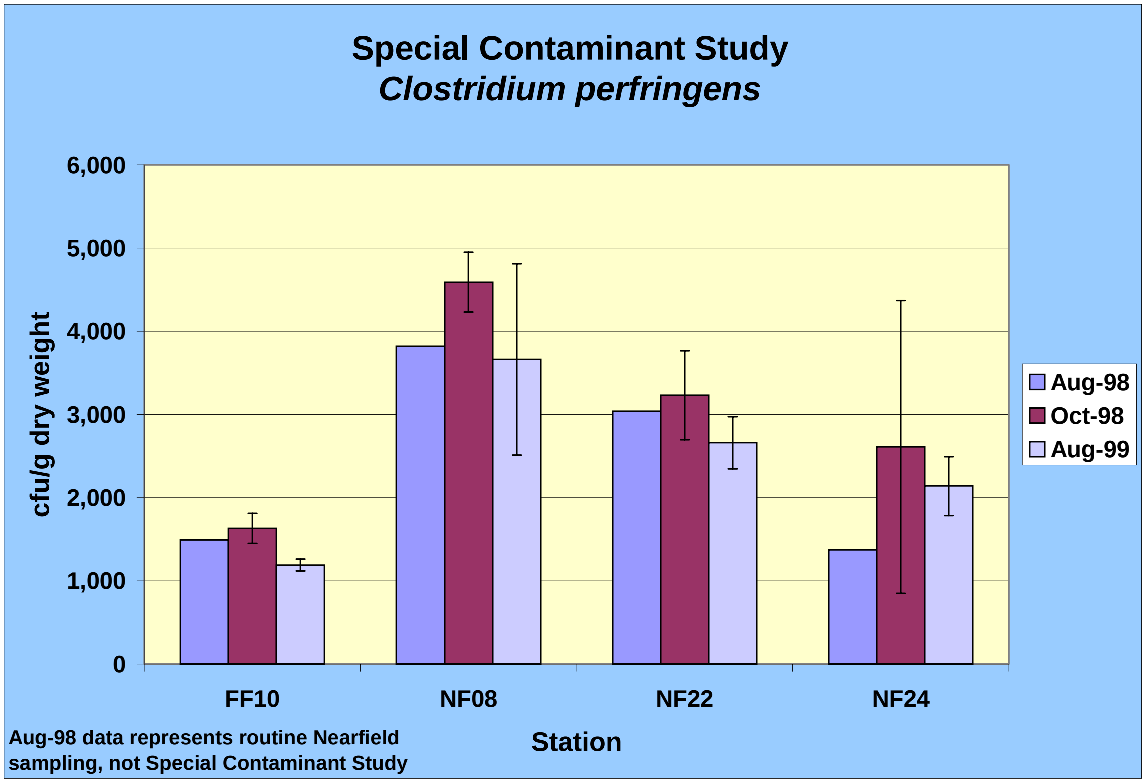
