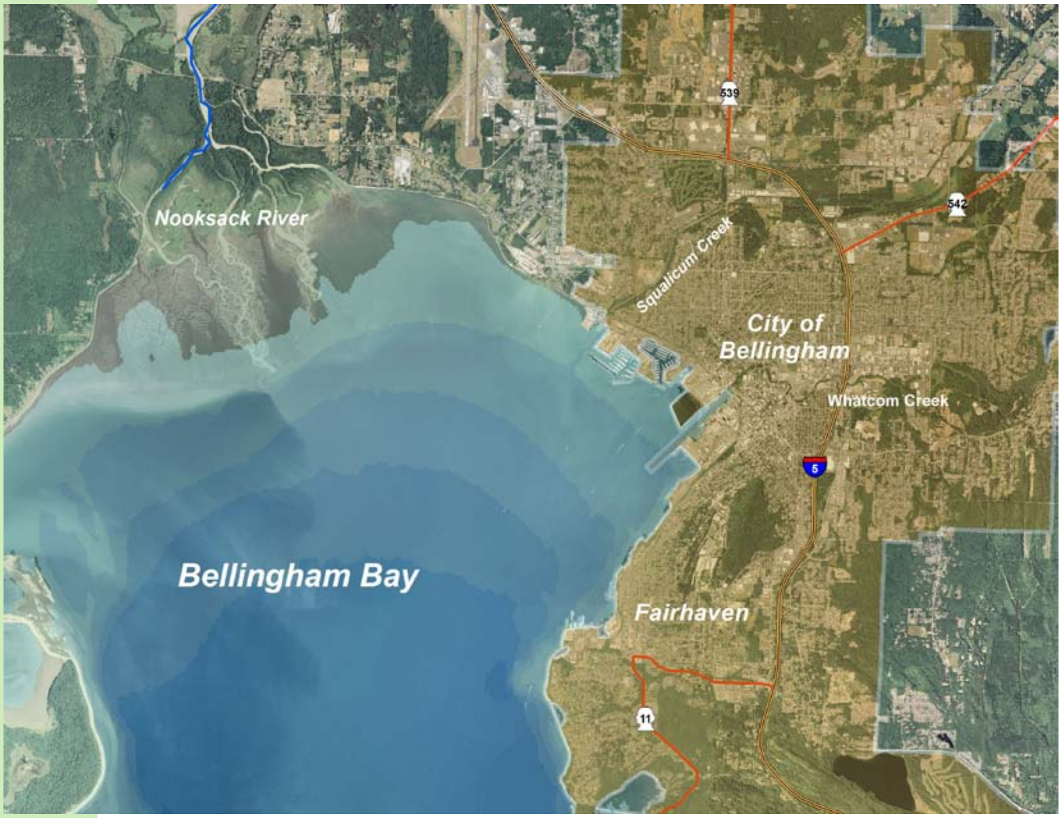

Polychlorinated Dibenzodioxins and Dibenzofurans in Surface Sediments of Bellingham Bay, 2010

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Cover photo: Aerial photograph of Bellingham Bay, with the Nooksack River entering from the north and the City of Bellingham to the east-northeast.

Polychlorinated Dibenzodioxins and Dibenzofurans in Surface Sediments of Bellingham Bay, 2010

by

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Abstract

Site-specific cleanup studies show polychlorinated dibenzodioxins and dibenzofurans (PCDD/Fs) are present in surface and subsurface sediments of Bellingham Bay. However, relatively little is known about PCDD/Fs beyond cleanup site boundaries and away from other point sources. The present study characterizes PCDD/F concentrations in surface sediments throughout a large area of the inner bay.

During the summer of 2010, the Washington State Department of Ecology collected sediment samples from the biologically-active zone (0-12 cm) of 21 stations throughout inner Bellingham Bay. The samples were analyzed for PCDD/Fs, total organic carbon, and grain size distribution. Assuming nondetect congener concentrations equal to one-half the estimated detection limit, total PCDD/Fs in the study area range from 0.54 - 19.8 ng/Kg toxic equivalents (TEQ) and average 6.54 ng/Kg TEQ. Kaplan-Meier estimation of nondetect congener concentrations yields slightly lower minimum and average total TEQ concentrations. Much of the variability in PCDD/F concentrations relates to sediment total organic carbon content.

The spatial distribution of total PCDD/F TEQs in Bellingham Bay surface sediments, based on this and another recent study, reveals a group of 12 contiguous stations with similarly low concentrations. The average total PCDD/F TEQ concentration at these 12 stations is 1.39 or 1.62 ng/Kg TEQ, depending on how nondetect congener results are handled. Both averages are statistically indistinguishable from the average concentration for 97 nonurban stations located throughout Puget Sound. The 12 stations are located in an area receiving sediment from the Nooksack River and may represent background conditions for the bay.

Results of this 2010 study may facilitate cleanup decisions and will help future studies to document changes in PCDD/F concentrations over time.

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Introduction

Background

The Washington State Department of Ecology (Ecology) recognizes 8 active marine sediment cleanup sites in Bellingham Bay [1]. The sites are in various phases of being cleaned up under the Model Toxics Control Act (MTCA) and the Sediment Management Standards (SMS) (Ecology, 1995; Ecology, 2003). Sediments at the sites contain elevated concentrations of mercury, other trace metals, tributyl tin, polycyclic aromatic hydrocarbons (PAHs), phenols, polychlorinated dibenzodioxins and dibenzofurans (PCDD/Fs), and other organic compounds historically released from industrial and municipal sources. Surface sediments beyond cleanup site boundaries also contain PCDD/F concentrations that are of concern.

Ecology's goal for cleanups that involve bioaccumulative contaminants such as PCDD/Fs, which have no promulgated numerical sediment quality criteria, is usually driven by risk to human health from seafood consumption. The risk level, combined with the MTCA risk threshold of 10^{-6}, often means having to reduce contaminant concentrations in sediment to natural background [2]. Therefore, determining natural background concentrations is vital to the cleanup process.

Prior to this 2010 study, PCDD/F concentration data for surface sediments in Bellingham Bay were limited. This made it difficult to:

- Compare concentrations to other areas in Puget Sound.
- Determine if concentrations attributable to nonurban non-point sources differ from natural background.
- Document bay-wide changes in concentration over time.

Previous studies

There have been many studies of sediment quality in Bellingham Bay over the past three decades. Of the studies conducted in the past ten years, only a few have measured PCDD/Fs in biologically-active surface sediments [3]. Table 1 and Figure 1 summarize results of these studies.

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[1] The 8 sites are: Central Waterfront, Cornwall Avenue Landfill, Harris Avenue Shipyard, I & J Waterway, R.G. Haley, South State Street MGP, Weldcraft Steel and Marine, and Whatcom Waterway (McInerney, 2011).

[2] MTCA cleanup standards default to natural background in sediments when risk-based concentrations fall below natural background. MTCA defines natural background as "the concentration of hazardous substance consistently present in the environment that has not been influenced by localized human activities" (Ecology, 2003). An example of a natural background concentration is one that can only be attributed to an unavoidable diffuse source such as aerial deposition. See Glossary in Appendix A for the complete MTCA definition of natural background.

[3] The biologically-active zone of Bellingham Bay sediments is defined as 0-12 centimeters deep.

The highest PCDD/F concentrations in Bellingham Bay sediments are near the R.G. Haley site, a wood treatment facility and known source of PCDD/F contamination [4]. Surface sediments in the waterways, along the waterfront (except near the R.G. Haley facility), and associated with the Dredged Material Management Program (DMMP) disposal site, contain 1.11 - 22.0 ng/kg toxic equivalents (TEQ). Table 1 and Figure 1 do not reflect data more than ten years old because they no longer represent current conditions. Two earlier studies reported 18.5 to 5940 ng/Kg PCDD/F TEQ [5].

Table 1. PCDD/Fs in Bellingham Bay surface sediments from recent studies, 2004 - 2008.

Sampling Area Locations	Sample Year	Sample Number *	PCDD/F Concentrations (ng/Kg TEQ; ND = RL/2)		Reference/ Study
			Minimum	Maximum	
R.G. Haley – Nearshore	2004	3	51.6	125	GeoEngineers (2007)
DMMP Disposal Site	2007	11	4.34	22.0	SAIC (2008)
Boulevard Park – Nearshore	2008	3	1.11	16.1	Hart Crowser (2009)
R.G. Haley – Nearshore		3	80.5	169	
Whatcom Waterway – Inner		3	13.5	14.8	Anchor QEA (2010)
Whatcom Waterway – Outer		5	1.50	12.7	
Total		28	1.11	169	

***** Numbers do not include subsurface sediment samples analyzed for PCDD/Fs.
ND: nondetect.
RL: reporting limit.

PCDD/F concentrations have also been measured in surface sediments at some nearby stations outside of Bellingham Bay. One sample collected near the main ARCO refinery loading dock west of Ferndale, Washington, contained less than 6.23 ng/Kg TEQ (ThermoRetec, 2001). And in 2008, DMMP staff collected five surface sediment samples from Samish Bay and two samples from north of Lummi and Orcas Islands (EPA, 2008). PCDD/F TEQ concentrations in these 7 samples were in the 0.90 - 1.89 ng/Kg range and averaged 1.30 ng/Kg (DMMP, 2009).

[4] R.G. Haley used pentachlorophenol, often with traces of PCDD/Fs, as a wood preservative (GeoEngineers, 2007).
[5] The Oeser Company, a wood pole treatment facility, released PCDD/Fs into Little Squalicum Creek (E&E, 2002). Georgia Pacific released PCDD/Fs directly into the bay via a deep water outfall (Anchor Environmental, 2000).

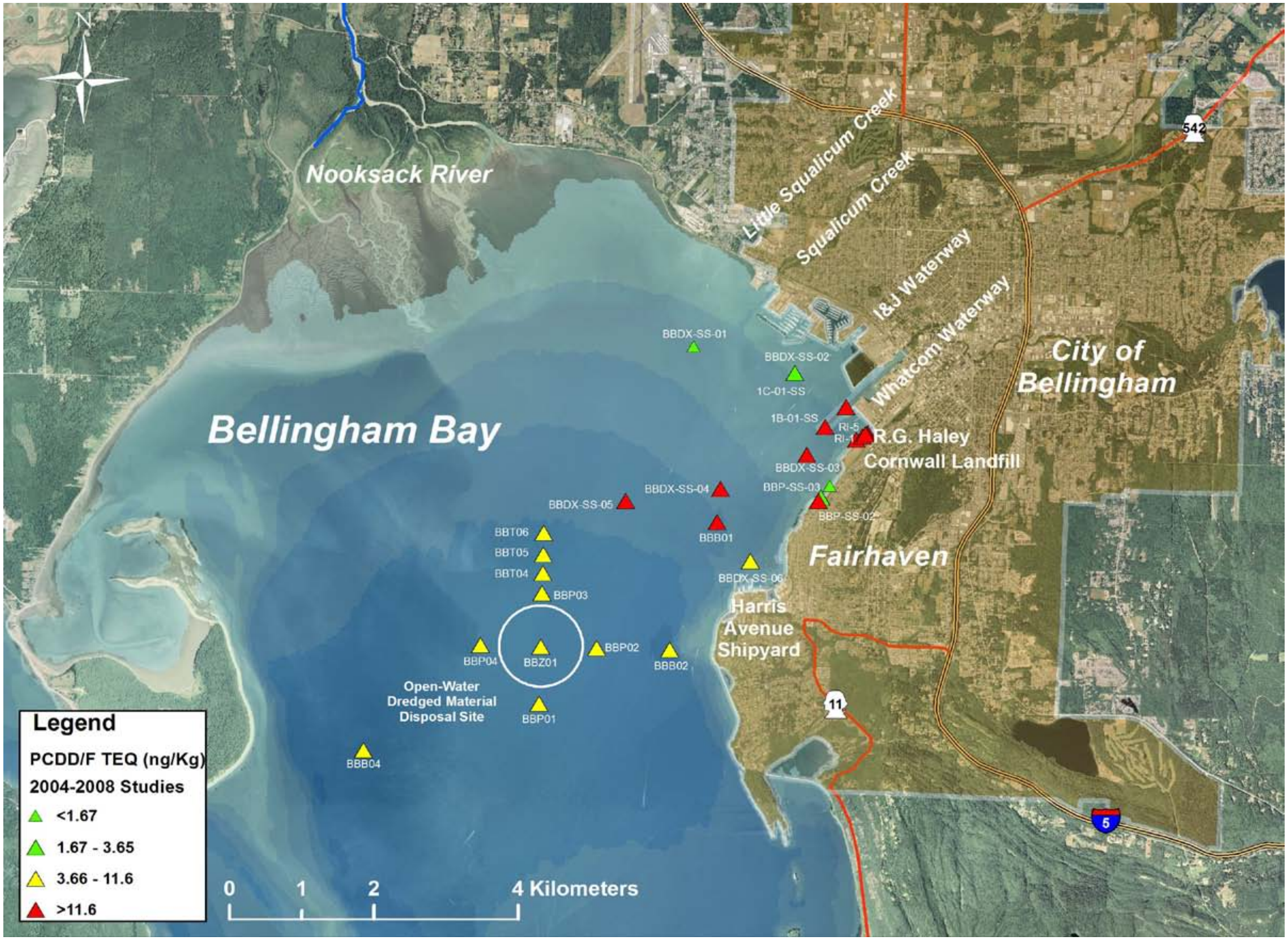

Figure 1. PCDD/F concentrations in Bellingham Bay surface sediments, 2004-2008.

Present study

Previous studies of surface sediments in Bellingham Bay did not measure PCDD/F concentrations intending to compare them to concentrations in greater Puget Sound or to calculate background concentrations for the bay. Neither did the previous studies intend to describe bay-wide baseline conditions to which future results can be compared. The present 2010 study will provide PCDD/F concentration data useful for these purposes.

Goals and objectives

The main goal of the present study was to characterize concentrations of PCDD/Fs in the biologically-active surface sediments of inner Bellingham Bay. Specific objectives were to:

- Collect 0-12 cm deep surface sediment samples from 21 locations that provide good spatial coverage of the inner bay.
- Measure concentrations of 17 high-risk PCDD/F congeners in each sample.
- Calculate and map TEQs for all samples.
- Compare results to historic concentrations of total PCDD/Fs in surface sediments.
- Identify results that might represent background concentrations of total PCDD/F for Bellingham Bay.
- Compare these background concentrations, if identified, to the total PCDD/F concentrations in surface sediments in nonurban areas that may represent natural background conditions for greater Puget Sound.
- Evaluate total PCDD/F results for use as baseline conditions in surface sediments of the bay.
- Optional: Compare total PCDD/F TEQs when calculated using two common methods of handling nondetect concentrations.
- Optional: Identify potentially useful relationships between parameters.

Study Design

Ecology's Marine Sediment Monitoring Program staff collected samples of biologically-active surface sediment from 21 locations chosen to provide good spatial coverage of inner Bellingham Bay [6]. Nine of the sampling locations coincided with ones chosen using a stratified-random sampling design (Partridge et al., 2011; Long et al., 1999; Long et al., 1996). The remaining 12 locations were chosen subjectively to fill spatial data gaps.

All samples were analyzed for 17 high-risk PCDD/F congeners, along with total organic carbon (TOC) and grain size distribution. PCDD/F concentrations were converted to TEQs using accepted toxic equivalent factors (TEFs) (Van den Berg, 2006). TEQ concentrations were mapped to elucidate spatial patterns and analyzed to address objectives of the study.

[6] The study design took advantage of ongoing marine sediment monitoring efforts and did not attempt to collect sediment samples from outer Bellingham Bay.

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Methods

Field

Field methods used to collect surface sediment samples are described in other documents (Dutch et al., 2010; Aasen, 2007; PSEP, 1997a) and summarized here.

Upon arrival at target sampling locations, a stainless steel double van Veen grab sampler was lowered to one meter above the bottom. It was then dropped into surface sediment and retrieved to the deck of the *RV Kittiwake*. Penetration depth of the sampler was recorded and the sample was deemed acceptable, with a few exceptions, if the "bite" of sediment was at least 12 cm deep. Sediment was removed to a depth of 12 cm (unless noted otherwise) using stainless steel spoons and homogenized in a stainless steel bucket. Subsamples were placed in appropriately-sized glass jars and stored in ice coolers or in the dark at 4^{o}C. Samples were transferred to laboratories using standard chain-of-custody procedures.

The van Veen grab sampler and all field equipment (e.g., stainless steel spoons and bucket) were cleaned prior to sampling as described by Dutch et al. (2009). Between being deployed at different sampling locations, the van Veen was scrubbed with soap and rinsed thoroughly with site water. Glass sample containers were certified as pre-cleaned by the manufacturer.

Laboratory

Quality Assurance (QA) Project Plans for the Marine Sediment Monitoring Program list the analytical methods used to measure conventional parameters and PCDD/F concentrations in surface sediment samples (Dutch et al., 2009 and 2010, respectively). The methods are summarized in Table 2.

Table 2. Summary of methods used to analyze Bellingham Bay sediments.

Parameter	Method	Description	Laboratory
Grain Size Distribution (% of dry weight)	PSEP (1986)	Gravimetric	Analytical Resources, Inc.
TOC (% of dry weight)	PSEP (1986)	Combustion at 70^{o}C Infrared detection	Manchester Environmental Laboratory
PCDD/Fs (ng/Kg)	EPA 1613B (EPA, 1994)	HRGC/HRMS	Pace Analytical Laboratories

HRGC/HRMS: high resolution gas chromatography/mass spectrometry.

Calculating TEQ

Concentrations of individual PCDD/F congeners were converted to 2,3,7,8-tetrachlorodibenzo-dioxin (TCDD) TEQs using TEF values published by the World Health Organization (Van den Berg, 2006). Individual congener TEQs were summed to obtain total PCDD/F TEQ concentrations. The total TEQ of a sample was considered an estimate if at least 10% of the individual congener TEQ concentrations were assigned a "J" qualifier. Appendix D provides an example calculation.

Ecology used 2 approaches to assign concentration values to congeners not detected in a sample (nondetects).

