Using Sediment Profile Imaging (SPI) to Evaluate Sediment Quality at Two Cleanup Sites in Puget Sound

Part I – Lower Duwamish Waterway

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Using Sediment Profile Imaging (SPI) to Evaluate Sediment Quality at Two Cleanup Sites in Puget Sound

Part I — Lower Duwamish Waterway

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Waterbody No. WA-09-1010 (Duwamish River)

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Acronyms and Abbreviations

This list contains acronyms used frequently in this document. Other acronyms are used infrequently and defined only in the text.

ARI	Analytical Resources, Inc.
BHQI	Benthic Habitat Quality Index
CSL	Cleanup Screening Level
DGPS	digital GPS
DMMP	Dredged Material Management Program
Ecology	Washington State Department of Ecology
EIM	Ecology's Environmental Information Management system
EPA	U.S. Environmental Protection Agency
FTE	full time equivalent
GPS	Global Positioning System
H'	Shannon Weiner diversity metric
HDPE	high density polyethylene
IQR	interquartile range
J'	Pielou's evenness metric
LCS	Laboratory control standard
MDS	multidimensional scaling
MEL	Ecology's Manchester Environmental Laboratory
NMDS	non-metric MDS
OSI	Organism Sediment Index
ppt	parts per thousand (for salinity)
QA	quality assurance
REMOTS™	remote ecological monitoring of the seafloor
RM	river mile
RPD	redox potential discontinuity
RV	research vessel
SDI	Swartz dominance index
SEDQUAL	Ecology's Sediment Quality information system
SMS	Sediment Management Standards rule (Chapter 173-204 WAC)
SPI	Sediment Profile Imaging
SQS	Sediment Quality Standards
SWI	sediment water interface
TOC	total organic carbon
TVS	total volatile solids
WAC	Washington Administrative Code

Abstract

During 2006, the Washington State Department of Ecology conducted exploratory studies to determine if preliminary Sediment Profile Imaging (SPI) survey results might predict traditional sediment quality indicators and thereby reduce the need for detailed investigations at cleanup sites. One of the sites chosen for these studies was the Lower Duwamish Waterway Superfund site (Seattle).

Surface sediment samples were collected at 30 of the 87 locations in the Lower Duwamish Waterway where SPI photographs had previously been taken. Sediment conventionals, contaminant chemistry, and toxicity were measured, along with characteristics of the *in situ* benthic community.

SPI survey results distinguished areas of fine sands and silts from sandier sediments and provided evidence that the study site generally had aerobic benthic habitats with relatively complex infaunal communities. Results for sediment conventionals and chemistry supplemented existing data while showing similar distributional patterns. Significant toxicity, measured using two standard test protocols, was found at only four sampling locations.

SPI results had limited ability to predict levels of contaminant chemistry or biological effects that failed regulatory criteria. However, analysis of benthic infaunal results did reveal distinct communities and, more importantly, SPI and sediment quality indicators were capable of distinguishing between them. If regulators determined that one or more of the communities was unacceptably altered or impaired, then future SPI surveys could cost-effectively screen for their spatial distribution and likely cause.

This study, together with other published findings, provides several good reasons to recommend that SPI be used more frequently in cleanup site investigations. The SPI and sediment quality results help fill data gaps and characterize baseline conditions prior to remedial actions and effectiveness monitoring. SPI results can also augment studies of sediment fate and transport, identify areas of severe impact (anoxia, azoic sediments), predict sediment conventional parameters, and provide additional lines of evidence for evaluating benthic community health.