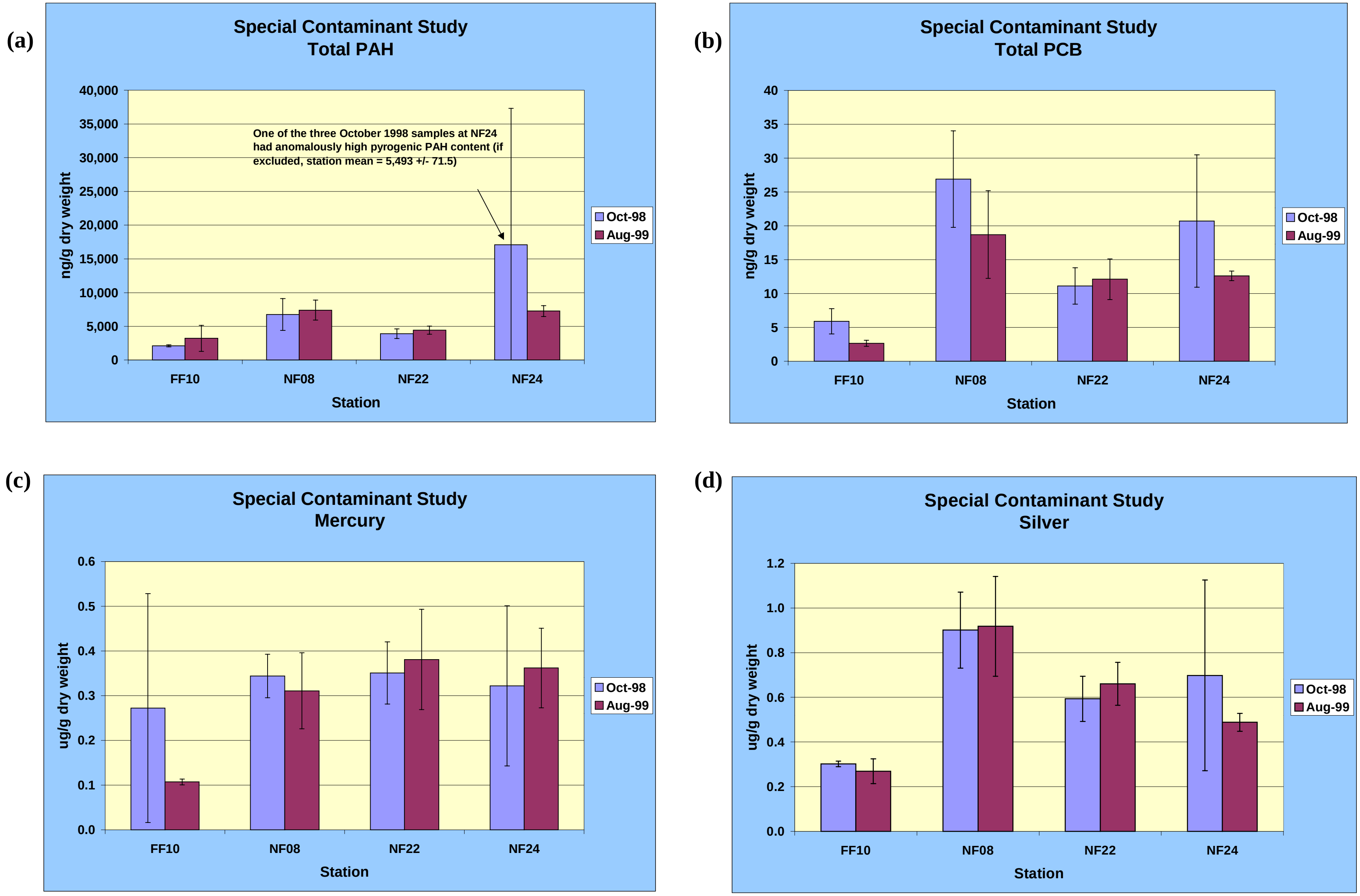