- The first approach was to assume nondetect concentrations equal to one-half the detection limit. This has been a common practice until recently and is reported to be an adequate alternative to more rigorous statistical approaches (Antweiler et al., 2008; DMMP, 2009). Unless stated otherwise, results presented and discussed in this report are based on this assumption and substitution.
- The second approach for addressing nondetects was to use the often-recommended Kaplan-Meier statistical method (Kaplan and Meier, 1958; Helsel, 2005; Michelsen, 2008). This method uses detected concentrations and detection limits to estimate nondetect concentrations in a population of samples. The spreadsheet *KMStats.xls version 1.4* (Practical Stats, 2011) was used to calculate the average of the 17 individual congener TEQs for each sample. Each average was multiplied by 17 to obtain the Kaplan-Meier total TEQ.

Statistical

Spatial distributions of concentration results were mapped using ArcMap (ESRI, Version 9.3.1). Data distributions and potential outliers were identified using Scout 2008 version 1.0, which includes ProUCL version 4.0 (EPA, 2011). Descriptive statistics summarizing study results were compiled using SPSS release 11.0 or release 14.0 (SPSS, 2001/2005). The same software applications were used to explore relationships between parameters:

- Correlation Analysis (Pierson; Kendall's Tau and Spearman rank correlations)
- Regression Analysis (stepwise)
- Principal Components Analysis
- Hierarchical Cluster Analysis

ProUCL was used with a subset of results from this and other recent studies to calculate PCDD/F TEQ concentrations that may represent background in Bellingham Bay surface sediments.

Data Quality

Data verification

Manchester Laboratory staff, contract laboratory chemists, and the project manager conducted QA reviews to verify that samples and analyses met requirements of the QA Project Plan (Dutch et al., 2010) and consistent with regional guidance (PSEP, 1997b).

Sample storage conditions and holding times reflected plan requirements, as did the sample preparation, extraction, and analytical methods used. Initial and ongoing calibrations of instruments analyzing PCDD/Fs were acceptable. Estimated detection limits (EDLs) for conventional parameters and PCDD/F congeners met QA Project Plan or contract requirements.

Field split results

The field crew did not collect a true field duplicate to evaluate small-scale spatial variability of PCDD/F concentrations in surface sediments. Instead, sediment collected at station BBDIOX-08 was homogenized and split to also form BBDIOX-88. The relative percent difference (RPD) between individual PCDD/F congener concentrations in the sample and field split ranged from 19% to 74% and averaged 51%. RPD values for total PCDD/F concentrations and total PCDD/F TEQ were 35% and 55%, respectively.

Quality control sample results

The laboratories analyzed QC samples as prescribed by the QA Project Plan. The QC samples included blanks, lab control samples (LCSs), lab replicates, duplicate matrix spikes, and certified or standard reference materials. Results for the QC samples used to assess data quality and usability are summarized in Appendix C.

Grain size distribution and TOC results were within acceptance limits with one exception. Table C-2 shows a relative standard deviation (RSD) of 33% for the sand content in lab triplicates of sample UWI 35. This exceeded the guideline for precision (±20%).

PCDD/F concentrations in the sediment samples were analyzed in two batches, as indicated in Tables C-3 and C-4. Table C-5 shows PCDD/F results for the QC samples. The results met method quality objectives with the following exceptions.

- Batch 2 laboratory blank. The initial blank contained an elevated background concentration of OCDD. Samples in this batch (BBDIOX-3A, BBDIOX-7 to BBDIOX-12, and UWI 27) were re-extracted and analyzed along with an acceptable lab blank.
- Batch 2 laboratory duplicates. The RPD between congener concentrations in sample UWI 27 and the duplicate exceeded the 50% control limit for all congeners except 2,3,7,8-TCDF. This was not sufficient cause to qualify Batch 2 sample results. The most likely explanation was incomplete homogenization of the sample prior to creating the duplicate. The duplicate had consistently lower congener concentrations and a lower total PCDD/F, while analysis of a certified reference material (CRM) did not show this bias.

- Batch 2 CRM [7]. Concentrations of 15 PCDD/F congeners were measured with acceptable accuracy. Analysis of two furan congeners in the CRM yielded results with a high bias that was probably caused by interference from closely-eluting polychlorinated diphenyl ethers:
  - 1,2,3,7,8,9-HxCDF = 685% recovery (51 ng/Kg measured vs. 7.44 ng/Kg in CRM)
  - 2,3,4,6,7,8-HxCDF = 176% recovery (85 ng/kg measured vs. 48.4 ng/Kg in CRM)

  Concentrations of these congeners in Batch 2 samples were already qualified as estimates ("J") for other reasons. These congeners also made up less than 0.3% of the total PCDD/F concentrations and less than 3% of the total TEQ in the Batch 2 samples.

Data validation

Pace Laboratory submitted a Level IV data package containing complete PCDD/F results to Manchester Laboratory. The QA officer then reviewed the package and validated the PCDD/F concentrations reported. No results were rejected. Data quality issues associated with lab QC samples caused some PCDD/F concentrations to be assigned qualifier codes.

Data usability

Results were evaluated in terms of completeness, representativeness of samples, and comparability of results, as well as analytical precision, bias, and accuracy.

Results of the present 2010 study are deemed complete and representative of biologically-active surface sediments (0-12 cm) found within a large portion of inner Bellingham Bay. Results are methodologically comparable to those from previous studies. However, results may not be representative of the surface sediments in outer Bellingham Bay (outside the study area) or of subsurface sediments.

QC sample results indicate good quality data that are usable for the purposes of this study (Table C-5). Spiked sample results show acceptable congener recoveries and precision. High RPDs between Batch 2 laboratory duplicates are likely due to incomplete homogenization of the sediment sample, not poor analytical precision. Results for internal standards and a CRM show minimal bias and acceptable accuracy.

The variability represented by the RPD between PCDD/F congener concentrations in the field splits is an issue of interest. The RPD for one-half of the congeners was greater than ±50%, and the RPD for total PCDD/F TEQ was 55%. This may reflect incomplete homogenization in the field, unavoidable heterogeneity of surface sediments, variability introduced in the lab, or a combination of these factors. Because there is no data quality objective for field split sample results, this variability did not cause total TEQ concentrations to be qualified. However, this level of variability indicates that uncertainty remains about final validated PCDD/F concentrations.

[7] Cambridge Isotope Laboratories provided the CRM (EDF 5184) used in this study.

Results and Discussion

Field sampling and summary of analyses

The field crew collected samples of the biologically-active surface sediment from 21 locations in inner Bellingham Bay between June 29 and July 1, 2010. They were unable to collect samples from stations BBDIOX-01 and BBDIOX-03 because the weighted sampler did not adequately penetrate sandy substrates. The crew instead collected samples from pre-determined alternate stations labeled BBDIOX-1A and BBDIOX-3A, respectively. The average distance between the target and final coordinates for the 21 stations was approximately 1 meter. Water depths ranged from 3.1 to 30 m, averaging 14.8 m. Station data appear in Appendix B (Table B-1).

The van Veen sampler penetrated substrates to a depth of 9-17 cm (average 14.4 cm), from which the top 9-12 cm of sediment was collected (average 11.5 cm). The field crew accepted 5 samples that were shallower than the top 12 cm but still thought to represent biologically-active surface sediments. Relevant field notes are in Appendix B, Table B-2.

Subsamples from each location and QC samples were analyzed for grain size distribution, TOC, 7 PCDD congeners, and 10 PCDF congeners. Table 3 lists the samples and analyses that were conducted. This *Results and Discussion* section summarizes and discusses analytical results, and Appendix C contains complete results.

Table 3. Summary of samples collected and analyses conducted.
All parameters were analyzed in two separate batches.

Sample Type	PCDD/Fs	TOC	Grain Size Distribution	Total
Field Samples	21	21	21	63
Field Replicates	0	0	0	0
Field Splits	1	0	0	1
Field Blanks	0	0	0	0
Lab Blanks	2	2	0	4
Lab Replicates	1	4	4	9
Matrix Spike	1	0	0	1
Matrix Spike Duplicate	1	0	0	1
LCS	2	0	0	2
LCS Duplicate	1	0	0	1
CRM or SRM	1	1	0	2
Total	31	28	25	84

PCDD/Fs: polychlorinated dibenzodioxins and dibenzofurans
TOC: Total organic carbon
LCS: Lab control sample
CRM: Certified reference material
SRM: Standard reference material

Conventional parameters

Table 4 summarizes results for conventional parameters measured in the surface sediment samples. The samples contained predominantly very fine-grained, cohesive sediments that contained moderate amounts of organic carbon.

Table 4. Grain size distribution and TOC in Bellingham Bay surface sediments, 2010.

Parameter (dry wt.)	Size Class (um)	N	Minimum	Median	Mean	CV	Maximum
% Gravel	>2000	19	0.1	0.6	4.4	2.06	34.7
% Sands	63-2000	21	2.2	6.1	8.4	0.92	31.0
% Fines	<63	21	60.9	92.5	87.6	0.12	97.5
% Silts	4-63	21	36.8	64.3	62.3	0.15	76.4
% Clays	<4	21	8.3	25.8	25.3	0.37	41.9
% TOC	--	21	0.66	1.64	1.68	0.26	2.66

N: number of samples analyzed.
CV: coefficient of variation (standard deviation divided by the mean).

Fine-grained material averaged 87.6% of each sample, with silts averaging approximately 60-65% and clays averaging 25%. The coarse-grained materials (gravel and sands) making up the rest of each sample were much more variable (CV = 0.92 - 2.06).

Figure 2 shows 4 locations that contained relatively unusual amounts of coarse-grained material:

- Two inner Bellingham Bay stations, BBDIOX-2 and UWI 28, contained 28.7% and 31% sands, respectively.
- Two outer Bellingham Bay stations, BBDIOX-9 and UWI 32, contained 22.4% and 34.7% gravel, respectively.

TOC concentrations in surface sediments ranged from 0.66 - 2.66% of dry weight and averaged 1.68%. Potential outlier concentrations (Table E-2) were included in analysis because they were within the range common for sediments in Puget Sound urban bays [8].

Shallow nearshore stations (e.g., BBDIOX-12 and UWI 28) and stations in deeper water but near known sources tended to have higher TOC concentrations (Figure 3). Many of the surface sediment samples that contained lower TOC (BBDIOX-2 to BBDIOX-5, UWI 23 and UWI 35) were located in an area that receives sediment discharged from the Nooksack River [9].

[8] From records in Ecology's EIM database.
[9] See Figure 15 in Anchor QEA (2010) and Retec (2006).

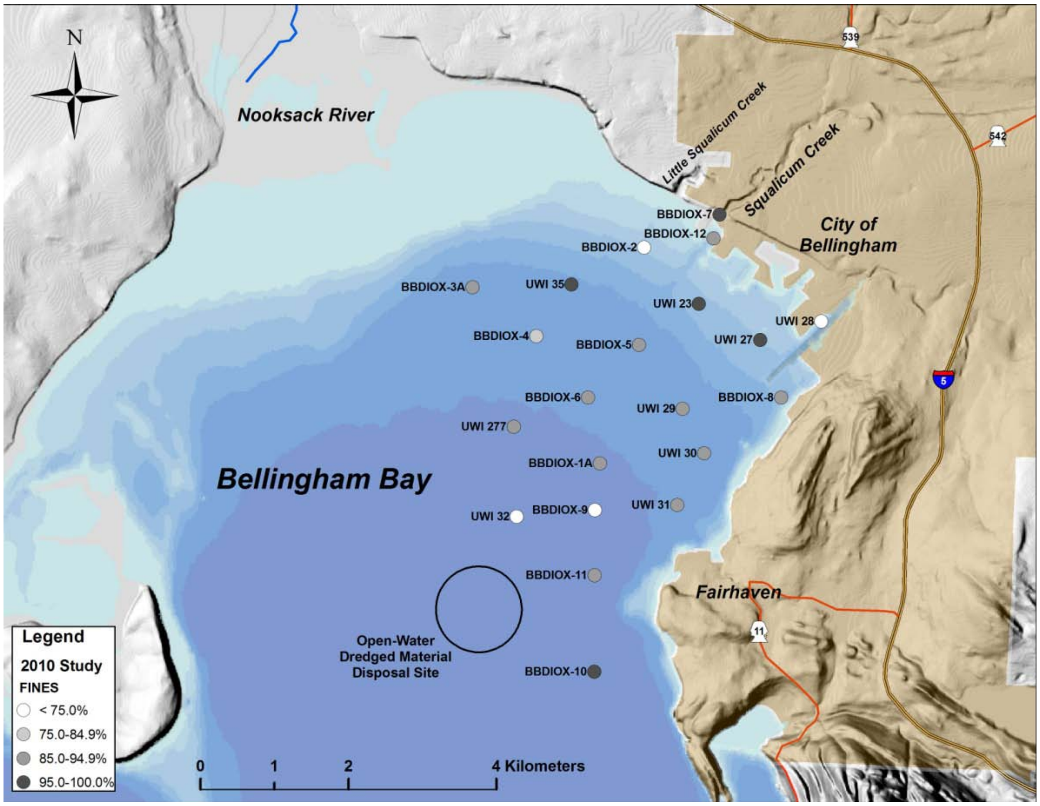

Figure 2. Distribution of fine-grained surface sediments in Bellingham Bay, 2010.

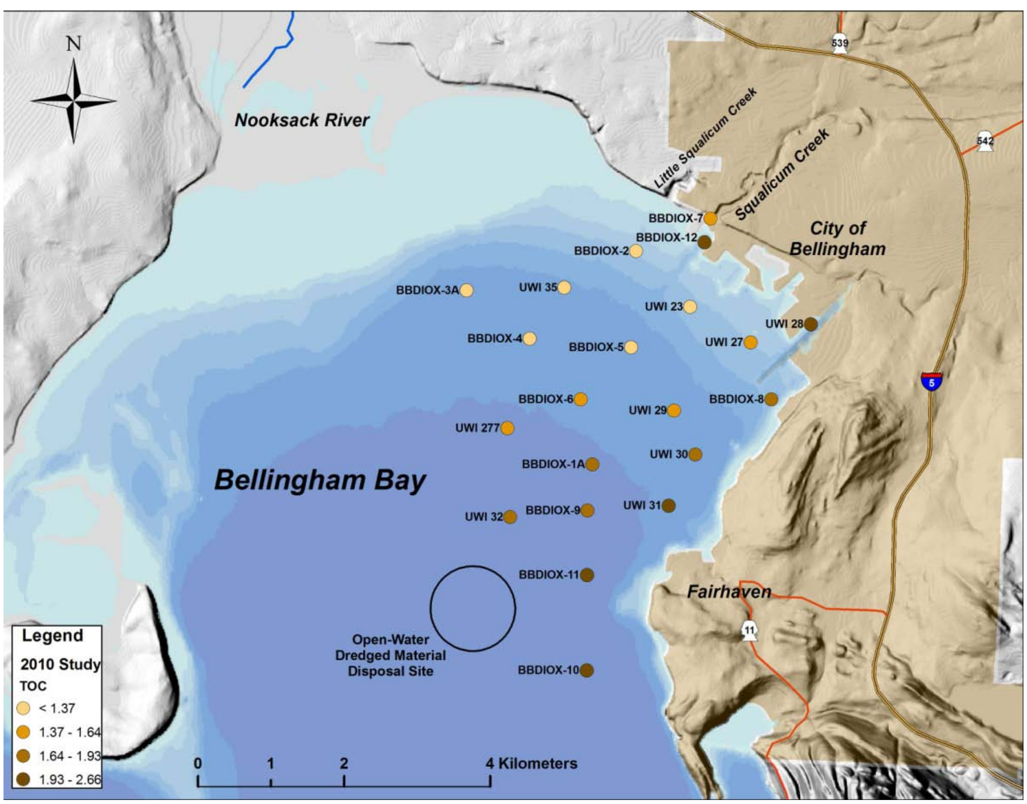

Figure 3. Distribution of TOC in surface sediments of Bellingham Bay, 2010.

PCDD/F concentrations and distribution

Summary of 2010 results

All surface sediment samples collected for this study contained detectable concentrations of PCDD/Fs. Six of the 17 congeners analyzed, including 2,3,7,8-TCDF, were found in all 21 of the samples collected. Eleven congeners were present in at least 75% of the samples. Congeners with the highest TEF values (2,3,7,8-TCDD, 1,2,3,7,8-PeCDD, and 2,3,4,7,8-PeCDF) were found in 24%, 67%, and 86% of the samples, respectively. 1,2,3,7,8-PeCDF was the only other congener found in fewer than 50% of the samples.

Total PCDD/F concentrations ranged from 88.1 to 6210 ng/Kg (Table 5), with OCDD contributing an average 76.8% of the total. High concentrations in a few samples caused the mean concentration (981 ng/Kg) to be about twice the median (494 ng/Kg). Assigning different concentrations to undetected congeners resulted in little change to the summary statistics.

Table 5. Summary of 2010 PCDD/F concentrations in Bellingham Bay surface sediments, 2010.

Statistics for individual congeners assume nondetect (ND) concentrations (samples with U, N, and NJ qualifier codes) equal to one-half the estimated detection limit (EDL).

Parameter (ng/Kg)	N	Percent Detected	Min.	Median	Mean	CV	Max.
Dioxin Congeners							
2,3,7,8-TCDD	21	19	0.06	0.20	0.34	0.93	1.20
1,2,3,7,8-PeCDD	21	62	0.08	0.47	1.35	1.04	3.90
1,2,3,4,7,8-HxCDD	21	86	0.12	2.50	4.97	1.09	18.0
1,2,3,6,7,8-HxCDD	21	95	0.32	3.70	8.28	0.99	24.0
1,2,3,7,8,9-HxCDD	21	100	0.27	2.80	5.73	1.02	17.0
1,2,3,4,6,7,8-HpCDD	21	100	6.00	58	116	1.23	570
OCDD	21	100	73.0	360	759	1.58	5200
Furan Congeners							
2,3,7,8-TCDF	21	100	0.23	4.80	7.55	1.03	28.0
1,2 3,7,8-PeCDF	21	48	0.06	0.36	0.54	1.03	2.40
2,3,4,7,8-PeCDF	21	90	0.06	0.60	1.15	1.04	4.50
1,2,3,4,7,8-HxCDF	21	76	0.14	0.56	1.17	1.44	7.10
1,2,3,6,7,8-HxCDF	21	67	0.06	0.29	0.65	1.20	3.40
1,2,3,7,8,9-HxCDF	21	57	0.08	0.22	0.49	1.45	3.10
2,3,4,6,7,8-HxCDF	21	71	0.06	0.46	0.79	1.04	3.30
1,2,3,4,6,7,8-HpCDF	21	100	1.80	8.40	14.4	1.37	82.0
1,2,3,4,7,8,9-HpCDF	21	67	0.12	0.61	0.99	1.37	5.50
OCDF	21	100	4.60	21.0	57.3	1.64	330
Total PCDD/Fs							
ND = EDL	21	100	88.8	495	982	1.48	6214
ND = EDL/2	**21**	**100**	**88.1**	**494**	**981**	**1.48**	**6212**
ND = 0	21	100	87.3	493	980	1.48	6211

N: Number of samples. CV: Coefficient of variation (standard deviation divided by the mean).