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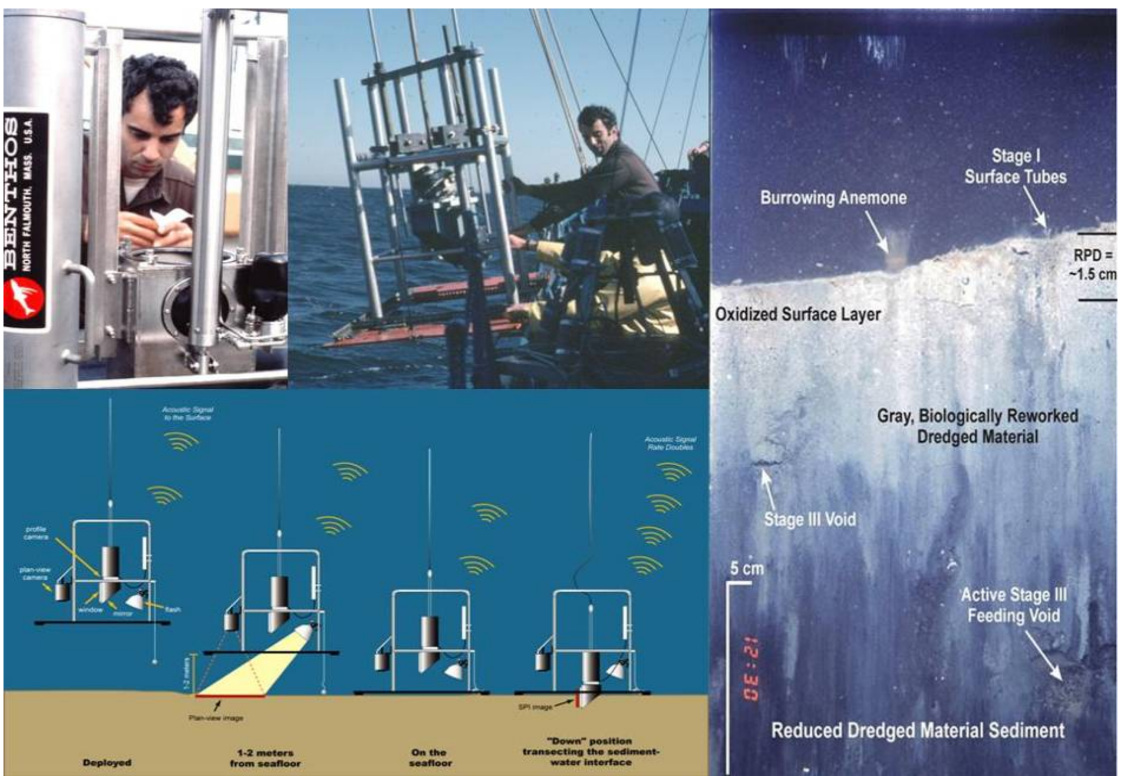
Introduction

Background

Development of REMOTS/SPI Technology

Sediment Profile Imaging (SPI) technology refers to the scientific instruments, methods, and expertise associated with photographing the cross-sectional profile of the upper 15 cm of the seafloor, including the boundary between surface sediment and overlying water, and interpreting the results. After being lowered to the bottom of a waterbody, a camera housed above a sealed, wedge-shaped chamber filled with distilled water operates like an upside-down periscope and penetrates the sediment surface. After a slight delay to allow the camera prism to obtain maximum sediment penetration, a photograph is taken through a vertical window with aid of a high-intensity flash. The photograph is later analyzed for physical, chemical, and biological features using image analysis software and professional expertise. The technology, the image acquisition process, and an example SPI photograph are shown in Figure 1.



Images provided by Germano and Associates

Figure 1. Deployment of the SPI camera, image acquisition, and example photograph of the sediment water interface.

The two photographs at the top left show one of the earliest sediment profile imaging cameras being readied for deployment from a research vessel. The graphic at the bottom left depicts how the camera works. The SPI photograph at the right shows some of the interpretable features of the sediment water interface.

This technology was developed because studies being conducted in the 1970s of the fossil record in sedimentary rock were still hampered by a limited understanding of interactions between sediments and bottom-dwelling or "benthic" organisms (Rhoads and Young, 1972). To study these interactions, a sampling device was needed that preserved fine sediment structures and biological features without compromising them. This led to the development of a diver-deployed camera designed to take detailed photographs of the sediment-water interface.