Figure 4-11. ***Clostridium perfringens*** **density (cfu/gdw) at Special Contaminant Study stations in August 1998, October 1998 and August 1999.**

Chemistry Interrelationships—Correspondence within bulk sediment properties and against contaminants was evaluated for all Special Contaminant Study stations (NF08, NF22, NF24, FF10) sampled in October 1998 and August 1999. Correspondence was evaluated using the individual replicates from each station, not station mean values. Grain size was strongly correlated with TOC for both sampling years, however the correspondence in August 1999 was considerably stronger (October 1998: $r = 0.549$, $n = 12$, $p > 0.05$; August 1999: $r = 0.836$, $n = 12$, $p < 0.01$) (Figure 4-13). Organic and metal contaminants correlated well with bulk sediment parameters, indicating that variability was primarily controlled by grain size and TOC (Figures 4-14). However, the correspondence between grain size and contaminants was considerably stronger in August 1999 compared to October 1998. In contrast, the correspondence between TOC and most contaminants was generally stronger in October 1998 compared to August 1999 (Figure 4-14).

Comparison to Nearfield— Data from all Special Contaminant Study stations (NF08, NF22, NF24, FF10) were averaged by year to determine yearly mean values and associated 95 % confidence intervals. Yearly mean values from October 1998 and August 1999 for the Special Contaminant Study were then compared to Nearfield baseline mean values from 1992 to 1999 to address the question *"how well do the*



One of the three October 1998 samples at NF24 had anomalously high pyrogenic PAH content (if excluded, station mean = 5,493 +/- 71.5)

Figure 4-12. Distribution of representative contaminants (total PAH, total PCB, mercury, silver) at Special Contaminant Study stations in 1998 and 1999.

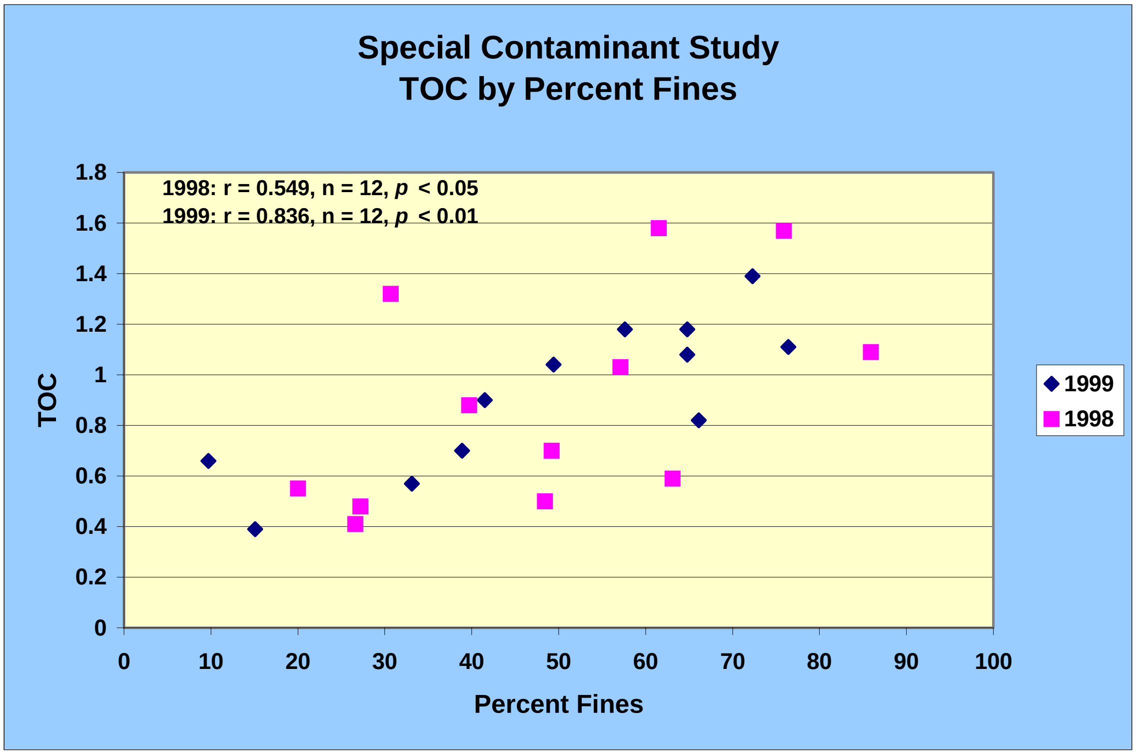


Figure 4-13. Correspondence within bulk sediment properties at Special Contaminant Study stations in October 1998 and August 1999.

Special Contaminant Study stations represent the Nearfield?". The temporal response of the baseline for representative organic and metal contaminants was similar for both the Special Contaminant Study stations and the Nearfield (Figure 4-15). The 95 % confidence intervals generally overlapped across all sampling years, further suggesting that the four Special Contaminant Study stations are reasonably representative of the Nearfield.