Table 6 shows that the range of total PCDD/F concentrations, expressed as TEQ, was 0.54 - 19.8 ng/Kg. The average and median concentrations were 6.54 and 2.65 ng/Kg, respectively. Chlorinated dioxins, especially the penta- and heptachlorinated congeners, accounted for an average of 73.4% of total TEQs (Figure 4). Of the furans, 2,3,7,8-tetrachlorinated dibenzofuran contributed the most to total TEQs, averaging 11.5%.

Table 6. Summary of PCDD/F TEQs in Bellingham Bay surface sediments, 2010.

Statistics for individual congeners assume nondetect (ND) concentrations equal to one-half the estimated detection limit (EDL).

Parameter (ng TEQ/Kg)	N	Percent Detected	Min.	Median	Mean	CV	Max.
Dioxin Congeners							
2,3,7,8-TCDD	21	24	0.060	0.195	0.32	1.01	1.20
1,2,3,7,8-PeCDD	21	67	0.080	0.470	1.35	1.04	3.90
1,2,3,4,7,8-HxCDD	21	86	0.013	0.250	0.497	1.09	1.80
1,2,3,6,7,8-HxCDD	21	95	0.032	0.370	0.828	0.99	2.40
1,2,3,7,8,9-HxCDD	21	100	0.027	0.280	0.573	1.02	1.70
1,2,3,4,6,7,8-HpCDD	21	100	0.060	0.580	1.16	1.23	5.70
OCDD	21	100	0.022	0.108	0.228	1.58	1.56
Furan Congeners							
2,3,7,8-TCDF	21	100	0.023	0.480	0.76	1.03	2.8
1,2 3,7,8-PeCDF	21	43	0.002	0.011	0.016	1.03	0.072
2,3,4,7,8-PeCDF	21	86	0.016	0.180	0.34	1.04	1.35
1,2,3,4,7,8-HxCDF	21	76	0.014	0.056	0.116	1.44	0.71
1,2,3,6,7,8-HxCDF	21	67	0.006	0.029	0.065	1.20	0.34
1,2,3,7,8,9-HxCDF	21	57	0.008	0.022	0.049	1.46	0.31
2,3,4,6,7,8-HxCDF	21	71	0.006	0.046	0.079	1.04	0.33
1,2,3,4,6,7,8- HpCDF	21	100	0.018	0.084	0.144	1.37	0.82
1,2,3,4,7,8,9-HpCDF	21	76	0.001	0.006	0.010	1.35	0.055
OCDF	21	100	0.001	0.006	0.017	1.64	0.099
Total PCDD/F TEQs							
ND = EDL	21	100	0.77	3.06	6.79	0.95	19.9
ND = EDL/2	**21**	**100**	**0.54**	**2.65**	**6.54**	**0.99**	**19.8**
ND = 0	21	100	0.28	2.23	6.30	1.04	19.8

N: Number of samples. CV: Coefficient of variation (standard deviation divided by the mean).

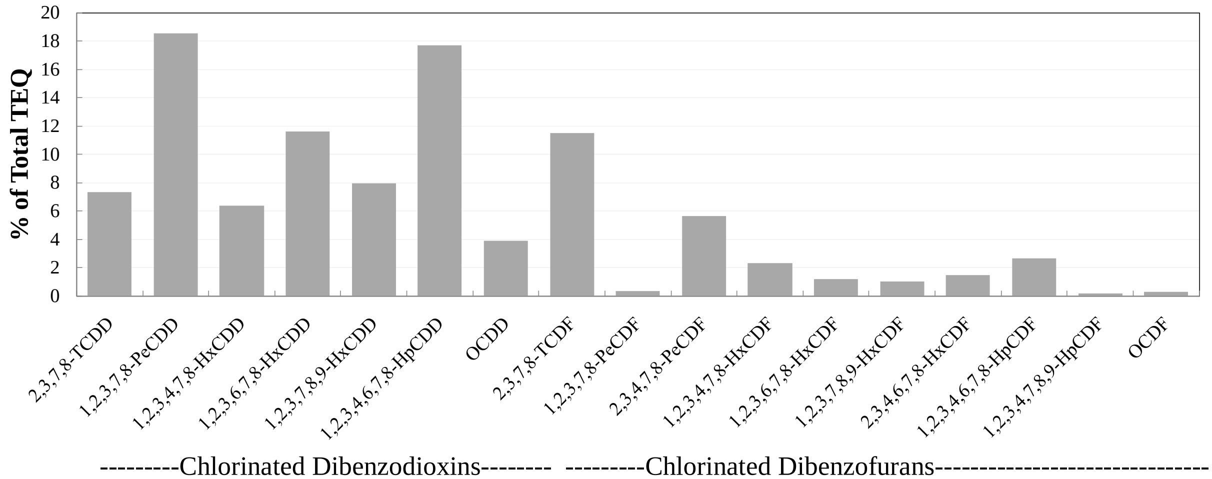

Figure 4. Average contribution of individual congeners to total TEQ.

Figure 5 shows the distribution of PCDD/F TEQ concentrations in surface sediments throughout a large area of inner Bellingham Bay in 2010. Sediments collected from stations near shorelines or near known sources (historic or ongoing) contain relatively high concentrations. The three highest concentrations are found at UWI 28 (inner Whatcom Waterway), BBDIOX-8 (near the Cornwall Avenue landfill and R.G. Haley cleanup sites), and UWI 30 (shoreward of the historic Georgia Pacific outfall). Most lower concentrations occur at deeper offshore stations between the urban waterfront (Bellingham and Fairhaven) and mouth of the Nooksack River. Sediments at 7 of these stations contain less than 1.67 ng/Kg PCDD/F TEQ.

The distribution of PCDD/F concentrations in Figure 5 seems to reflect weak tide- and wind-driven circulation within the bay that causes limited horizontal transport of sediment away from shallow intertidal and subtidal waters (Wang et al., 2010) [10]. The figure also provides additional evidence for the following:

- Sediment discharged by the Nooksack River into Bellingham Bay dilutes surface sediment contaminant levels, including PCDD/F concentrations, in portions of the inner bay (Retec, 2006, Chapter 6)
- Circulation sometimes transports suspended sediment clockwise along urban shorelines and westward toward the outer bay (Anchor QEA, 2010; Figure 15)

[10] "Circulation inside the bay is weak and complex and is affected by various forcing mechanisms, including tides, winds, freshwater inflows, and other local (forcing) factors."

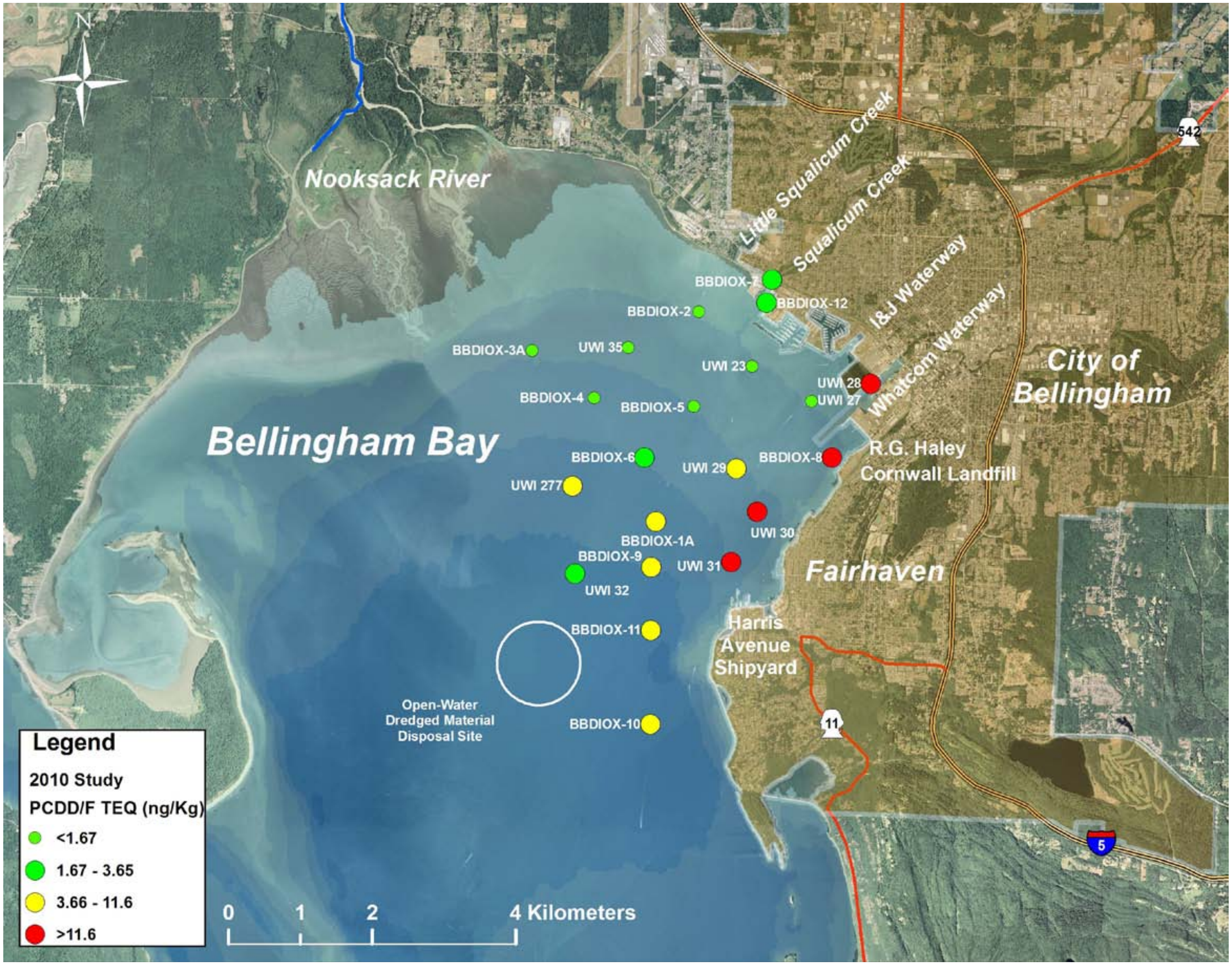

Figure 5. Distribution of PCDD/F TEQs surface sediments of Bellingham Bay, 2010.

Comparison to other studies

Figure 6 shows PCDD/F concentrations in surface sediments of Bellingham Bay for the 5 studies conducted between 2004 and 2010. None of the concentrations measured in 2010 were as high as reported previously near the R.G. Haley cleanup site. However, the general pattern of concentrations did not change:

- Stations with sediment PCDD/F concentrations greater than 11.6 ng/Kg TEQ in 2010 (red circles) are often near stations sampled earlier that contain similar concentrations (red triangles)
- Stations with sediment PCDD/F concentrations less than 3.66 ng/Kg TEQ in 2010 (green circles) are often near stations sampled earlier that contained similar concentrations (green triangles)

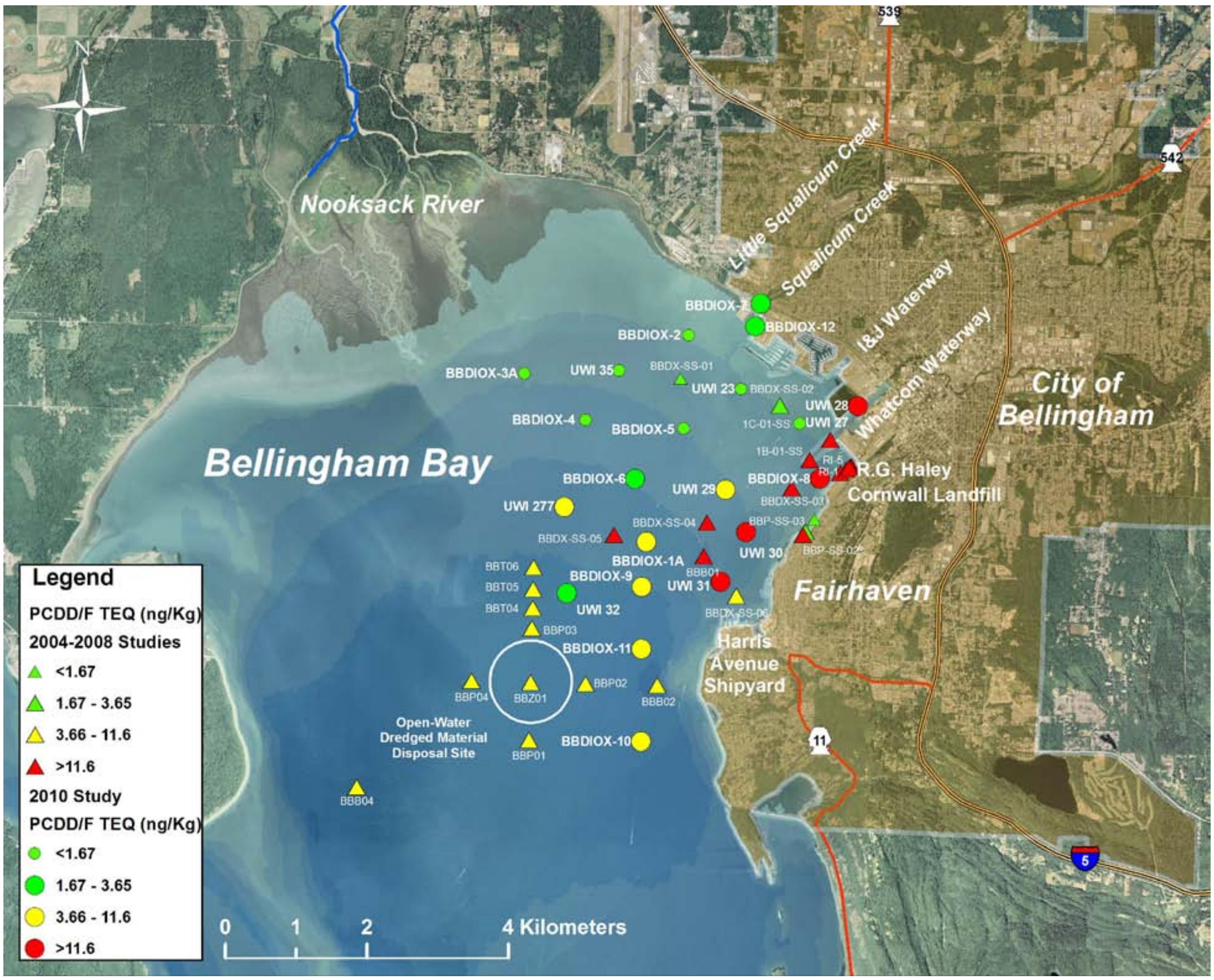

Figure 6. Distribution of PCDD/F TEQs in surface sediments of Bellingham Bay, 2004 to 2010.

Background values for PCDD/Fs

This section does three things:

- It describes PCDD/F TEQ concentrations in surface sediments collected from nonurban areas throughout greater Puget Sound that *may* represent natural background conditions.
- It identifies PCDD/F concentrations from this study and another recent study that may represent background for surface sediments for Bellingham Bay.
- It compares the two data sets.

Puget Sound

In 2008, the Dredged Material Management Program (DMMP) measured concentrations of PCDD/Fs and PCBs in surface sediment samples collected from nonurban areas thought to represent background conditions for greater Puget Sound. DMMP staff worked from EPA's research vessel *OSV Bold* (BOLD) to collect surface sediment far from anthropogenic sources of pollution (EPA, 2008). PCDD/F congener concentrations in these samples were summed and expressed as total TEQ. Nondetect congener concentrations were set equal to one-half the estimated detection limit and also estimated using the Kaplan-Meier method (Kaplan and Meier, 1958; Helsel, 2005; Michelsen, 2008).

Total TEQ results from the BOLD survey were combined with historic results from reference bays to form a 97 sample data set referred to as *BOLD+*. The DMMP used ProUCL software to examine the data set and calculate various statistics for PCDD/F TEQ concentrations that might serve as threshold values for nonurban background. The 95% upper confidence limit (UCL) of the 90^{th} percentile concentration, or upper tolerance limit (UTL), for the BOLD+ data was calculated to be 3.66 ng/Kg TEQ. This is the total TEQ concentration below which 90% of the BOLD+ data are expected to fall 95% of the time. The DMMP rounded the UTL to 4 ng/Kg TEQ and adopted it as an interim guideline for determining the suitability of dredged material for open-water disposal (DMMP, 2009; DMMP, 2010a).

Ecology also considers the BOLD+ data set appropriate for calculating natural background (as defined by MTCA) for greater Puget Sound.

Bellingham Bay

The BOLD+ data set may not accurately represent nonurban or natural background in a smaller area of interest, such as Bellingham Bay [11]. Therefore, an objective of this study was to measure PCDD/Fs in surface sediments and identify total PCDD/F TEQ concentrations that might represent background conditions for Bellingham Bay. Approaches used to identify stations and concentrations that might represent background for Bellingham Bay involved statistical, fingerprint, and spatial analysis.

- ***Statistical analysis.*** After examining distributional characteristics of the 2010 data, correlation and regression analyses were conducted to understand relationships between different parameters. Results are summarized in Appendix E. Of note was a significant correlation between the PCDD/F TEQ concentrations and TOC. A log-linear regression explained 55% of the variability observed in the former (Figure E-1).