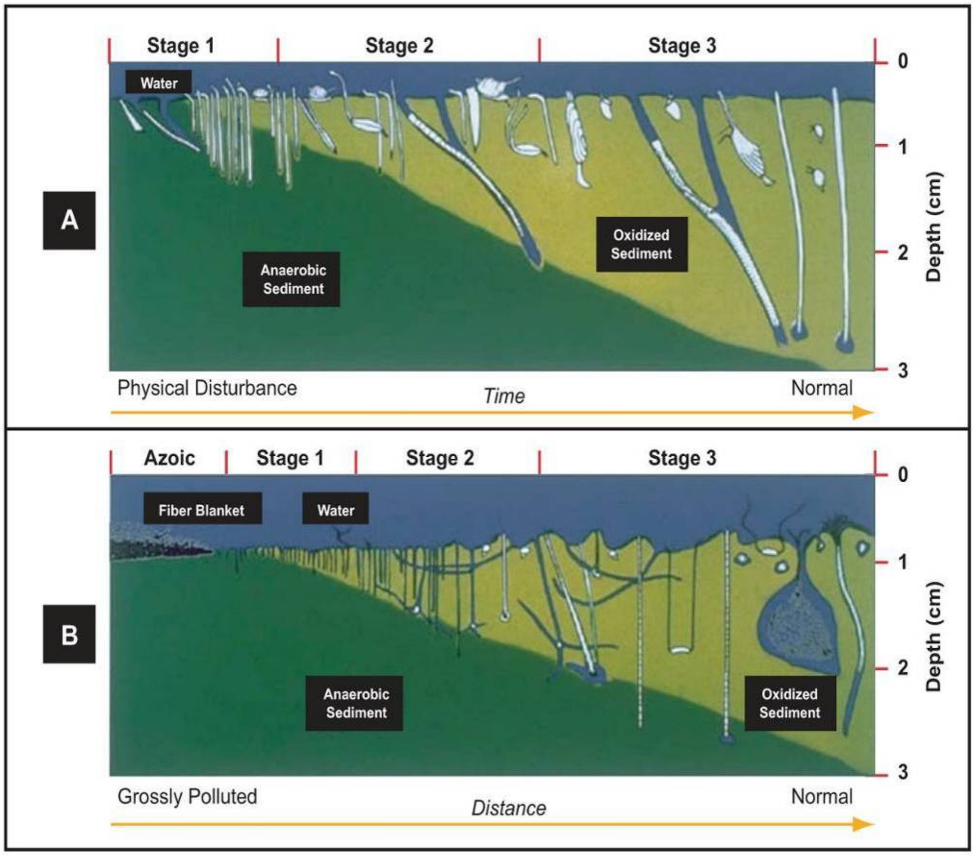
The camera was subsequently modified for deployment from the deck of an oceanographic research vessel and trademarked as REMOTS™ (Remote Ecological Monitoring Of The Seafloor). It was used successfully in early studies of how keystone organisms in Buzzards Bay and Cape Cod Bay altered sediment and community structure. The technology subsequently saw increased use as a reconnaissance tool for monitoring deposits of dredged material in Long Island Sound. This led to development of similar sediment profile imaging or "SPI" cameras.

Interpretation of SPI results over the following decade was aided by the development of models describing how succession in benthic communities is influenced by various disturbances (Rhoads and Germano, 1982, 1986). The model depicted in Figure 2 was based on extensive benthic recolonization and enrichment studies done in the eastern United States and elsewhere (McCall, 1977, Pearson and Rosenberg, 1978). It illustrates the animal-sediment relationships that are visible in sediment profile images.

These "Stage I" communities were replaced by more complex Stage II and Stage III communities comprised of infauna that mixed oxygen into progressively deeper sediments via bioturbation. Figure 2A shows benthic community succession after physical disturbances such as episodic dredged material disposal or propeller scour. Figure 2B shows similar succession with distance away from a source of organic enrichment.

The 1980s also saw use of SPI technology migrate into freshwater systems (Boyer and Shen, 1982), and image analysis software was developed to improve the efficiency of data analysis. SPI is now used around the world to evaluate disturbance due to biological recovery from dredged material placement (Valente, 2004), pollution discharges (Diaz, et al, 1993; Olsgard, 1999), eutrophication (Karlson, et al, 2002), and anoxia (Nilsson and Rosenberg, 2000).