4.3 Comparison of Baseline Data to Thresholds

Baselines levels of contaminants in the Nearfield were established for contaminants in sediment based on the mean aerial distribution for Nearfield stations. Baseline and 95 % confidence intervals were determined for each sampling year from 1992–1999 and were evaluated against the MWRA monitoring thresholds based on the Long *et al*. (1995) ER-M values (Table 4-7). Note that Nearfield contaminant results from 1998 are only available for the Contaminant Special Study stations (FF10, NF08, NF22, and NF24). These data are included in Table 4-7 and Figure 4-16 for illustrative purposes only; formal threshold testing will only be conducted when contaminant data are available for all nearfield stations. The temporal response of the baseline for organic and metal contaminants showed relatively constant means without substantial variability (see Figure 4-16 for representative parameters). Baseline mean values for any given year (*i.e.*, 1999) were generally representative of the baseline over time (1992–1999) and were well below ER-M thresholds (Table 4-7).

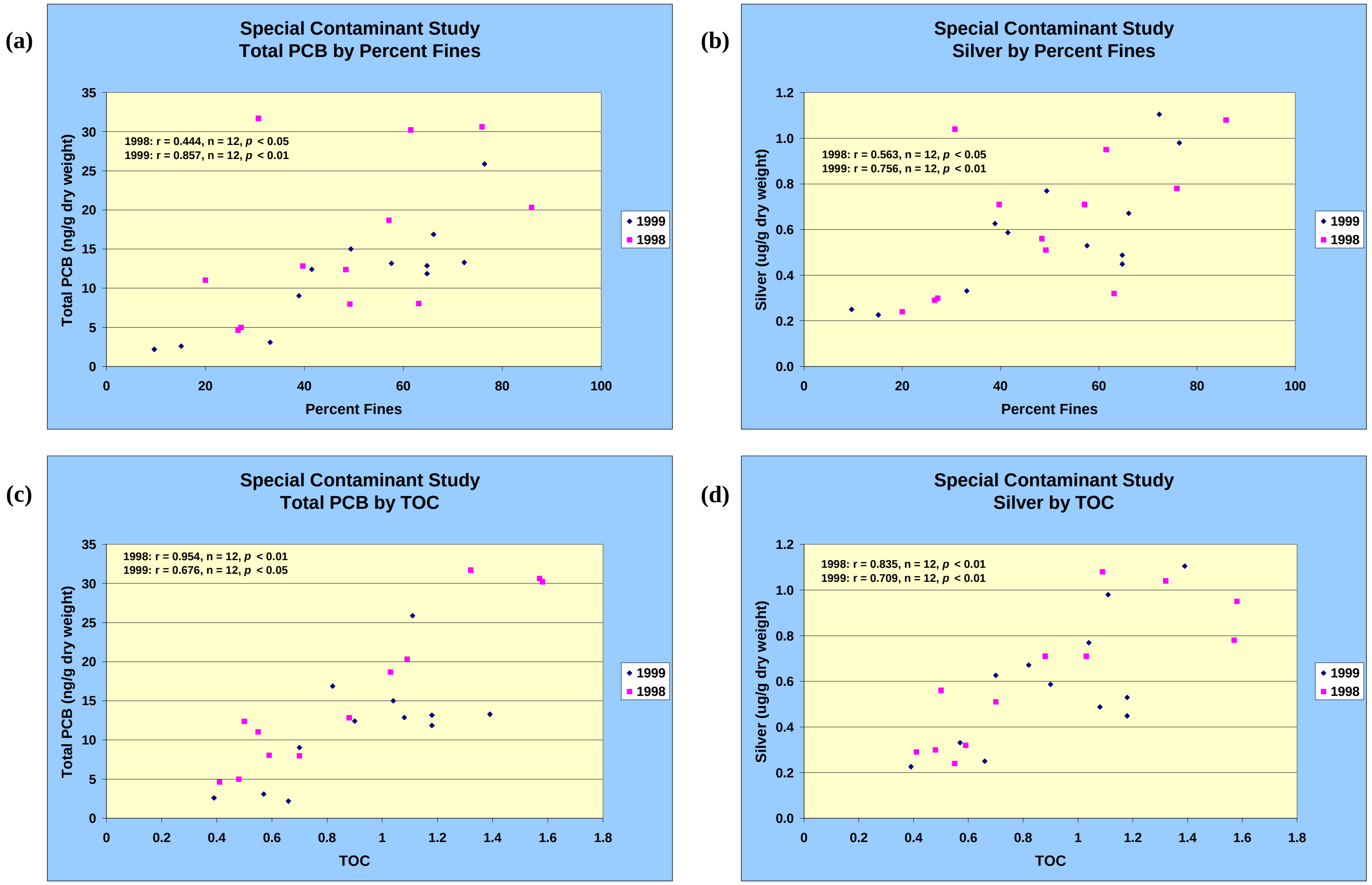


Figure 4-14. Correspondence between bulk sediment properties and representative contaminants (total PCB, silver) at Special Contaminant Study stations in 1998 and 1999.

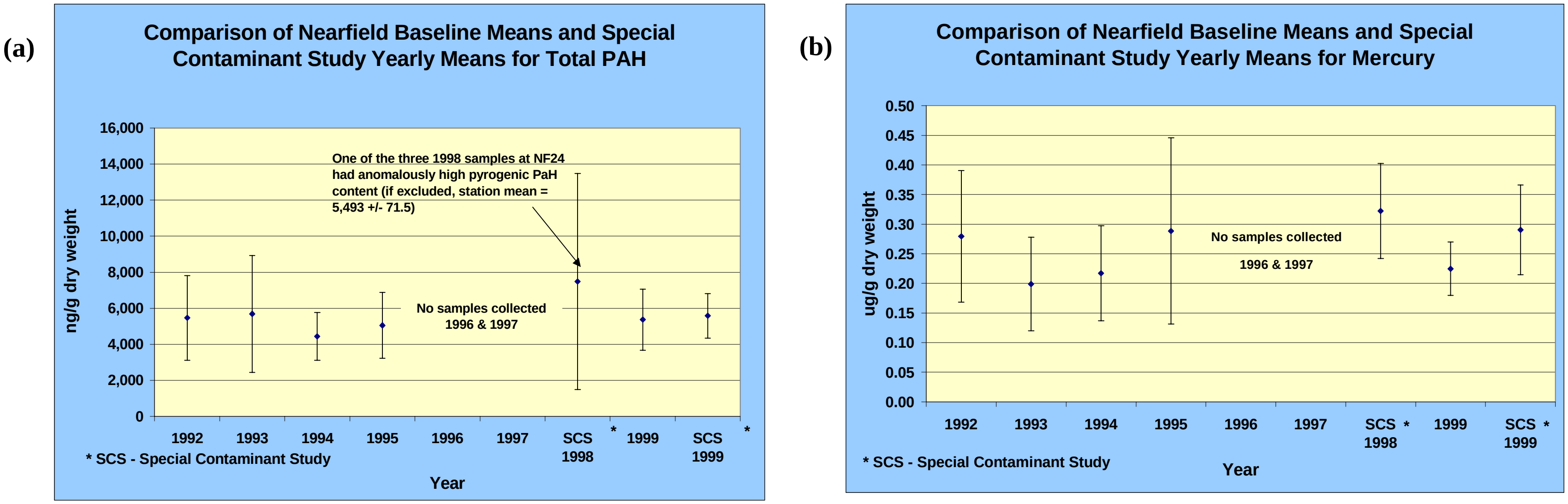


Figure 4-15. Comparison of Special Contaminant Study and Nearfield baseline mean values for total PAH (a) and mercury (b).