  Principal component analysis (PCA) and hierarchical cluster analysis (HCA) used total PCDD/F TEQ concentrations, TOC, and other parameters to successfully classify 2010 results into station groups (Figures E-2 and E-3). Two principal components explained 72% of the variance among analysis parameters. Some groups were made up of spatially contiguous stations (areas) that had relatively low PCDD/F TEQ concentrations and that were similar in other ways.

- ***Fingerprint analysis***. Appendix F describes the results of an exploratory-level analysis of PCDD/F congener concentration patterns (fingerprints). The fingerprints based on PCDD/F concentrations in the 21 samples collected for this 2010 study revealed little because octachlorinated congeners were dominant (Figure F-1). Fingerprints based on the proportional contribution of each PCDD/F congener to total TEQs identified at least 2 different patterns (Figures F-2 and F-3). However, stations with sediment having similar PCDD/F TEQ fingerprints were not spatially-contiguous.

- ***Spatial analysis.*** Finally, GIS software mapped the distribution of PCDD/F TEQ concentrations in surface sediment samples collected recently from Bellingham Bay (Figure 7). The figure uses inverse distance weighting to interpolate between the point concentrations shown in Figure 6, out to a maximum distance of 0.8 kilometer (½ mile). The equal concentration contours represent the 95% UCL, UTL, and maximum of the nonurban Bold+ data set (1.67 ng/Kg, 3.66 ng/Kg, and 11.6 ng/Kg, respectively). Areas of surface sediments between contours contain similar PCDD/F TEQ concentrations.

[11] Natural background might differ in a smaller area of interest (urban bay) that receives the same unavoidable toxic chemical loading as a larger area (greater Puget Sound) because of factors such as external loading of clean sediment from major rivers, basin depth and water circulation, and particulate transport patterns.

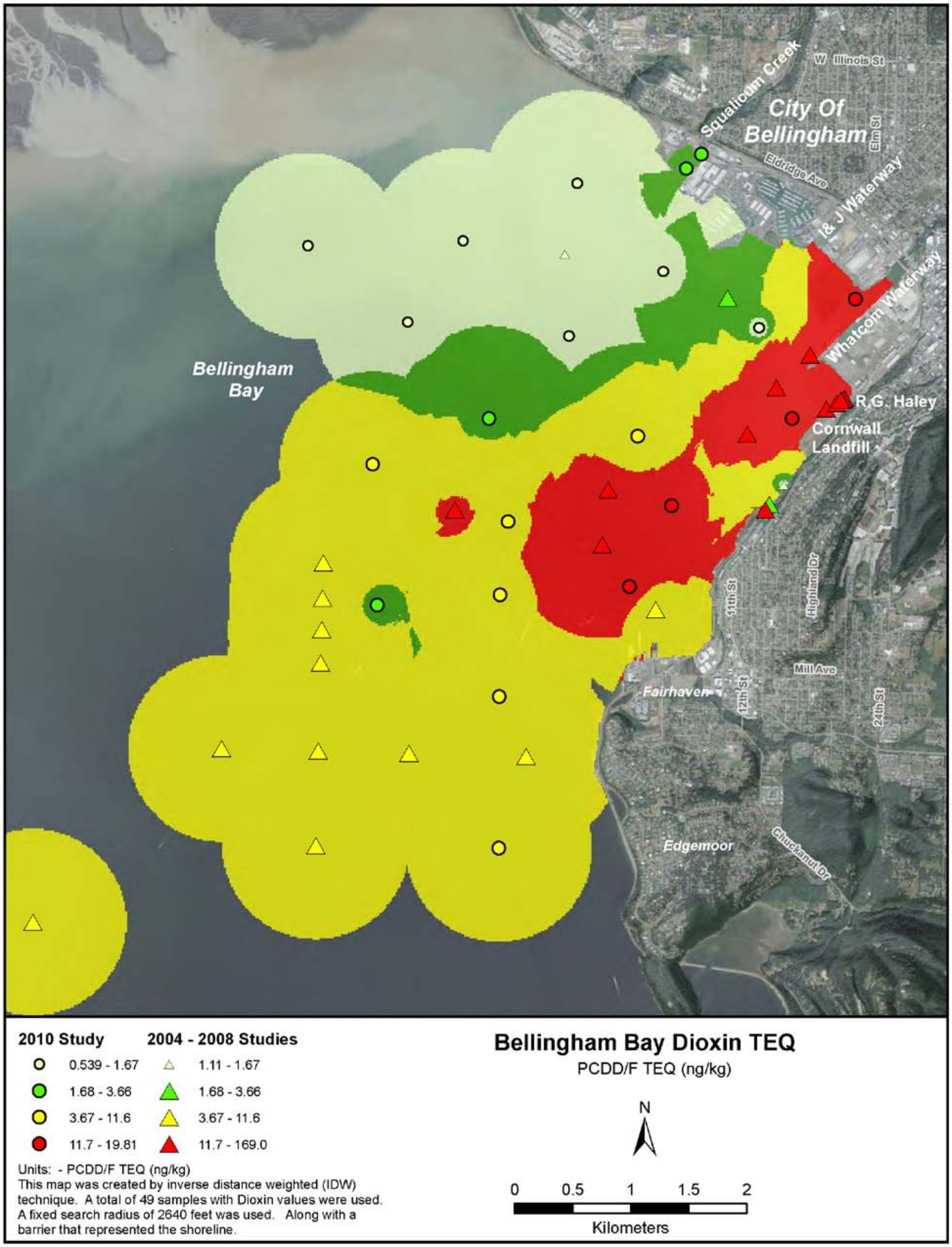

Figure 7. Areas of Bellingham Bay where surface sediments contain similar total PCDD/F TEQ concentrations.

Figure 7 shows a green area 2-6 kilometers southeast of the Nooksack River delta where surface sediments contain similarly low total PCDD/F TEQs [12]. The 12 contiguous stations in this area all have a total PCDD/F concentration less than the UTL of the BOLD+ data set (3.66 ng/Kg TEQ). The low concentrations reflect the influence of sediment discharged by the Nooksack River. BBDIOX-2 and BBDIOX-7 sediments, in particular, are evidence that clean river sediments may negate the influence of nearshore sources of PCDD/Fs that might otherwise preclude the area from representing background conditions.

PCDD/F results for the 12 stations, referred to as the *Bellingham Bay background* data set, were evaluated for their potential to represent background conditions for Bellingham Bay. Total PCDD/F TEQs were calculated with nondetects set equal to one-half the EDL and also with nondetect concentrations estimated using the Kaplan-Meier method. Table 7 compares the results. For this data set, the Kaplan-Meier method of treating nondetects resulted in consistently lower total TEQ concentrations.

Table 7. Results for a Bellingham Bay background data set, calculated using two methods of treating nondetects.

Station ID	Total TEQ (ng/Kg)		Relative Percent Difference (%)	Reference
	ND = EDL/2	ND = Kaplan-Meier		
BBDIOX-2	0.54	0.41	27.4	This 2010 study
BBDIOX-3A	0.55	0.35	44.4	
BBDIOX-4	1.48	1.32	11.4	
BBDIOX-5	1.60	1.45	9.9	
BBDIOX-6	2.65	2.42	9.1	
BBDIOX-7	2.01	1.87	7.2	
BBDIOX-12	2.32	2.23	4.0	
UWI 23	1.37	1.27	7.8	
UWI 27	0.86	0.78	9.8	
UWI 35	1.33	1.17	12.8	
BBDX-SS-01	1.50*	1.03	37.2	Hart Crowser (2009)
BBDX-SS-02	3.21*	2.70	17.3	
Average	1.62	1.42	16.5	

* ND = Practical Quantitation Limit/2 (EDL not available)

Three upper-threshold statistics for total PCDD/F TEQs at the 12 stations were calculated according to most of the recommendations made at a recent workshop (Michelsen, 2008) using Scout 2008 and ProUCL version 4.0 (EPA, 2011) software applications:

- The upper 95th percent confidence limit of the mean concentration (95% UCL)
- The 90th percentile concentration (90%)
- The 95th percent UCL of the 90th percentile concentration (95%/90% UTL)

[12] Most of the stations in this area also belong to station groups also identified using PCA or HCA.

The total PCDD/F TEQ concentrations in the 12 station Bellingham Bay background data set are similar to those in the 97 station BOLD+ data set representing nonurban Puget Sound (Table 8). For example, the average total PCDD/F concentration for the Bellingham Bay background data set is 1.62 ng/Kg TEQ when nondetect congeners are assumed to equal one-half the EDL concentration. The average concentration for the BOLD+ stations is 1.56 ng/Kg when the same assumption is made.

The 95% UCL of the average PCDD/F concentration in the Bellingham Bay background data set is 2.04 ng/Kg TEQ, about 10% greater than the 95% UCL for the Bold+ data set. Concentrations representing the 90th percentile and the UTL are also very similar for the two data sets.
All of the statistics are slightly lower when based on the Kaplan-Meier method of handling nondetect concentrations.

Table 8. Statistical evaluation of PCDD/F TEQ concentrations in the Bellingham Bay background and BOLD+ data sets.

Data Set	N	Data Dist.	Median	Mean	95% UCL	Dist.	90th Percentile	Data Dist.	95%/90% UTL	Dist.
			Total TEQ (ng/Kg)				Total TEQ (ng/Kg)		Total TEQ (ng/Kg)	
Substitution method: ND=EDL/2										
Bellingham Bay background	12	N	1.49	1.62	2.04	N	2.66/ 3.04	N/ NP	3.42/ 3.21	N/ NP
BOLD+	97	G	1.07	1.56	1.82/ 1.85	G/ NP	3.06/ 3.35	NP/ G	4.06	NP
Estimation method: ND=Kaplan-Meier										
Bellingham Bay background	12	N	1.30	1.42	1.81	N	2.39/ 2.62	N/ NP	3.10/ 2.7	N/ NP
BOLD+	97	G	0.877	1.39	1.67/ 1.68	G/ NP	3.25/ 2.89	G/ NP	3.66	NP

N = number of samples
Data Dist. = data distribution (G = gamma; N = normal; NP = nonparametric, no distribution assumed)
EDL = estimated detection limit
ND = nondetect
BOLD+ = nonurban Puget Sound (70 Bold survey samples plus 27 reference bay samples) (DMMP, 2009)
UCL = upper confidence limit of mean concentration
UTL = upper tolerance limit

The difference between the average concentrations of the two data sets is not statistically significant regardless of the method of treating nondetects (Figure 8 and Table 9). In other words, average total PCDD/F TEQ concentrations in surface sediments of the Bellingham Bay background data set cannot be distinguished from the 97 station BOLD+ data set representing nonurban areas of greater Puget Sound.

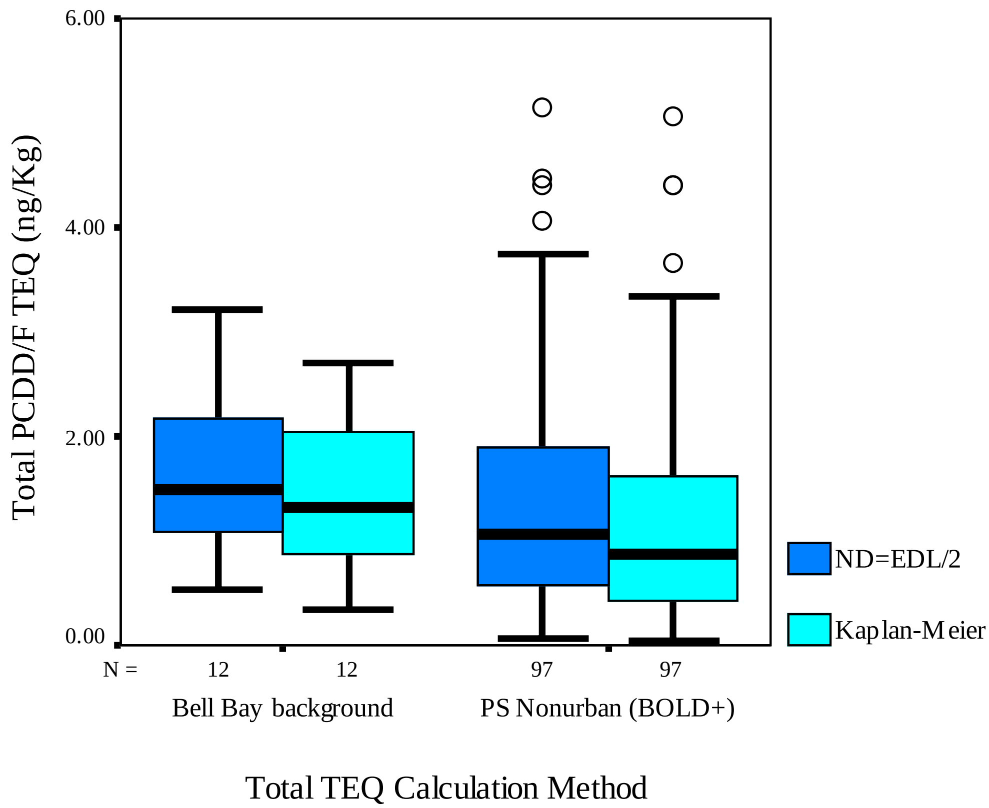

Figure 8. Total PCDD/F TEQs in a Bellingham Bay background data set and a nonurban Puget Sound data set (BOLD+), calculated using two methods of treating nondetects.

The bottom of each box, dark bar, and the top of each box represent the 25th percentile, median, and 75th percentile concentrations, respectively. Whiskers are minimum and maximum values not including the potential outliers represented by the open circles. (Note: The vertical scale is truncated so the three highest concentrations in the BOLD+ data set are not shown).

Table 9. Comparison of average total PCDD/F TEQs in surface sediments collected from two different areas, calculated using two methods of handling nondetects.

Question	Probability of no difference	Answer
Is the average total PCDD/F TEQs in the Bellingham Bay background data set different from the average in the BOLD+ data set (nonurban areas of greater Puget Sound)?	ND=EDL/2 0.185 [b] 0.233 [c]	No
	Kaplan-Meier 0.224 [b] 0.346 [c]	No
Does the method of handling nondetects result in different average total PCDD/F TEQs for a given data set?	Bellingham Bay background (n=12) **<0.001**[a]	Yes
	Nonurban Puget Sound BOLD+ (n=97) **<0.001**[d]	Yes

[a] paired t-Test, normal distribution and equal variance
[b] Mann-Whitney Test (nonparametric)
[c] 2 sample Kolmogorov-Smirnov Test (nonparametric)
[d] Wilcoxon Signed Ranks Test and Sign Test

Finding that the average surface sediment PCDD/F TEQ in the Bellingham Bay background data set is indistinguishable from the average in nonurban Puget Sound sediments was unexpected because most urban bay sediments are influenced by past and continuing sources of contaminants. In the case of Bellingham Bay, historic sediment quality data show large areas where surface sediments contain elevated PCDD/F concentrations (Figure 1). These areas reflect the influence of contaminated sites and shoreline sources. Sediments in outer Bellingham Bay (west and south of 2010 stations) that remain unstudied may also reflect the influence of urban sources. However, it appears that the Bellingham Bay background data set represents an area where terrestrial material discharged by the Nooksack River is deposited (Retec, 2006; Anchor QEA, 2010) and thereby minimizes the influence from shoreline sources.

Table 9 also shows levels of statistical significance associated with the differences between average concentrations based on two different methods of handling nondetect results. Substituting one-half the detection limit concentration for nondetect congeners produces average total TEQ concentrations for the Bellingham Bay background and BOLD+ data sets that are slightly but significantly greater than the Kaplan-Meier averages ($p<0.001$). The RPDs between total TEQs for the 12 stations, calculated using the two methods of handling nondetects, range from 4.0 - 44.4% and average 16.5%. This average methodological bias is less than the observed variability in concentrations measured in field splits and laboratory duplicates (RPDs of 55% and 92% respectively). Whether future Puget Sound sediment quality data sets will reveal the same methodological bias, field or lab variability is not known.

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Conclusions

Results from this 2010 study support the following conclusions:

- PCDD/F toxic equivalent (TEQ) concentrations in biologically-active surface sediment (0-12 cm) collected throughout a large area of inner Bellingham Bay, with nondetect congeners set equal one-half the estimated detection limit, range from 0.54 to 19.8 ng/Kg and average 6.54 ng/Kg.

- Total PCDD/F TEQ concentrations in quality control samples show field and laboratory variability to be on the order of 50 - 100%.

- Low total PCDD/F TEQ concentrations at 12 contiguous stations located near the mouth of the Nooksack River may be indicative of background conditions for Bellingham Bay.
  - Surface sediments in this Bellingham Bay background data set contain an average total PCDD/F concentration (1.62 ng/Kg TEQ) that is not statistically different from the average concentration found in a 97 station data set (BOLD+) that represents nonurban areas of greater Puget Sound (1.56 ng/Kg TEQ).
  - Upper end statistics for total PCDD/F concentrations in the area represented by Bellingham Bay background data set are in the range of 1.8 - 3.4 ng/Kg TEQ, similar to statistics for the BOLD+ data set.

- The method of handling nondetects yields statistically significant differences between average total PCDD/F TEQs calculated for the Bellingham Bay background and BOLD+ data sets.
  - The magnitude of the differences between average total PCDD/F TEQs is small. This supports the conclusion of Antweiler (2008) that substitution may be an adequate alternative to the Kaplan-Meier method of handling nondetect data.
  - For the Bellingham Bay background data set, total TEQs based on substitution are an average of 16.5% greater than total TEQs based on Kaplan-Meier estimated values.

- Results of the present study may provide a useful baseline for PCDD/Fs in surface sediments within the study area. Results for individual stations may be useful for documenting temporal changes at specific locations. However, the study design does not support evaluation of changes in PCDD/F concentrations in sediments near known sources or in the outer bay (further west and south of stations sampled for this study).

- Most spatial variability of total PCDD/F TEQ concentrations in surface sediments of Bellingham Bay is related to sediment TOC content. Total TEQ concentrations are usually highest where % TOC is also high.

- Statistical methods of classification and spatial analysis may be helpful for (1) identifying groups of stations with similar characteristics and (2) distinguishing between areas influenced by shoreline sources from areas with background concentrations of PCDD/Fs.