Note: The preceding background was adapted in part from Rhoads (2004).



Graphic provided by Germano and Associates

Figure 2. Model of benthic infaunal community succession relative to physical or chemical disturbance.

Regulatory Applications in the Pacific Northwest

SPI technology is most commonly used to characterize general sediment structure, benthic habitat, successional stage of benthic infaunal community development, and interactions between all of these. Regulatory applications of SPI in the Pacific Northwest usually address the following three purposes.

1. Identify sites for disposal or beneficial use of dredged material, and monitor their use.
2. Identify areas of disturbance and their likely causes (e.g., physical factors or pollutant loading).
3. Assess change in benthic infaunal communities (e.g., recovery from disturbance).

These applications are exemplified by the regional programs and projects listed in Table A-1 (Appendix A). With some exceptions, SPI has not been used to assess sediment quality at cleanup sites. Regional investigations of freshwater sediments that have used SPI (Quendall/Baxter Terminals in Lake Washington, Seattle; Lower Willamette River, Portland, Oregon) are not listed in the table.

Study goals and objectives

The primary goal of the overall study was to determine the feasibility of SPI survey results to streamline and reduce overall costs of cleanup site investigations in Puget Sound. This might be possible if relationships could be found between SPI results and accepted indicators of sediment quality. The ideal relationships would accurately predict the degree of impairment throughout a sediment cleanup site, but a more likely scenario may be that SPI results help identify areas where the likelihood of impairment is high or low. Subsequent sediment quality investigations could then focus on smaller areas where probability of impairment is less certain. These investigations would be easier to design and implement, and would cost less. Such relationships also might help monitor recovery over time.

Specific objectives of this study are to:

1. Identify relationships between SPI survey data and direct measurements of sediment quality.
2. Fill gaps in knowledge of existing sediment quality.
3. Provide data that may serve as part of an environmental *baseline* to which post-remedial action monitoring results can be compared.

The main goal and objective #1 were addressed by collecting images and samples from the Lower Duwamish Waterway that provided SPI, sediment conventionals, contaminant chemistry, sediment toxicity, and benthic infaunal community data. Objective #2 was addressed by a sampling strategy that was designed for good spatial coverage of the site (see below). The data were also used to summarize and map conditions at the study site as of August 2006 (objective #3).

Methods

Study design

The general sequence of events for planning and implementation of this study are depicted in Figure 3.