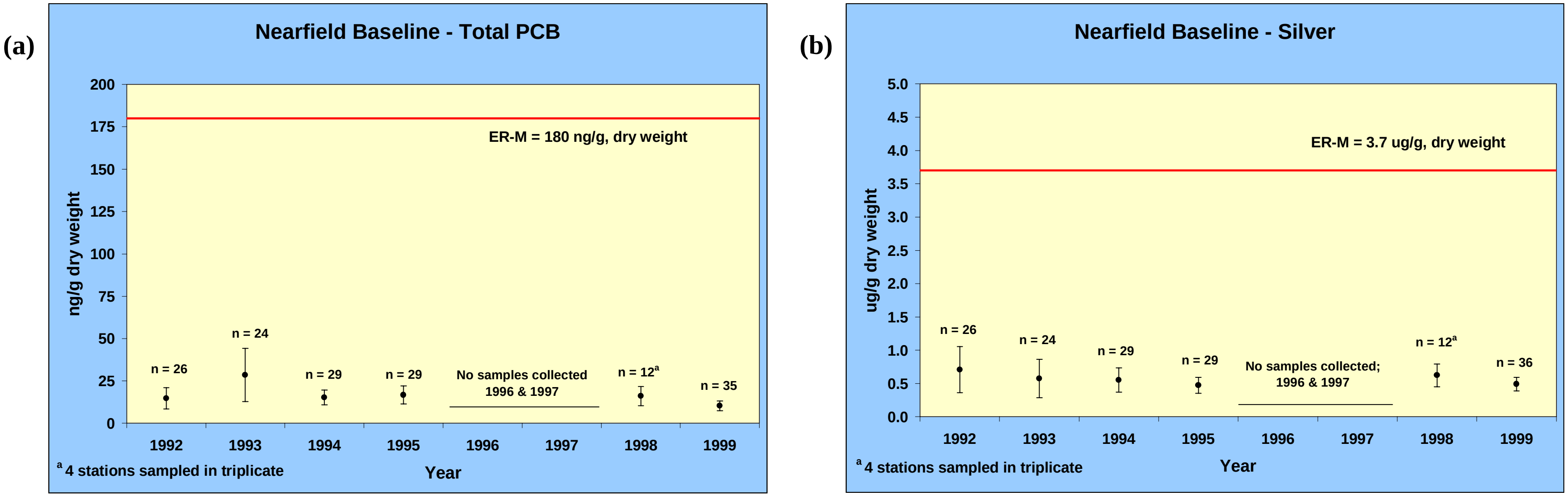


Figure 4-16. Baseline comparison to thresholds in the Nearfield for the period 1992–1999.

Table 4-7. Comparison of Nearfield baseline mean concentrations and thresholds for the period 1992–1999. 1998 data not threshold relevant and included for illustrative purposes only.