Recommendations

Based on findings from this 2010 study, Ecology recommends:

- In order to improve the understanding of background concentrations and current bay-wide conditions, PCDD/Fs, TOC, and other relevant parameters should be analyzed in surface sediments collected from the outer portions of Bellingham Bay [13].
- To evaluate temporal changes in PCDD/F concentrations near past and ongoing sources, additional sampling should target those sources.
- Studies of PCDD/F concentrations in surface sediment should include analysis of more field replicates, field splits, and laboratory replicates to better determine sources of variability.
- Future studies should use multiple methods of handling nondetect results when calculating total PCDD/F TEQ concentrations. These should include substitution with one-half detection limits and the interpolation method of Kaplan-Meier.
- Future analysis of PCDD/F concentrations in surface sediments should consider additional parameters (e.g., linear distance to known sources of pollutants such as industrial, municipal, and stormwater outfalls).
- Additional analysis of PCDD/F fingerprints of surface sediment should be conducted if it is important to:
  - Identify sediments influenced by specific sources of PCDD/Fs.
  - Verify that surface sediments at specific locations are not influenced by shoreline sources.
  - Compare sediments within the bay to PCDD/Fs in samples representing nonurban or natural background for greater Puget Sound (DMMP, 2009).

[13] For example, areas northwest and south of the open water disposal site shown in several of the figures contained in this report.

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Appendices

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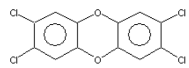
Appendix A. Glossary, Acronyms, and Abbreviations

Glossary

Anthropogenic: Human-caused.

Clay: Mineral particles having diameters ranging from 0.24 - 3.9 um (Wentworth Scale).

Congener: A chemical substance that is related to another substance, such as a derivative of a compound. For example, chlorinated dioxin congeners have different numbers of chlorine atoms bound to different carbon atoms in the basic dioxin structure:



Dredged Material Management Program (DMMP): A cooperative federal and state government program regulating the beneficial use and disposal of dredged material within in Puget Sound. Member agencies include the U.S. Army Corps of Engineers, U.S. Environmental Protection Agency, the Washington State Department of Ecology, and the Washington State Department of Natural Resources.

Estimated detection limit (EDL): The minimum concentration of a substance required to produce a specified signal-to-noise (S/N) ratio. For example, the blank sample noise multiplied by a S/N ratio of 2.5. EDLs are determined by the laboratory for each analyte in each sample.

Fines: Particle size classes encompassing all silts and clays (% Fines = % Silt plus % Clay).

Fingerprint: A multi-parameter chemical signature (distinctive chemical pattern) used to characterize the source of contaminants in an environmental sample or to differentiate the sample from contaminants present in samples representing background conditions.

Marine Sediment Monitoring Program: Ecology program designed to detect and document spatial and temporal changes in sediment quality over time.

Natural background: According to the State of Washington's Model Toxics Control Act (MTCA), natural background means "the concentration of hazardous substance consistently present in the environment that has not been influenced by localized human activities. For example, several metals and radionuclides naturally occur in the bedrock, sediments, and soils of Washington state due solely to the geologic processes that formed these materials and the concentration of these hazardous substances would be considered natural background. Also, low concentrations of some particularly persistent organic compounds such as polychlorinated biphenyls (PCBs) can be found in surficial soils and sediment throughout much of the state due to global distribution of these hazardous substances. These low concentrations would be considered natural background. Similarly, concentrations of various radionuclides that are present at low concentrations throughout the state due to global distribution of fallout from bomb testing and nuclear accidents would be considered natural background".

Nonpoint source: Pollution that enters any waters of the state from any dispersed land-based or water-based activities, including but not limited to atmospheric deposition, surface-water runoff from agricultural lands, urban areas, or forest lands, subsurface or underground sources, or discharges from boats or marine vessels not otherwise regulated under the National Pollutant Discharge Elimination System (NPDES) program. Generally, any unconfined and diffuse source of contamination. Legally, any source of water pollution that does not meet the legal definition of "point source" in section 502(14) of the Clean Water Act.

Parameter: Sediment quality constituent being measured (analyte). A physical, chemical, or biological property whose values determine environmental characteristics or behavior.

Point source: Source of pollution that discharges at a specific location from pipes, outfalls, and conveyance channels to a surface water. Examples of point source discharges include municipal wastewater treatment plants, municipal stormwater systems, industrial waste treatment facilities, and construction sites that clear more than 5 acres of land.

Pollution: Contamination or other alteration of the physical, chemical, or biological properties of any waters of the state. This includes change in temperature, taste, color, turbidity, or odor of the waters. It also includes discharge of any liquid, gaseous, solid, radioactive, or other substance into any waters of the state. This definition assumes that these changes will, or are likely to, create a nuisance or render such waters harmful, detrimental, or injurious to (1) public health, safety, or welfare, or (2) domestic, commercial, industrial, agricultural, recreational, or other legitimate beneficial uses, or (3) livestock, wild animals, birds, fish, or other aquatic life.

Quantitation limit: The minimum concentration of an analyte measured within specified limits of precision and accuracy. Lower and upper quantitation limits are often determined by the lowest and highest standard in the instrument calibration curve. A quantitation limit may also be set at a multiple of the detection limit (3X, 5X, or 10X).

Relative percent difference (RPD): A measure of analytical precision and bias. The difference between duplicates divided by the average of the duplicates:

$$\text{RPD}\ (\%) = \ |x - y| \,/\, (x + y)/2$$

Reporting limit (RL): This may be either a detection limit or a quantitation limit. When the reporting limit is a quantitation limit, then it is often set at the lowest (or highest) non-zero standard in the calibration curve. The reporting limit may also be set at some multiple of the detection limit.

Sand: Mineral particles having diameters ranging from 62.5 - 2000 um (Wentworth Scale).

Silt: Mineral particles having diameters ranging from 3.9 - 62.5 um (Wentworth Scale).

Stormwater: The portion of precipitation that does not naturally percolate into the ground or evaporate but instead runs off roads, pavement, and roofs during rainfall or snow melt. Stormwater can also come from hard or saturated grass surfaces such as lawns, pastures, playfields, and from gravel roads and parking lots.

Toxic equivalency factors (TEFs): Factors used by the World Health Organization, scientists, and regulators to evaluate the overall toxicity of highly variable dioxin, furan, and PCB mixtures in terms of the most toxic form of dioxin (2,3,7,8-tetrachlorodibenzodioxin).

Toxic equivalent quotient (TEQ): A toxicity-weighted total mass of a substance or family of substances. Total TEQ is calculated as the sum of products of the measured mass times the appropriate potency (TEF) for all compounds in a family of compounds.

Upper confidence limit (UCL): The high end of a confidence interval (of values) within which the true value of a population parameter (average) resides with a specified probability.

Upper tolerance limit (UTL): The high end of a tolerance interval where the tolerance interval is a defined probability that a specified proportion of a sample population resides within the interval. Commonly stated as the upper end of the *95% confidence interval for 90% coverage.*

Xth percentile: A statistical value obtained from a distribution of a data set. X% of the data exists below Xth percentile and (100-X)% of the data exists above the Xth percentile.

Acronyms and Abbreviations

BOLD	Research vessel *OSV Bold*
CRM	Certified reference material
DMMP	(See Glossary above)
Ecology	Washington State Department of Ecology
EDL	(See Glossary above)
EIM	Environmental Information Management database
EPA	U.S. Environmental Protection Agency
EQL	Estimated quantitation limit
GIS	Geographic Information System
HCA	Hierarchical cluster analysis
J	Chemical qualifier code indicating an estimated concentration
LCS	Laboratory control sample
ND	Nondetect
NJ	Qualifier code indicating an estimated concentration for tentatively-identified compounds
OCDD/Fs	Octachlorinated dibenzodioxins and dibenzofurans
OSV	Ocean Survey Vessel
PCA	Principal component analysis
PCB	Polychlorinated biphenyl
PCDDs	Polychlorinated dibenzodioxins
PCDFs	Polychlorinated dibenzofurans
PCDD/Fs	PCDDs and PCDFs or simply dioxins and furans
QA	Quality assurance
QC	Quality control
RL	(See Glossary above)
RPD	(See Glossary above)
RSD	Relative standard deviation

RV	Research vessel
SOP	Standard operating procedures
SPSS	Statistic Package for the Social Sciences (IBM software application)
SRM	Standard reference materials
TEF	Toxicity equivalency factor
TEQ	Toxicity equivalents
TOC	Total organic carbon
U	Not detected at the stated detection or quantitation limit
UCL	(See Glossary above)
UTL	(See Glossary above)

Units of Measurement

%	percent (parts per hundred)
cm	centimeter
dw	dry weight
ft	feet
g	gram, a unit of mass
kg	kilograms, a unit of mass equal to 1,000 grams.
km	kilometer, a unit of length equal to 1,000 meters.
m	meter
mg	milligrams
ng/Kg	nanograms per kilogram (parts per trillion)
um	micrometer or micron

Appendix B. Field Notes

Table B-1. Field data for 21 Bellingham Bay sediment sampling stations, June 2010.

Station ID	Date	Time	Target Latitude	Target Longitude	Final Latitude	Final Longitude	Distance to Target (m)	Measured Depth (m)	Corrected Depth (m)
BBDIOX-1	6/11/2010	1703	48.7638	-122.5179	-	-	-	-	-
BBDIOX-1A	6/15/2010	1552	48.7317	-122.5302	48.7317	-122.5302	1.2	21.8	-22.0
BBDIOX-2	6/10/2010	1621	48.7581	-122.5231	48.7581	-122.5231	1.0	5.2	-3.1
BBDIOX-3	6/11/2010	-	48.7622	-122.5336	48.7527	-122.5545	-	-	-
BBDIOX-3A	6/15/2010	1627	48.7527	-122.5545	48.7470	-122.5425	1.3	11.1	-11.0
BBDIOX-4	6/11/2010	1120	48.7470	-122.5425	48.7462	-122.5236	0.8	14.8	-15.5
BBDIOX-5	6/15/2010	1156	48.7462	-122.5236	48.7397	-122.5327	0.4	12.0	-12.2
BBDIOX-6	6/11/2010	1057	48.7397	-122.5327	48.7623	-122.5094	1.2	17.8	-18.5
BBDIOX-7	6/14/2010	1459	48.7623	-122.5094	48.7403	-122.4972	1.4	5.0	-8.4
BBDIOX-8	6/10/2010	1057	48.7403	-122.4972	*48.7403*	*-122.4972*	0.2	7.3	-7.7
BBDIOX-9	6/10/2010	1342	48.7260	-122.5309	48.7064	-122.5303	0.4	26.4	-25.7
BBDIOX-10	6/09/2010	-	48.7064	-122.5303	48.7182	-122.5307	1.1	32.0	-30.0
BBDIOX-11	6/09/2010	-	48.7182	-122.5307	48.7594	-122.5104	0.2	32.0	-30.0
BBDIOX-12	6/15/2010	1651	48.7594	-122.5104	48.7514	-122.5128	0.7	9.2	-8.9
UWI 23	6/14/2010	1135	48.7514	-122.5128	48.7472	-122.5014	0.9	6.0	-6.6
UWI 27	6/15/2010	1316	48.7472	-122.5014	48.7497	-122.4902	1.1	5.1	-5.7
UWI 28	6/11/2010	917	48.7497	-122.4902	48.7386	-122.5153	0.3	5.5	-5.8
UWI 29	6/09/2010	847	48.7386	-122.5153	48.7333	-122.5111	0.8	13.9	-13.9
UWI 30	6/09/2010	944	48.7333	-122.5111	48.7270	-122.5158	1.5	14.4	-14.4
UWI 31	6/09/2010	1100	48.7270	-122.5158	48.7250	-122.5453	1.1	17.8	-17.8
UWI 32	6/10/2010	1414	48.7250	-122.5453	48.7534	-122.5363	1.5	28.6	-27.7
UWI 35	6/11/2010	1541	48.7534	-122.5363	48.7359	-122.5462	1.5	12	-10.4
UWI 277	6/09/2010	1441	48.7359	-122.5462	48.7527	-122.5545	0.8	24.6	-22.8

Table B-2. Field notes for surface sediment samples collected, June 2010.

Station ID	Date	Time	Penetration Depth (cm)	Sample Depth (cm)	Sediment Type	Color	Odor	Lab ID
BBDIOX-1	6/11/2010	1703	-	-	-	-	-	-
BBDIOX-1A	6/15/2010	1552	17	12	Silt-Clay	O/B	H_2S	1006050-10
BBDIOX-2	6/10/2010	1621	9	8	Silt-Clay	O/O	-	1006050-11
BBDIOX-3	6/11/2010	-	-	-	-	-	-	-
BBDIOX-3A	6/15/2010	1627	17	12	Silt-Clay	O/G	-	1006050-22
BBDIOX-4	6/11/2010	1120	16	12	Silt-Clay	O/G	-	1006050-13
BBDIOX-5	6/15/2010	1156	17	12	Silt-Clay	B/B	**H_2S**	1006050-14
BBDIOX-6	6/11/2010	1057	16	12	Silt-Clay	O/G	-	1006050-15
BBDIOX-7	6/14/2010	1459	11	11	Silt-Clay	O/G	-	1006050-16
BBDIOX-8	6/10/2010	1057	17	12	Silt-Clay	O/B	-	1006050-17
*BBDIOX-88**	*6/10/2010*	*1057*	*17*	*12*	*Silt-Clay*	*O/B*	-	*1006050-18*
BBDIOX-9	6/10/2010	1342	17	12	Silt-Clay	O/G	-	1006050-19
BBDIOX-10	6/9/2010	-	17	12	Silt-Clay	G/B	-	1006050-20
BBDIOX-11	6/9/2010	-	17	12	Silt-Clay	O/B	H_2S	1006050-21
BBDIOX-12	6/15/2010	1651	17	12	Silt-Clay	O/G	-	1006050-24
UWI 23	6/14/2010	1135	11	11	Clay-Silt	O/G	-	1006050-01
UWI 27	6/15/2010	1316	9	8	Silt-Clay	O/G	-	1006050-02
UWI 28	6/11/2010	917	12	11	Sand Silt-Clay Wood	O/O	H_2S	1006050-03
UWI 29	6/9/2010	847	11	10	Clay-Silt	G/G	-	1006050-04
UWI 30	6/9/2010	944	13.5	13.5	Clay-Silt	G/G	-	1006050-05
UWI 31	6/9/2010	1100	11	10	Clay-Silt	O/G	-	1006050-06
UWI 32	6/10/2010	1414	17	12	Silt-Clay	O/GB	**H_2S**	1006050-07
UWI 35	6/11/2010	1541	10	9	Silt-Clay	O/G	-	1006050-08
UWI 277	6/9/2010	1441	17	12	Silt-Clay	O/G	-	1006050-09

* *BBDIOX-88* is a field split (not a true field replicate) of the homogenized surface sediment collected at station BBDIOX-8.
B: brown
G: grey
O: olive
O/G: olive-colored surface sediment over grey-colored deeper sediment.
H_2S: hydrogen sulfide odor present (bold font: relatively strong odor)

Appendix C. Chemistry Results

Table C-1. Concentrations of conventional parameters in surface sediments of inner Bellingham Bay, 2010.

Station ID ⟶		BBDIOX - ##													UWI - ##						
		1A	**02**	**3A**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	**23**	**27**	**28**	**29**	**30**	**31**	**32**	**35**	**277**
Lab ID = 1006050 - ##		10	11	22	13	14	15	16	17	19	20	21	24	01	02	03	04	05	06	07	08	09
Particle (Grain) Size Distribution (um)																						
Batch		2	2	2	2	2	2	2	2	2	1	1	2	2	2	2	1	1	1	2	2	1
Gravel (%)	>2000um	1.1	0.1	0.1	5.5	0.1	8.1	0.1	0.6	22.4	0.3	4.5	0.5	0.1	1.4	2.0	0.3	0.1	1.2	34.7	0.2	0.2
Total Sand (%)	62.5-2000um	9.1	28.7	7.4	12.3	7.4	6.1	2.4	6.1	3.8	3.8	7.4	13.3	2.6	2.2	31.0	5.2	5.9	7.4	4.4	3.0	7.2
Very Coarse Sand (%)	1000-2000um	3.2	0.2	0.4	5.0	0.9	3.8	0.1	1.3	2.2	1.9	4.2	0.9	0.1	0.3	3.0	0.2	2.6	3.8	1.9	0.1	3.9
Coarse Sand (%)	500-1000um	3.0	0.4	0.5	2.5	1.8	1.2	0.2	2.2	0.6	0.8	1.9	0.7	0.3	0.4	5.5	1.6	1.6	2.2	0.9	0.2	1.8
Medium Sand (%)	250-500um	1.4	1.6	0.5	2.7	1.8	0.5	0.6	1.2	0.4	0.4	0.7	1.7	0.2	0.4	9.9	1.5	0.8	0.7	0.6	0.3	0.7
Fine Sand (%)	125-250um	0.8	1.4	0.4	0.9	1.5	0.3	0.5	0.6	0.3	0.4	0.3	6.3	0.2	0.4	6.6	0.8	0.4	0.3	0.4	0.4	0.2
Very Fine Sand (%)	62.5-125um	0.7	25.1	5.6	1.2	1.4	0.3	1.1	0.7	0.3	0.3	0.4	3.8	1.7	0.7	6.1	1.0	0.5	0.4	0.5	2.1	0.6
Silt (%)	3.9-62.5um	52.0	63.0	75.6	64.9	76.4	66.5	64.3	66.9	50.6	54.0	53.1	72.6	70.4	58.4	57.0	68.7	68.3	59.0	36.8	70.2	59.0
Clay (%)	<3.9um	37.8	8.3	17.0	17.3	16.2	19.3	33.2	26.4	23.1	41.9	35.0	13.5	27.0	37.9	9.9	25.8	25.7	32.4	24.1	26.6	33.5
Fines (%)	<62.5um	89.8	71.3	92.6	82.2	92.6	85.8	97.5	93.3	73.7	95.9	88.1	86.1	97.4	96.3	66.9	94.5	94.0	91.4	60.9	96.8	92.5
Organic Carbon																						
Batch		1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1
TOC (%)		1.87	0.66	1.2	1.26	1.26	1.53	1.40	1.93	1.92	2.02	1.99	2.39	1.37	1.64	2.66	1.56	1.83	1.94	1.85	1.31	1.61

Table C-2. Quality control sample results for grain size distribution, and TOC analyses.