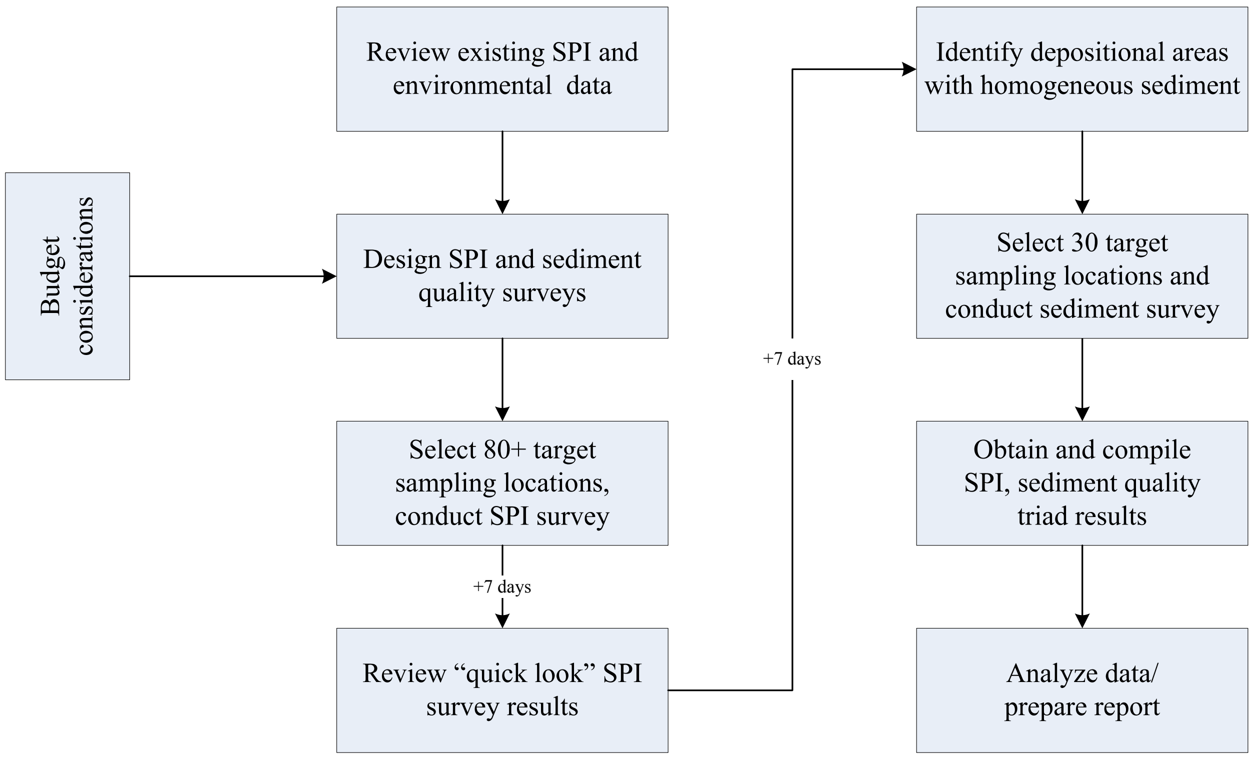


Figure 3. General sequence of events for planning and implementation of the SPI Feasibility Study of the Lower Duwamish Waterway, 2006.

Ecology reviewed goals, resources, and existing environmental data for the study site and decided to conduct two separate sampling events. This decision was based on several considerations. First, combining SPI and sediment quality sampling into a single survey was impractical. SPI surveys acquire images from 5-10 times the number of sampling locations each day as the number of grab samples collected and processed during sediment quality surveys. Conducting two surveys, however, meant it was very important to collect sediment samples soon after the SPI survey was complete and from locations as close as possible to the SPI sampling locations. This helped to ensure sediment samples would represent SPI locations and results.

The second design consideration was to stratify sampling of the study site. This approach was expected to maximize utility of information obtained from a limited number of locations and samples. Ecology chose three sampling strata defined as having a *high*, *moderate*, and *low* probability of exhibiting an altered or impaired benthic community. Areas previously shown to have at least one contaminant or with toxicity exceeding the Cleanup Screening Level (CSL) were designated *high*. Areas with at least one contaminant or with toxicity exceeding the Sediment Quality Standard (SQS) were *moderate* and those having no contaminants or toxicity greater than the SQS were *low* (Ecology, 1995). This was depicted in Figure 5 of the Quality Assurance (QA) Project Plan (Gries, 2006).

Target sediment sampling locations were chosen based on project goals, expected strata boundaries, unequal sample numbers per stratum, and preliminary interpretation of SPI survey images. Target *high* and *moderate* sampling locations were chosen for good spatial coverage within areas expected to contain relatively high concentrations of contaminants. Target l*ow* sampling locations were expected to have chemistry less than the SQS, more typical of sediments found throughout Puget Sound.

A preliminary or "quick-look" interpretation of triplicate SPI images for each SPI sampling location was discussed with and used by the principal investigator to select final target coordinates for collecting sediment quality samples.

Collecting sediment profiles and other images

The SPI survey of this study site was conducted from July 24-26, 2006. Weather and sea state were favorable for sampling and did not adversely affect vessel positioning or image collection. When each target sampling location was satisfactorily attained, Germano and Associates lowered the SPI instrument package at least three times. Precise coordinates and water depth were recorded for each field replicate. The instrument package was configured to collect three types of images of surface sediment: (1) a plan-view video during final descent, (2) a high resolution, plan-view digital still image, and (3) a high-resolution sediment profile image containing both surface sediment and overlying water. These three types of images were collected at each of three field replicate locations.