Parameter	Units (dry weight)	ER-M[a]	1992		1993		1994		1995		1996		1997		1998[b]		1999	
			Mean	**Stdev**	**Mean**	**Stdev**	**Mean**	**Stdev**	**Mean**	**Stdev**	**Mean**	**Stdev**	**Mean**	**Stdev**	**Mean**	**Stdev**	**Mean**	**Stdev**
Total PAH[c,d]	ng/g	44792	5460	6130	5690	8090	4430	3650	5050	5020	NA	NA	NA	NA	7480	10600	5360	5130
Total PCB[c]	ng/g	180	14.7	16.3	28.6	39.1	15.2	11.9	16.7	14.5	NA	NA	NA	NA	16.1	10.1	10.3	8.66
Total DDT[c]	ng/g	46.1	3.3	3.5	3.82	5.44	5.27	6.53	2.65	3.15	NA	NA	NA	NA	4.93	6.03	2.7	3.2
Total Chlordane[c]	ng/g	6[e,f]	0.108	0.322	0.52	0.652	0.862	0.826	0.465	1.26	NA	NA	NA	NA	0.331	0.259	0.175	0.193
Total Pesticide[c]	ng/g	NA	1.18	2.11	1.12	0.993	4.04	2.85	0.345	0.501	NA	NA	NA	NA	0.278	0.333	0.0664	0.152
Total LAB[c]	ng/g	NR	299	542	392	568	221	282	82.5	97.2	NA	NA	NA	NA	252	84.7	144	60.2
Al	µg/g	NR	5.26	0.686	4.97	0.938	5.14	1.13	4.55	1.02	NA	NA	NA	NA	5.69	0.511	4.98	0.858
Cd	µg/g	9.6	0.189	0.218	0.228	0.255	0.153	0.136	0.175	0.123	NA	NA	NA	NA	0.131	0.0856	0.0896	0.0644
Cr	µg/g	370	85.1	56	80.2	60.1	86.8	44.6	64.8	39.6	NA	NA	NA	NA	88.5	31.7	61.9	23.3
Cu	µg/g	270	27.6	23.9	26.1	19.2	22.8	12.5	19.2	13.1	NA	NA	NA	NA	25	8.63	23.2	9.33
Fe	µg/g	NR	2.31	0.733	2.15	0.829	2.25	0.676	1.8	0.535	NA	NA	NA	NA	2.41	0.507	2.33	0.446
Pb	µg/g	218	47.2	23.6	42.9	20.7	43.8	14.5	43	17	NA	NA	NA	NA	44	14	44.2	13.8
Hg	µg/g	0.71	0.28	0.29	0.199	0.198	0.217	0.22	0.289	0.432	NA	NA	NA	NA	0.322	0.142	0.225	0.138
Ni	µg/g	51.6	18.2	7.63	18.5	8.9	17	7.49	15.5	6.32	NA	NA	NA	NA	19.1	4.48	17.3	6.82
Ag	µg/g	3.7	0.707	0.902	0.575	0.719	0.553	0.495	0.471	0.332	NA	NA	NA	NA	0.624	0.302	0.493	0.314
Zn	µg/g	410	69.7	45	60.8	38.8	56.9	23.7	56.6	27.2	NA	NA	NA	NA	64.8	19	59.2	19.1
Gravel	pct	NR	8.04	17.3	4.03	10.7	4.08	9.09	3.3	6.5	7.02	16	2.21	5.31	6.68	15.7	5.9	11.3
Sand	pct	NR	59.5	23.6	68	22.8	60	26.1	61.4	26.9	59.7	24.5	64.7	24	61.1	23	59.6	23.5
Silt	pct	NR	24.7	18.3	23.1	20.2	28.1	22.1	25.5	21.5	24.9	19.6	24.5	19.6	24.6	18.7	26.2	19.8
Clay	pct	NR	7.74	6.95	4.88	3.98	7.79	6.55	9.8	14.4	8.31	5.9	8.56	5.88	7.59	5.52	8.3	5.92
Fines[c]	pct	NR	33.5	24.2	28	23.7	35.9	27.7	35.3	28	33.2	25	33.1	24.9	32.2	23.6	34.5	24.9
TOC	pct	NR	1.05	0.656	0.847	0.924	0.786	0.555	0.802	0.695	0.878	0.588	0.77	0.562	0.669	0.45	0.75	0.422
Clostridium	cfu/g	NR	2850	3110	3090	2600	3600	2540	4980	5750	3850	3350	3850	4720	1950	1350	1940	1410

[a] From Long *et al*. (1995)

[b] Four stations sampled in triplicate (special contaminant study).

[c] Grain size and contaminant groups defined in Section 4.1.3

[d] Total PAH reported was calculated from an extended list of individual PAHs that were not included in the ERM total PAH group (Long 1995)

[e] ERM value is for Total Chlordane

[f] From Long and Morgan (1991)

NA = Not applicable

NR = Not regulated

Table 4-8. Comparison of baseline mean concentrations, significantly increased levels, and threshold at the Nearfield.