Parameter (dry weight)	Batches	Sample EDL	Sample EQL	Blank Conc.	Lab Replicate (% RSD)	SRM (% Recovery)
Grain Size Distribution (%)						
Sand	1	0.1	0.1	-	12	-
	2	0.1	0.1	-	33 *	-
Silt	1	0.1	0.1	-	0.9	-
	2	0.1	0.1	-	3.4	-
Clay	1	0.1	0.1	-	2.2	-
	2	0.1	0.1	-	2.7	-
Organic Carbon (%)						
TOC	1	0.1	0.1	0.1U	0.7	90
	2	0.1	0.1	0.1U	8.9	90

* Higher RSD value due partly to low sand content (3.4%) in lab replicates for sample UWI 35
EDL: Estimated Detection Limit
EQL: Estimated Quantitation Limit
RSD: Relative Standard Deviation
SRM: Standard Reference Material

Table C-3. PCDD/F concentrations in surface sediments of inner Bellingham Bay, 2010.

Station ID →	**BBDIOX - ##**													
	1A		**02**		**3A**		**04**		**05**		**06**		**07**	
Lab ID 1006050 - ##	10		11		22		13		14		15		16	
Batch	1		1		2		1		1		1		2	
PCDDs (ng/Kg)														
2,3,7,8-TCDD	0.39	U	0.11	U	0.27	U	0.23	U	0.18	U	0.18	U	0.23	U
1,2,3,7,8-PeCDD	2.6	J	0.16	NJ	0.17	U	0.39	NJ	0.33	U	0.65	NJ	0.36	NJ
1,2,3,4,7,8-HxCDD	9.6		0.25	U	0.21	J	0.86	J	0.76	J	2.5	J	1.3	J
1,2,3,6,7,8-HxCDD	15		0.64	NJ	0.37	J	1.8	J	1.9	J	3.7	J	2.8	J
1,2,3,7,8,9-HxCDD	11		0.48	J	0.27	J	1.2	J	0.74	J	2.7	J	1.7	J
1,2,3,4,6,7,8-HpCDD	150		12		6.0		25		38		41		44	
OCDD	610		110		73		220		280		240		370	
PCDFs (ng/Kg)														
2,3,7,8-TCDF	15		0.23	J	0.76	J	1.9		1.9		4.8		2.3	
1,2,3,7,8-PeCDF	1.2	NJ	0.17	J	0.16	J	0.20	NJ	0.28	J	0.40	J	0.36	J
2,3,4,7,8-PeCDF	1.9	J	0.19	NJ	0.11	U	0.31	J	0.30	J	0.53	J	0.39	J
1,2,3,4,7,8-HxCDF	1.6	J	0.33	J	0.29	NJ	0.52	J	0.56	J	0.52	J	0.56	J
1,2,3,6,7,8-HxCDF	0.79	J	0.22	NJ	0.14	U	0.29	J	0.28	J	0.35	J	0.29	NJ
1,2,3,7,8,9-HxCDF	0.31	U	0.23	J	0.13	J	0.18	J	0.21	NJ	0.22	J	0.34	J
2,3,4,6,7,8-HxCDF	1.2	NJ	0.20	NJ	0.12	NJ	0.37	J	0.46	J	0.45	J	0.49	J
1,2,3,4,6,7,8-HpCDF	16		2.0	J	1.8	J	4.0	J	9.2		4.7	J	6.4	
1,2,3,4,7,8,9-HpCDF	0.96	J	0.30	J	0.40	U	0.43	J	0.65	J	0.44	J	0.28	U
OCDF	56		6.4	J	4.6	J	12		29		14		13	
Total PCDD/Fs (ng/Kg)														
ND=DL	894		134		88.8		270		365		317		445	
ND=DL/2	892		133		88.1		269		364		317		444	
ND=0	890		132		87.3		269		364		316		444	

Italics: qualifier codes added by the project manager

Table C-3 (continued). PCDD/F concentrations in surface sediments of inner Bellingham Bay, 2010.

Station ID →	**BBDIOX - ##**												**UWI - ##**			
	08		**88 (Split)**		**09**		**10**		**11**		**12**		**23**		**27**	
Lab ID 1006050 - ##	17		18		19		20		21		24		01		02	
Batch	2		2		2		2		2		2		1		2	
PCDDs (ng/Kg)																
2,3,7,8-TCDD	1.2		0.89	J	0.8	NJ	0.81	J	0.74	J	0.32	U	0.29	U	0.12	U
1,2,3,7,8-PeCDD	3.4	J	1.9	J	2.4	J	2.8	J	1.6	J	0.39	J	0.27	J	0.15	U
1,2,3,4,7,8-HxCDD	14		7.1		9.6		8.0		5.0		0.70	J	0.40	NJ	0.54	J
1,2,3,6,7,8-HxCDD	24		13		14		14		8.1		2.6	J	1.3	J	0.96	J
1,2,3,7,8,9-HxCDD	16		8.2		9.5		9.4		5.5		1.2	J	0.71	J	0.59	J
1,2,3,4,6,7,8-HpCDD	420		240		120		130		75		58		31		17.0	
OCDD	3100		2300		470		640		360		520		290		150	
PCDFs (ng/Kg)																
2,3,7,8-TCDF	17		8.5		14		12		7.7		1.0		0.89	J	1.3	
1,2,3,7,8-PeCDF	2.4	J	1.1	NJ	1.2	J	1.3	J	0.94	J	0.38	NJ	0.11	U	0.15	J
2,3,4,7,8-PeCDF	3.6	J	1.8	J	1.6	J	2.0	J	1.2	J	0.60	J	0.30	J	0.23	J
1,2,3,4,7,8-HxCDF	4.8	J	2.5	J	1.4	J	0.98	J	1.1	J	0.80	J	0.49	J	0.26	J
1,2,3,6,7,8-HxCDF	1.7	J	1.4	J	0.74	J	1.1	J	0.77	J	0.55	J	0.28	J	0.13	UJ
1,2,3,7,8,9-HxCDF	1.8	J	1.3	J	0.47	J	0.68	J	0.63	NJ	0.37	J	0.17	U	0.16	NJ
2,3,4,6,7,8-HxCDF	3.3	J	2.0	J	1.2	J	1.8	J	1.0	J	0.48	NJ	0.24	J	0.23	J
1,2,3,4,6,7,8-HpCDF	56		39		11		17		8.4		8.5		4.6	J	2.70	J
1,2,3,4,7,8,9-HpCDF	3.9	J	2.6	J	0.82	J	1.2	J	0.86	J	0.61	J	0.31	U	0.29	U
OCDF	220		110		28		30		21		27		13		6.1	J
Total PCDD/Fs (ng/Kg)																
ND=DL	3893		2741		687		873		500		624		344		181	
ND=DL/2	3893		2741		686		873		499		623		344		180	
ND=0	3893		2740		686		873		499		623		343		180	

Italics: qualifier codes added by the project manager

Table C-3 (continued). PCDD/F concentrations in surface sediments of inner Bellingham Bay, 2010.

Station ID →	UWI - ##													
	28		29		30		31		32		35		277	
Lab ID 1006050 - ##	03		04		05		06		07		08		09	
Batch	1		1		1		1		1		1		1	
PCDDs (ng/Kg)														
2,3,7,8-TCDD	0.43	U	0.59	U	0.90	J	0.44	U	0.43	U	0.33	U	0.62	U
1,2,3,7,8-PeCDD	3.3	J	1.1	J	3.9	J	3.6	J	0.25	U	0.47	J	1.2	J
1,2,3,4,7,8-HxCDD	7.2		6.4		18		14		2.2	J	0.46	NJ	2.9	J
1,2,3,6,7,8-HxCDD	23		8.0		21		20		3.7	J	0.83	J	6.5	
1,2,3,7,8,9-HxCDD	13		6.4		17		16		2.8	J	0.58	J	3.6	J
1,2,3,4,6,7,8-HpCDD	570		93		240		180		44		14		130	
OCDD	5200		340		940		670		290		120		950	
PCDFs (ng/Kg)														
2,3,7,8-TCDF	6.8		9.0		28		22		4.4		1.1		6.4	
1,2,3,7,8-PeCDF	2.0	NJ	0.56	NJ	0.88	NJ	0.97	NJ	0.80	NJ	0.61	NJ	0.35	U
2,3,4,7,8-PeCDF	4.5	J	0.95	J	2.1	J	2.0	J	0.62	J	0.45	J	0.69	NJ
1,2,3,4,7,8-HxCDF	7.1		0.76	J	1.6	NJ	1.8	NJ	0.62	NJ	0.39	J	0.27	U
1,2,3,6,7,8-HxCDF	3.4	J	0.39	NJ	1.2	J	1.1	J	0.36	NJ	0.24	NJ	0.34	U
1,2,3,7,8,9-HxCDF	3.1	J	0.19	U	0.71	J	0.92	J	0.23	U	0.33	U	0.23	U
2,3,4,6,7,8-HxCDF	2.2	J	0.64	J	1.0	J	1.4	J	0.44	J	0.20	U	0.34	U
1,2,3,4,6,7,8-HpCDF	82		6.1		10		13		6.1		2.3	J	30	
1,2,3,4,7,8,9-HpCDF	5.5		0.33	U	0.78	J	1.2	J	0.23	U	0.24	U	2.0	J
OCDF	280		21		32		38		15		7.1	J	330	
Total PCDD/Fs (ng/Kg)														
ND=DL	6214		495		1319		986		372		150		1465	
ND=DL/2	6212		494		1318		985		371		148		1464	
ND=0	6211		493		1317		983		369		147		1463	

Italics: qualifier codes added by the project manager

Table C-4. PCDD/F TEQ concentrations in surface sediments of inner Bellingham Bay, 2010.

Station ID →	**BBDIOX - ##**													
	1A		**02**		**3A**		**04**		**05**		**06**		**07**	
Lab ID 1006050 - ##	10		11		22		13		14		15		16	
Batch	1		1		2		1		1		1		2	
PCDDs (ng/Kg TEQ assuming ND=DL/2)														
2,3,7,8-TCDD	0.20	U	0.055	U	0.14	U	0.12	U	0.090	U	0.090	U	0.12	U
1,2,3,7,8-PeCDD	2.6	J	0.080	NJ	0.085	U	0.20	NJ	0.17	U	0.32	NJ	0.18	NJ
1,2,3,4,7,8-HxCDD	0.96		0.012	U	0.021	J	0.086	J	0.076	J	0.25	J	0.13	J
1,2,3,6,7,8-HxCDD	1.5		0.032	NJ	0.037	J	0.18	J	0.19	J	0.37	J	0.28	J
1,2,3,7,8,9-HxCDD	1.1		0.048	J	0.027	J	0.12	J	0.074	J	0.27	J	0.17	J
1,2,3,4,6,7,8-HpCDD	1.5		0.12		0.060		0.25		0.38		0.41		0.44	
OCDD	0.18		0.033		0.022		0.066		0.084		0.072		0.11	
PCDFs (ng/Kg TEQ assuming ND=DL/2)														
2,3,7,8-TCDF	1.5		0.023	J	0.076	J	0.19		0.19		0.48		0.23	
1,2,3,7,8-PeCDF	0.018	NJ	0.0051	J	0.0048	J	0.0030	NJ	0.0084	J	0.012	J	0.011	J
2,3,4,7,8-PeCDF	0.57	J	0.028	NJ	0.016	U	0.093	J	0.090	J	0.16	J	0.12	J
1,2,3,4,7,8-HxCDF	0.16	J	0.033	J	0.014	NJ	0.052	J	0.056	J	0.052	J	0.056	J
1,2,3,6,7,8-HxCDF	0.079	J	0.011	NJ	0.0070	U	0.029	J	0.028	J	0.035	J	0.014	NJ
1,2,3,7,8,9-HxCDF	0.016	U	0.023	J	0.013	J	0.018	J	0.010	NJ	0.022	J	0.034	J
2,3,4,6,7,8-HxCDF	0.060	NJ	0.010	NJ	0.0060	NJ	0.037	J	0.046	J	0.045	J	0.049	J
1,2,3,4,6,7,8-HpCDF	0.16		0.020	J	0.018	J	0.040	J	0.092		0.047	J	0.064	
1,2,3,4,7,8,9-HpCDF	0.0096	J	0.0030	J	0.0020	U	0.0043	J	0.0065	J	0.0044	J	0.0014	U
OCDF	0.017		0.0019	J	0.0014	J	0.0036		0.0087		0.0042		0.0039	
Total PCDD/F TEQs (ng/Kg)														
ND=DL	10.9		0.77		0.81		1.79		1.86		3.06		2.32	
ND=DL/2	10.6	J	0.54	J	0.55	J	1.48	J	1.60	J	2.65	J	2.01	J
ND=0	10.3		0.31		0.28		1.17		1.33		2.23		1.70	
% Total TEQ = ND	2.7		51		49		21		17		16		15	

Italics: qualifier codes added by the project manager

Table C-4 (continued). PCDD/F *TEQ* concentrations in surface sediments of inner Bellingham Bay, 2010.

Station ID →	BBDIOX - ##												UWI - ##			
	08		88 (Split)		09		10		11		12		23		27	
Lab ID 1006050 -	17		18		19		20		21		24		01		02	
Batch	2		2		2		2		2		2		1		2	
PCDDs (ng/Kg TEQ assuming ND=DL/2)																
2,3,7,8-TCDD	1.2		0.89	J	0.40	NJ	0.81	J	0.74	J	0.16	U	0.14	U	0.060	U
1,2,3,7,8-PeCDD	3.4	J	1.9	J	2.4	J	2.8	J	1.6	J	0.39	J	0.27	J	0.075	U
1,2,3,4,7,8-HxCDD	1.4		0.71		0.96		0.80		0.50		0.070	J	0.02	NJ	0.054	J
1,2,3,6,7,8-HxCDD	2.4		1.3		1.4		1.4		0.81		0.26	J	0.13	J	0.096	J
1,2,3,7,8,9-HxCDD	1.6		0.82		0.95		0.94		0.55		0.12	J	0.071	J	0.059	J
1,2,3,4,6,7,8-	4.2		2.4		1.2		1.3		0.75		0.58		0.31		0.17	
OCDD	0.93		0.69		0.14		0.19		0.11		0.16		0.087		0.045	
PCDFs (ng/Kg TEQ assuming ND=DL/2)																
2,3,7,8-TCDF	1.7		0.85		1.4		1.2		0.77		0.10		0.089	J	0.13	
1,2,3,7,8-PeCDF	0.072	J	0.016	NJ	0.036	J	0.039	J	0.028	J	0.0057	NJ	0.0017	U	0.0045	J
2,3,4,7,8-PeCDF	1.08	J	0.54	J	0.48	J	0.60	J	0.36	J	0.18	J	0.090	J	0.069	J
1,2,3,4,7,8-HxCDF	0.48	J	0.25	J	0.14	J	0.098	J	0.11	J	0.080	J	0.049	J	0.026	J
1,2,3,6,7,8-HxCDF	0.17	J	0.14	J	0.074	J	0.11	J	0.077	J	0.055	J	0.028	J	0.0065	UJ
1,2,3,7,8,9-HxCDF	0.18	J	0.13	J	0.047	J	0.068	J	0.032	NJ	0.037	J	0.0085	U	0.0080	NJ
2,3,4,6,7,8-HxCDF	0.33	J	0.20	J	0.12	J	0.18	J	0.10	J	0.024	NJ	0.024	J	0.023	J
1,2,3,4,6,7,8-	0.56		0.39		0.11		0.17		0.084		0.085		0.046	J	0.027	J
1,2,3,4,7,8,9-	0.039	J	0.026	J	0.0082	J	0.012	J	0.0086	J	0.0061	J	0.0016	U	0.0015	U
OCDF	0.066		0.033		0.0084		0.0090		0.0063		0.0081		0.0039		0.0018	J
Total PCDD/F TEQs (ng/Kg)																
ND=DL	19.8		11.3		10.3		10.7		6.67		2.51		1.55		1.01	
ND=DL/2	19.8	J	11.3	J	9.87	J	10.7	J	6.63	J	2.32	J	1.37	J	0.86	J
ND=0	19.8		11.3		9.47		10.7		6.60		2.13		1.20		0.71	
% Total TEQ = ND	0.0		0.1		4.1		0.0		0.5		8.2		13		18	

Italics: qualifier codes added by the project manager

Table C-4 (continued). PCDD/F ***TEQ*** concentrations in surface sediments of inner Bellingham Bay, 2010.

Station ID →	UWI - ##													
	28		**29**		**30**		**31**		**32**		**35**		**277**	
Lab ID 1006050 - ##	03		04		05		06		07		08		09	
Batch	1		1		1		1		1		1		1	
PCDDs (ng/Kg TEQ assuming ND=DL/2)														
2,3,7,8-TCDD	0.22	U	0.30	U	0.90	J	0.22	U	0.22	U	0.17	U	0.31	U
1,2,3,7,8-PeCDD	3.3	J	1.1	J	3.9	J	3.6	J	0.12	U	0.47	J	1.2	J
1,2,3,4,7,8-HxCDD	0.72		0.64		1.8		1.4		0.22	J	0.023	NJ	0.29	J
1,2,3,6,7,8-HxCDD	2.3		0.80		2.1		2.0		0.37	J	0.083	J	0.65	
1,2,3,7,8,9-HxCDD	1.3		0.64		1.7		1.6		0.28	J	0.058	J	0.36	J
1,2,3,4,6,7,8-HpCDD	5.7		0.93		2.4		1.8		0.44		0.14		1.3	
OCDD	1.6		0.10		0.28		0.20		0.087		0.036		0.28	
PCDFs (ng/Kg TEQ, assuming ND=DL/2)														
2,3,7,8-TCDF	0.68		0.90		2.8		2.2		0.44		0.11		0.64	
1,2,3,7,8-PeCDF	0.030	NJ	0.0084	NJ	0.013	NJ	0.015	NJ	0.012	NJ	0.0092	NJ	0.0052	U
2,3,4,7,8-PeCDF	1.35	J	0.28	J	0.63	J	0.60	J	0.19	J	0.14	J	0.10	NJ
1,2,3,4,7,8-HxCDF	0.71		0.076	J	0.080	NJ	0.090	NJ	0.031	NJ	0.039	J	0.014	U
1,2,3,6,7,8-HxCDF	0.34	J	0.020	NJ	0.12	J	0.11	J	0.018	NJ	0.012	NJ	0.017	U
1,2,3,7,8,9-HxCDF	0.31	J	0.0095	U	0.071	J	0.092	J	0.012	U	0.016	U	0.012	U
2,3,4,6,7,8-HxCDF	0.22	J	0.064	J	0.10	J	0.14	J	0.044	J	0.010	U	0.017	U
1,2,3,4,6,7,8-HpCDF	0.82		0.061		0.10		0.13		0.061		0.023	J	0.30	
1,2,3,4,7,8,9-HpCDF	0.055		0.0017	U	0.0078	J	0.012	J	0.0012	U	0.0012	U	0.020	J
OCDF	0.084		0.0063		0.0096		0.011		0.0045		0.0021	J	0.099	
Total PCDD/F TEQs (ng/Kg)														
ND=DL	19.9		6.27		17.1		14.6		2.96		1.57		6.10	
ND=DL/2	19.7	J	5.94	J	17.0	J	14.2	J	2.55	J	1.33	J	5.62	J
ND=0	19.4		5.60		16.9		13.9		2.13		1.10		5.14	
% Total TEQ = ND	1.2		5.5		0.5		2.3		16		18		8.5	

Italics: qualifier codes added by the project manager

Table C-5. Quality control sample results for 2010 study of PCDD/Fs in surface sediments of Bellingham Bay.

QC Sample ID →	EDL	EQL	Blank		LCS (%)	MS (%)	MSD (%)	% RPD	Blank		LCS	1006050-02 DUP		% RPD* (UWI 27)	CRM		CRM (%)
						(UWI 23)											
Batch			1		1	1	1	1	2		2	2			2		2
PCDDs (ng/Kg)																	
2,3,7,8-TCDD	0.10-	0.97-1.0	0.10	U	100	96	94	2.1	0.043	U	96	0.10	U		2	NJ	102
1,2,3,7,8-PeCDD	0.11-	4.8-5.0	0.090	U	96	88	85	2.6	0.042	U	96	0.11	U		5.2	J	90
1,2,3,4,7,8-HxCDD	0.06-0.95		0.086	U	100	95	94	1.0	0.039	U	105	0.16	J	109	5.5	J	98
1,2,3,6,7,8-HxCDD			0.10	U	102	96	95	0.4	0.045	U	107	0.25	J	117	12	J	110
1,2,3,7,8,9-HxCDD			0.083	U	101	97	95	2.0	0.045	U	99	0.18	J	106	6.6	J	96
1,2,3,4,6,7,8-HpCDD	0.10-1.9		0.14	NJ	97	97	110	13.1	0.11	J	102	4.5	J	116	220		95
OCDD	0.11-2.9	9.7-10	1.0	J	108	112	164	37.5	0.41	NJ	111	35		124	2300		112
PCDFs (ng/Kg)																	
2,3,7,8-TCDF	0.07-	0.97-1.0	0.14	U	108	116	108	7.1	0.047	U	123	0.89	J	37	200		91
1,2,3,7,8-PeCDF	0.05-0.36	4.8-5.0	0.11	U	103	101	97	3.4	0.028	NJ	113	0.07	U		110		90
2,3,4,7,8-PeCDF			0.065	U	101	99	93	6.2	0.024	U	109	0.09	NJ		190		116
1,2,3,4,7,8-HxCDF	0.06-0.95		0.083	U	96	96	94	1.3	0.034	U	106	0.12	J	74	310		112
1,2,3,6,7,8-HxCDF			0.059	U	100	103	96	6.9	0.042	J	107	0.10	NJ		160		101
1,2,3,7,8,9-HxCDF			0.083	U	103	96	97	1.1	0.051	U	106	0.10	J		51		685
2,3,4,6,7,8-HxCDF			0.071	U	99	99	93	5.9	0.043	NJ	107	0.08	J	97	85		176
1,2,3,4,6,7,8-HpCDF	0.10-0.73		0.079	NJ	102	102	98	3.6	0.085	NJ	108	0.68	J	120	340		98
1,2,3,4,7,8,9-HpCDF			0.097	U	99	91	91	0.4	0.049	U	104	0.11	U		85		106
OCDF	0.12-1.7	9.7-10	0.18	U	102	94	86	8.9	0.23	J	116	2.1	UJ		360		120
Total PCDD/Fs (ng/Kg)																	
ND=DL			2.57						1.37			44.6			4442		
ND=DL/2			1.28	J					0.87	J		43.3	J	122	4441		110
ND=0			0.00						0.38			42.0			4440		
ND=DL			0.29						0.13			0.49					
ND=DL/2			0.14						0.07			0.37		80	157		111
ND=0			0.00						0.005			0.24					
Total PCDD/F TEQs (ng/Kg)																	

* For congeners detected in both sample and duplicate
EDL: estimated detection limit, EQL: estimated quantitation limit
LCS: Laboratory Control Sample
%: percent recovery

MS: matrix spike, MSD: matrix spike duplicate
DUP: laboratory duplicate
CRM: Certified Reference Material (EDF 5184, Cambridge Isotope Laboratories)

Appendix D. Calculation of Total TEQ

Table D- 1. Example calculation of total TEQ for PCDD/Fs (taken from DMMP, 2010b).

Analyte	TEF (WHO 2005)	Sample C-1			
		Conc. ng/kg-dw	LQ[1]	TEQ U=1/2 EDL	TEQ U=0
2,3,7,8-TCDD	1	0.1	U	0.05	0
1,2,3,7,8-PeCDD	1	0.4		0.4	0.4
1,2,3,4,7,8-HxCDD	0.1	0.4		0.04	0.04
1,2,3,6,7,8-HxCDD	0.1	2.4		0.24	0.24
1,2,3,7,8,9-HxCDD	0.1	1.3		0.13	0.13
1,2,3,4,6,7,8-HpCDD	0.01	39.3		0.393	0.393
OCDD	0.0003	253		0.0759	0.0759
2,3,7,8-TCDF	0.1	0.7		0.07	0.07
1,2,3,7,8-PeCDF	0.03	0.224		0.00672	0.00672
2,3,4,7,8-PeCDF	0.3	0.305	U	0.0458	0
1,2,3,4,7,8-HxCDF	0.1	0.433		0.0433	0.0433
1,2,3,6,7,8-HxCDF	0.1	0.294	U	0.0147	0
2,3,4,6,7,8-HxCDF	0.1	0.321		0.0321	0.0321
1,2,3,7,8,9-HxCDF	0.1	0.087	U	0.00435	0
1,2,3,4,6,7,8-HpCDF	0.01	6.61		0.0661	0.0661
1,2,3,4,7,8,9-HpCDF	0.01	0.409		0.00409	0.00409
OCDF	0.0003	15.1		0.00453	0.00453
Total TEQ:				1.62	1.50

[1]Laboratory Qualifiers
U: Analyte was not detected at or above the reported result.

Appendix E. Statistical Analysis

This appendix describes the statistical analysis of 2010 study results. The analysis sought to determine if:

- Other parameters could explain the variability observed in PCDD/F TEQ concentrations.
- Other parameters could be used to predict PCDD/F TEQ concentrations
- Groups of stations with similar characteristics could be identified

Data distributions and outliers

Results for several of the parameters were normally distributed (Table E-1), but PCDD/F results fit only lognormal and gamma distributions. A distribution for % fines could not be identified. The few outlier values identified in the data set (Table E-2) were included in all analyses.

Table E-1. Data distributions for results from Bellingham Bay surface sediments, 2010.
Analysis using ProUCL version 4.0, with α = 0.05.

Parameter (units)	Normal?	Gamma?	LogNormal?
Distance to Shore (m)	Yes	Yes	No
Water Depth (m)	Yes	Yes	Yes
PCDD/F Conc. (ng/Kg)	No	Yes	Yes
PCDD/F TEQ (ng/Kg)	No	Yes	Yes
Silt (%)	Yes	Yes	No
Clay (%)	Yes	Yes	Yes
Fines (%)	No	No	No
TOC (%)	Yes	Yes	Yes

Table E-2. Statistical outliers among results from Bellingham Bay surface sediments, 2010.
Analysis using ProUCL version 4.0 and Dixon's test, with α = 0.05.
No results were excluded from analyses and discussion.

Parameter (units)	High Outlier	Low Outlier
Water Depth (m)	None	None
PCDD/F Conc. (ng/Kg)	6,212	None
PCDD/F TEQ (ng/Kg)	None	None
Silt (%)	None	None *
Clay (%)	None	None
Fines (%)	None	None
TOC (%)	2.66	0.66

* 36.8% value significant at α = 0.10

Correlation analysis

Spearman rank correlations showed several significant relationships between pairs of parameters (Table E-3). A few were expected because the parameters were mathematically related (% fines and % clay; PCDD/F concentrations and TEQ). Others were physically related (water depth increases with the distance from shore). The highly significant correlation between PCDD/Fs and % TOC ($p<0.01$) has been observed by others and was expected for hydrophobic organic compounds. There was no significant relationship between PCDD/F concentrations and particle size classes.

Table E-3. Spearman rank correlations between parameters measured in surface sediments of Bellingham Bay, 2010.

Analysis using SPSS version 11.0.

	Distance to Shore (m)	Depth (m)	PCDD/F (ng/Kg)	PCDD/F TEQ (ng/kg)	Silt (%)	Clay (%)	Fines (%)	TOC (%)
Distance to Shore (m)	1.000							
Depth (m)	**-0.538**	1.000						
PCDD/F (ng/Kg)	-0.339	-0.260	1.000					
PCDD/F TEQ (ng/kg)	-0.271	-0.394	**0.919**	1.000				
Silt (%)	-0.034	**0.486**	-0.331	-0.390	1.000			
Clay (%)	-0.042	-0.350	0.218	0.221	-0.391	1.000		
Fines (%)	-0.245	0.255	-0.099	-0.149	0.433	**0.570**	1.000	
TOC (%)	**-0.455**	-0.312	**0.761**	**0.776**	**-0.506**	0.268	-0.218	1.000

Bold values are significant at $p<0.05$
Values enclosed in bold border are significant at $p<0.01$

Regression analysis

A simple linear model shows that 46% of the variability observed in the total PCDD/F TEQ concentrations in the 2010 surface sediment samples was related to % TOC. Linear regression using multiple independent parameters to predict total PCDD/F TEQs explained marginally more of the variability. Using a logarithmic model to represent the relationship between the two parameters explained 55% of the variability (Figure E-1).

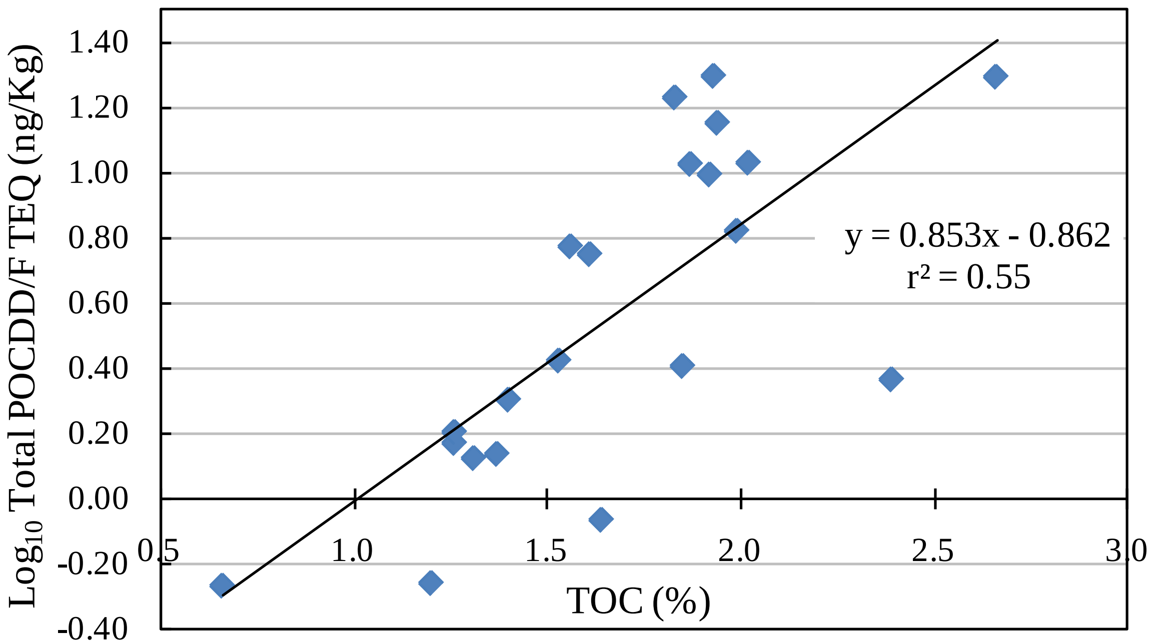


Figure E-1. Prediction of total PCDD/F TEQ concentrations using % TOC results.

Principal Components Analysis (PCA) and Hierarchical Cluster Analysis (HCA)

PCA and HCA identified 2 or 3 distinct groups of stations within a large area of inner Bellingham Bay. Each station group had similar physical and chemical characteristics (e.g., distance to shore, % fines, and % TOC).

Figure E-2 shows that PCA classified 16 of the 21 sediment samples into 2 main groups.

- Group 1 = 8 samples of fine-grained sediment containing relatively low concentrations of TOC and total TEQs, collected relatively far from shore.
- Group 2 = 8 samples of fine-grained sediment containing relatively high concentrations of TOC and total TEQs, collected relatively close to shore.

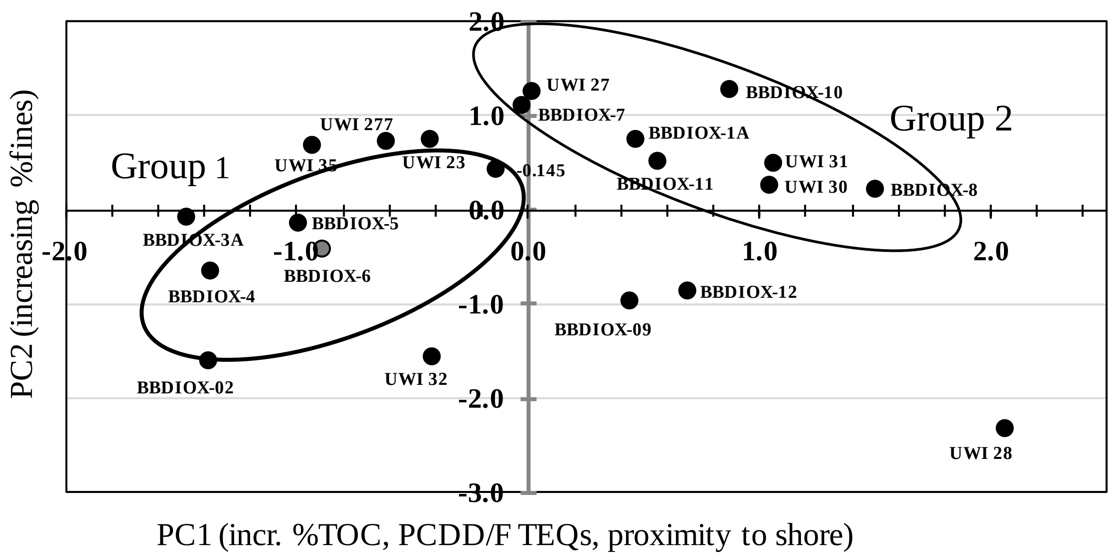


Figure E-2. Principal component analysis (PCA) of results for Bellingham Bay surface sediment samples, 2010.

Analysis was conducted using SPSS version 11.0, with parameters including distance to shore, PCDD/F concentration, % TOC, and % fine-grained material. PCA 1 and PCA 2, combined, explain 72% of the variability in sample characteristics (41% + 31%, respectively).

Figure E-3 shows HCA classification that results in 2 station groups. Other HCA analyses can be conducted that result in a greater number of station groups.

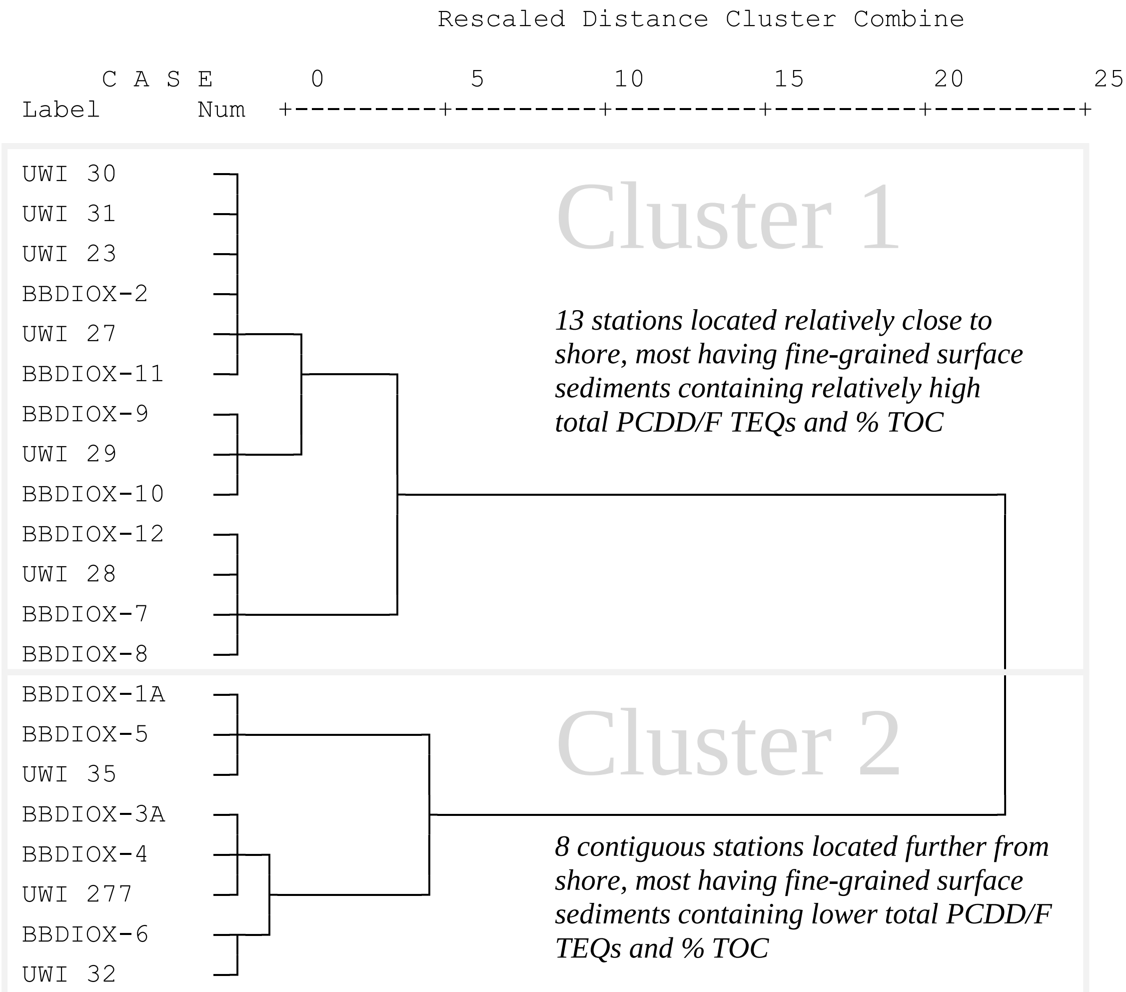


Figure E-3. Hierarchical Cluster Analysis (HCA) based on results for Bellingham Bay surface sediments, 2010.