Parameter	Baseline Mean[a]	Baseline Standard Error	N	Significant Increase[b]	Warning Level[c]	Ratio between Threshold and Significant Increase
Total PAH[d,e]	5200	217	5	5660	44792	7.9
Total PCB[d]	17.1	3.05	5	23.6	180	7.6
Total DDT[d]	3.55	0.482	5	4.57	46.1	10.1
Total Chlordane[d]	0.426	0.135	5	0.714	6[f,g]	8.4
Cd	0.167	0.0229	5	0.216	9.6	44.5
Cr	75.8	5.2	5	86.9	370	4.3
Cu	23.8	1.44	5	26.8	270	10.1
Pb	44.2	0.784	5	45.9	218	4.8
Hg	0.242	0.0178	5	0.28	0.71	2.5
Ni	17.3	0.519	5	18.4	51.6	2.8
Ag	0.56	0.0415	5	0.648	3.7	5.7
Zn	60.6	2.39	5	65.7	410	6.2
Clostridium perfringens	3260	365	8	3950	NR	-

[a] Mean concentration of Annual Means, 1992–1995 and 1999 (Contaminants; no 1996 and 1997 data; October 1998 Contaminant Special Study data not used in determination of Baseline Mean)

[b] The significant increase is the concentration at which an increase from the baseline mean is considered statistically significant at the 0.05 level (*i.e.*, 95th percent UCL = mean + $t_{0.1,n-1}$ * S.E.).

[c] Based on ER-M sediment quality guidelines from Long *et al.* (1995)

[d] Contaminant groups defined in Section 4.1.3

[e] Total PAH reported was calculated from an extended list of individual PAHs that were not included in the ERM total PAH group (Long 1995)

[f] ERM value is for Total Chlordane

[g] From Long and Morgan (1991)

To establish when significant increases above the baseline would be detected, a statistical value was established. The significant increase value was set as the 95th percentile upper confidence limit (based on the “t” distribution) of the mean of the annual means. The significant increase values are well within the range of detection; suggesting change can be detected well in advance of threshold issues (Table 4-8). Moreover, each threshold is at least 2.4 times higher than the level of significant increase.

4.4 Conclusions

The PCA, the *Clostridium perfringens* regional analysis, and the correlation analyses all support the picture of two areas with very different factors influencing contaminant concentrations. In the Nearfield, with Mass Bay, there are a series of stations with very heterogeneous sediments in relatively close proximity to the historic leading source of contaminants (*i.e.*, Boston Harbor). Nearfield stations are for the most part equidistant from the source and the major factors influencing concentration of contaminants and sewage tracers are grain size factors, such as how depositional the site is. This is supported by the Nearfield PCA which showed that the primary factors responsible for the variance in the data were Factor 1 (sand, total PAH) and to a lesser extent Factor 2 (*Clostridium perfringens*).

In contrast, the Farfield stations are for the most part less heterogeneous in terms of sediments but are substantially more dispersed. The *Clostridium perfringens* regional analysis shows that a controlling factor in concentrations in the Farfield appears to be proximity to the historic source of sewage contaminants. This was supported by the Farfield PCA results, in which Factor 1 groups the stations more or less along a north-south alignment.

The above picture of the two disparate regions with different controlling factors agrees well with the correlation analyses run on the data from the two regions. Correlations between contaminants and the bulk sediment properties (that appear to control contaminant concentrations in that region) are quite high, with r^2 of 50% or higher for most parameters. Those correlations were generally weaker for Farfield stations (organic contaminants in particular), further supporting the evaluation of the primary controlling variables in the Fairfield being other than how depositional a station is.

Within each of these distinct regions, the spatial distribution of bulk sediment properties and contaminant parameters in 1999 was not substantially different from previous years (1992-1998). Similarly, with the exception of *Clostridium perfringens*, the temporal response of bulk sediment properties and contaminants was not substantially different over time. *Clostridium perfringens* abundances decreased in 1998 and 1999 for stations located closer to the Harbor (20-km of Deer Island Point), suggesting that a “cleaner effluent” with fewer particulates is being discharged possibly as a result of secondary treatment coming on-line in 1997. Baseline mean values for organic and metal contaminants in the Nearfield were well below the MWRA thresholds.

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