The analysis was conducted with SPSS version 11.0, using the same parameters as principal components analysis (PCA). The dendrogram was based on agglomerating groups using squared Euclidian distances and the average linkage between groups.

Table E-4. Total PCDD/F TEQ with nondetects estimated using Kaplan-Meier (K-M) method.

Shaded rows indicate contiguous samples of the Bellingham Bay background data set. All values shown assume nondetect concentrations estimated using KMStats.xls version 1.4 (Practical Stats, 2011). Results were entered into the spreadsheet as instructed. Nondetect congener concentrations were reported to the estimated detection limit (EDL), except as noted.

Station ID	K-M Mean	Standard Error	Standard Deviation	UCL95	25th Percentile	Median	75th Percentile	Total K-M TEQ
1A	0.616	0.190	0.784	0.947	0.017	0.160	1.100	10.46
2	0.024	0.008	0.031	0.038	0.002	0.020	0.033	0.41
3A	0.021	0.006	0.023	0.031	0.004	0.018	0.027	0.35
4	0.077	0.019	0.077	0.111	0.006	0.052	0.120	1.32
5	0.085	0.024	0.097	0.127	0.008	0.074	0.092	1.45
6	0.142	0.040	0.162	0.213	0.012	0.052	0.250	2.42
7	0.110	0.030	0.124	0.162	0.004	0.064	0.170	1.87
8	1.165	0.294	1.212	1.678	0.180	0.930	1.600	19.81
88	0.665	0.164	0.677	0.951	0.140	0.540	0.850	11.30
9	0.564	0.171	0.704	0.862	0.047	0.140	0.960	9.59
10	0.631	0.180	0.743	0.946	0.098	0.192	0.940	10.73
11	0.391	0.106	0.438	0.577	0.100	0.028	0.550	6.65
12	0.131	0.038	0.156	0.198	0.037	0.080	0.156	2.23
23	0.075	0.023	0.095	0.115	0.003	0.046	0.089	1.27
27	0.046	0.013	0.052	0.068	0.003	0.027	0.069	0.78
27DUP	0.017	0.006	0.024	0.028	0.001	0.010	0.018	0.29
28	1.158	0.357	1.471	1.781	0.220	0.710	1.350	19.68
29	0.334	0.099	0.406	0.506	0.006	0.076	0.640	5.67
30	0.999	0.296	1.222	1.517	0.071	0.282	1.800	16.99
31	0.827	0.262	1.080	1.285	0.092	0.140	1.600	14.07
32	0.132	0.041	0.166	0.205	0.005	0.061	0.220	2.25
35	0.069	0.029	0.118	0.119	0.002	0.036	0.083	1.17
277	0.313	0.103	0.424	0.493	0.020	0.099	0.360	5.32
BBDX-SS-01*	0.060	0.024	0.094	0.103	0.010	0.047	0.084	1.03
BBDX-SS-02*	0.159	0.061	0.246	0.266	0.011	0.110	0.189	2.70

** Nondetect congener concentrations reported to practical quantitation limit (PQL) (EDL not available).*

Appendix F. Fingerprint Analysis

Fingerprint analysis of organic compounds in sediment and other types of samples can help distinguish between areas (e.g., groups of stations) influenced by point (discrete) sources from areas influenced only by diffuse sources of pollutants (Barabas et al., 2004; Plumb, R., 2004; EPA, 2006). If this is true for PCDD/F concentrations in Bellingham Bay sediments, then the latter areas may be candidates to represent background conditions.

The 2010 PCDD/F results were assembled for a screening-level fingerprint analysis. TEQ concentrations were calculated for each congener in each sample (see Appendix D). Individual congener concentrations and TEQs were then normalized to total concentration and total TEQ. Finally, the fractional contribution of each congener concentration and TEQ was plotted, in the same order, as line charts. The PCDD/F fingerprints *based on concentrations* revealed little because OCDD/F congener concentrations were too dominant (Figure F-1). However, fingerprints based on normalized TEQs of individual congeners in each sample resulted in at least two distinct patterns.

Figure F-2 shows 8 stations (BBDIOX-5 through BBDIOX-12) that have 3 congeners contributing approximately 10% - 25% each to the total TEQs:

- 1,2,3,7,8,9-HxCDD
- 1,2,3,4,7,8-HxCDF
- 1,2,3,4,6,7,8-HpCDF

Figure F-3 shows six stations (BBDIOX-2, BBDIOX-4, UWI 23, UWI 27, UWI 28, and UWI 277) that have a 1,2,3,4,6,7,8-HpCDD peak accounting for 17 - 29% of total TEQs.

The fingerprints in these 2 figures reflect different combinations of PCDD/F sources and sinks, but stations with similar fingerprints are not spatially contiguous. Therefore, without additional analysis, fingerprints do not appear useful for defining an area of surface sediments in Bellingham Bay that represents background. Neither does this level of fingerprint analysis seem able to quantify the relative contribution of different sources to the PCDD/F concentrations observed at each station.

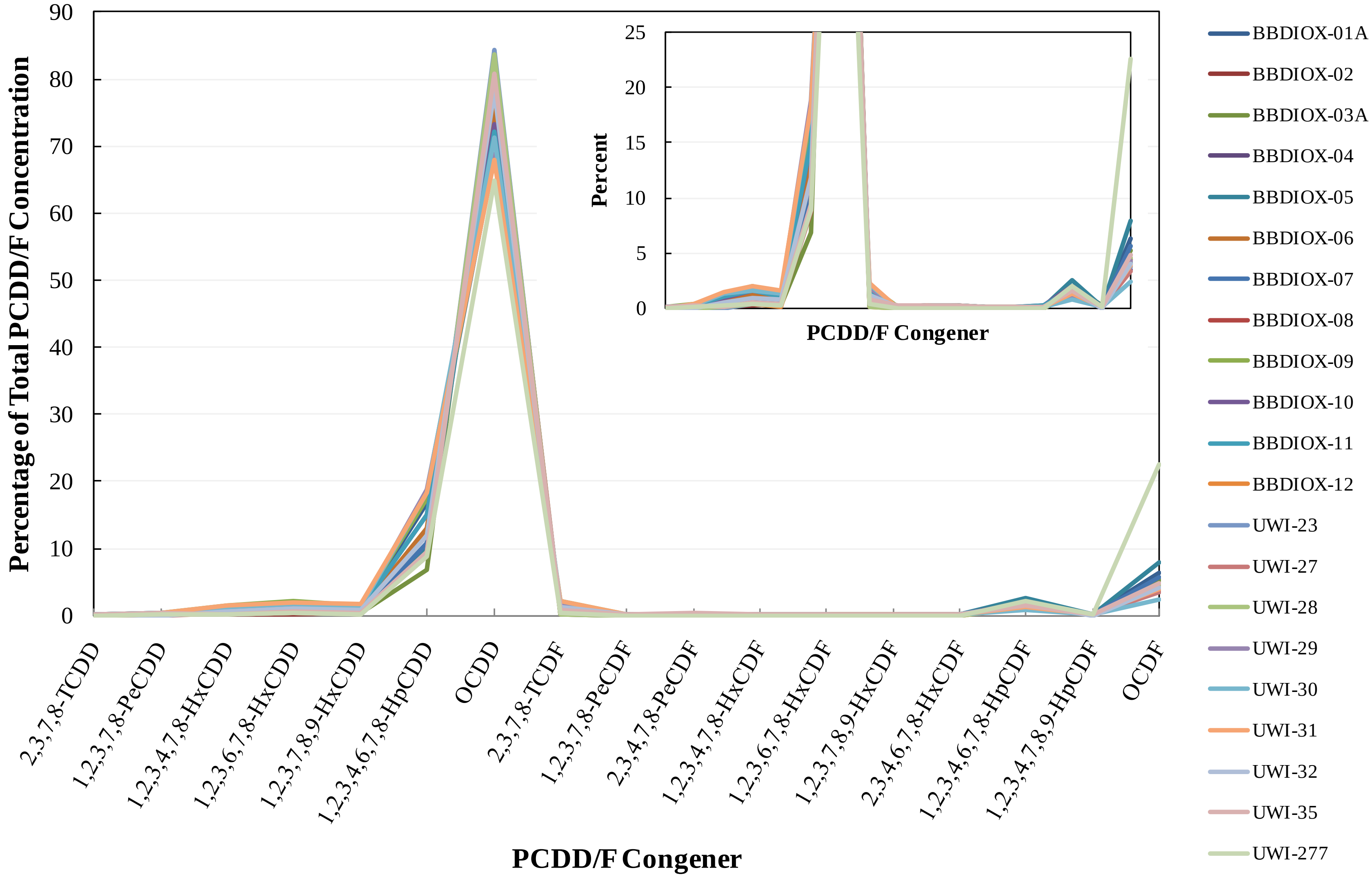


Figure F-1. PCDD/F fingerprints based on congener concentrations in 2010 samples.

Insert shows same sample congener concentrations with compressed y-axis scale for more detail.

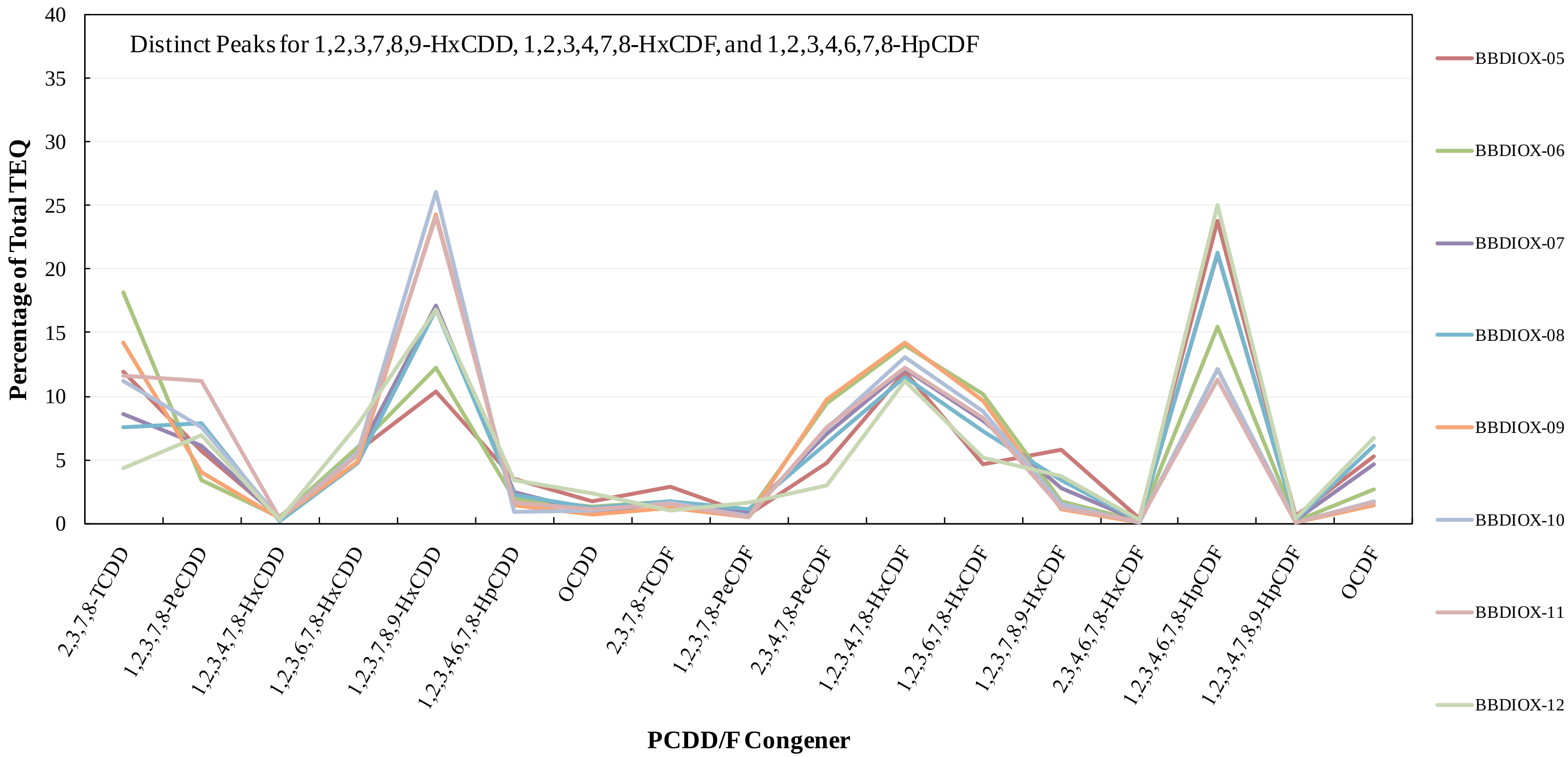


Figure F- 2. PCDD/F fingerprints based on congener TEQs.

Eight stations with peaks for three PCDD/F congeners in common.

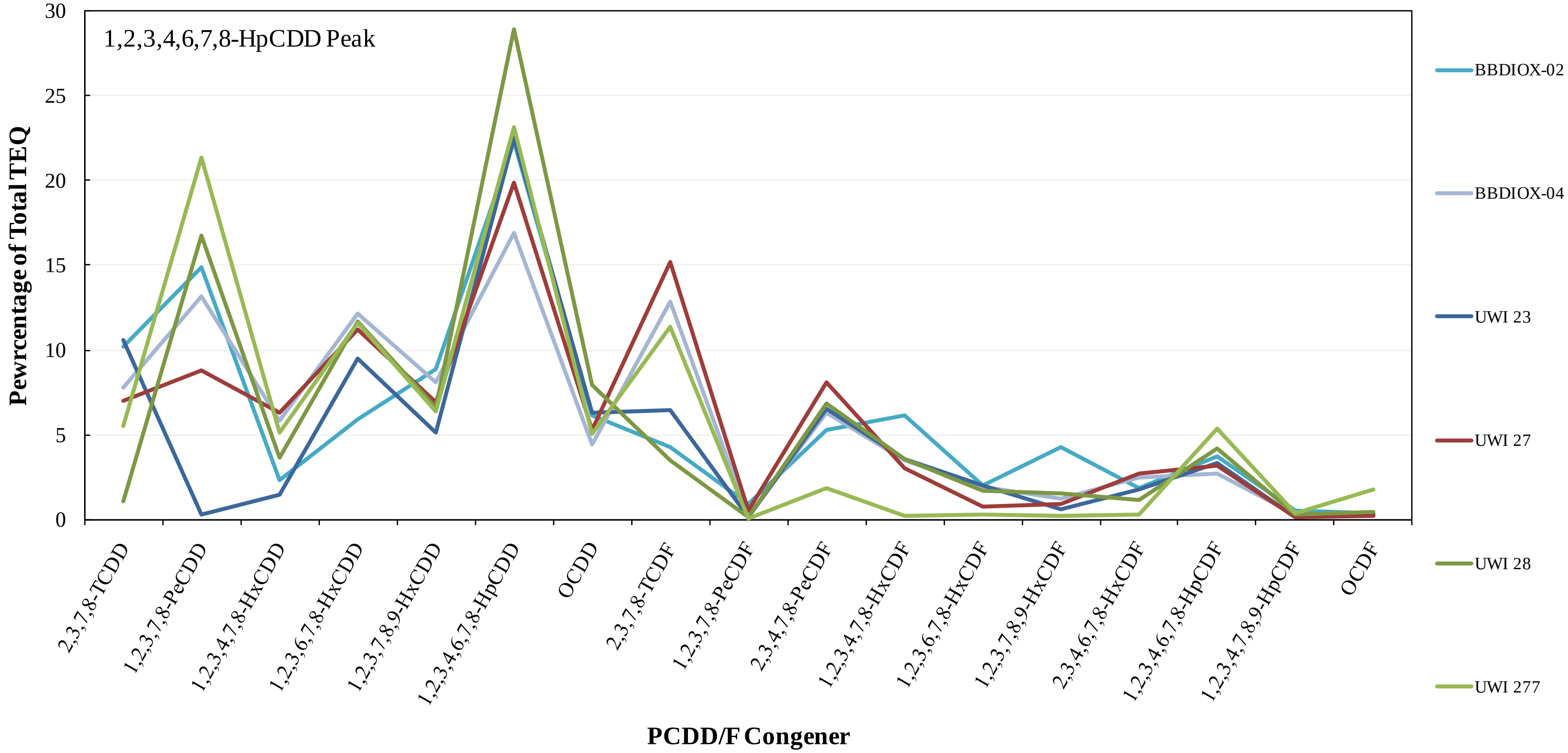


Figure F-3. PCDD/F fingerprints based on congener TEQs, Part 3.

Six stations with distinct peak for 1,2,3,4,6,7,8-heptachlorinated dibenzodioxin.