Triplicate images of the sediment water interface were taken at 85 of 87 final sampling locations. Only duplicate images could be obtained at the remaining two locations. The "quick look" results were used to distinguish locations showing evidence of physical disturbance or spatial heterogeneity from preferred sampling sediment locations that appeared to be depositional and homogeneous.

Members of the Germano and Associates team reviewed all digital images using both image analysis software and professional expertise. Twenty-four SPI parameters were measured, interpreted, and submitted to Ecology as a quality-assured, electronic data package. Findings were summarized and submitted to Ecology as draft and final reports (Germano and Associates, 2007).

The QA project plan for the SPI survey (Germano and Associates, 2006) provides complete descriptions of the methods and procedures used to acquire and interpret SPI and other photographic images of surface sediments at the study site.

Collecting sediment samples

Positioning

Ecology chose 30 primary target sediment quality sampling locations, and several alternates, after the "quick look" review of SPI results and prior to the survey. Two additional locations in Carr Inlet were chosen to serve as reference sample locations for toxicity tests. These were identified as CR-02 and CR-024. The final target sampling coordinates, chosen in the field, were based on the central-most latitude and longitude values from the set of triplicate SPI sample coordinates. These were sometimes obtained from different SPI replicates.

Ecology located target sediment sampling coordinates using a differentially corrected, 12-channel GPS receiver (Leica MX420) mounted on the stern corner of the RV Skookum, combined with a U.S. Coast Guard, land-based beacon differential receiver. The Skookum's GPS unit received radio signals from satellites, and the Coast Guard beacon receiver acquired corrections to those signals.

Ecology recorded the northing and easting coordinates at the moment the van Veen grab closed (e.g., when each sediment sample was collected). Washington State Plane Coordinates, North (NAD 83), were converted into degrees and decimal minutes. The vessel heading (compass bearing) was also recorded so that coordinates could be corrected for a known offset between GPS receiver and winch cable. Positioning accuracy was expected to be ± 1-2 meters, and no worse than ± 3 meters.

The water depth at the sampling location was also recorded and later corrected relative to Mean Lower Low Water using the actual and predicted tidal elevation in Elliott Bay for the same date and time (National Oceanic and Atmospheric Administration and BioMarine Enterprises). Corrected water depth was compared to the similarly-corrected water depth of the corresponding SPI sampling location as a means of verifying the accuracy of vessel positioning.

Additional details on vessel positioning are provided in the QA Project Plan (Gries, 2006).

Sampling

Multiple grabs of surface sediment samples were collected from the surface 10 cm of sediment using a 0.1 m^2 double van Veen grab sampler. Temperature and salinity of near-bottom water was recorded for at least one grab per sampling location. Overlying water was siphoned off the first grab, and a subsample of surface sediment was collected for sulfide analysis using a 60 mL syringe. Most of the remaining sediment was then homogenized manually using a stainless steel spoon or mechanically using an electric drill and stainless steel stirring paddle.

Homogenized sediment was distributed into adequately-sized sample containers made of materials appropriate for each type of analysis. All containers were stored on ice in the field and later transferred to 4°C refrigeration or -20°C freezer units until subsamples could be analyzed. Some surplus sediment was archived at -20°C in case any reanalysis was warranted. Details of sampling, handling, and storage procedures are provided in the QA Project Plan (Gries, 2006).

Only a few field complications and procedural exceptions were noted:

- Numerous attempts to collect surface sediment from target location TRI-002 failed because substrate within the Harbor Island Marina was too hard for adequate penetration of the van Veen sampler.
- The field crew consistently decontaminated the van Veen grab sampler between sampling locations using soap (Liquinox) and a thorough rinse with site water. Rinsing with distilled/deionized water and acetone was inconsistent.
- Grab samples collected from location TRI-004 were 8.5-9.0 cm, slightly less than the minimum recommended acceptance depth (10 cm).

Measuring sediment quality

Conventionals

Ecology's Manchester Environmental Laboratory (MEL) measured total solids and total organic carbon (TOC) in the 30 surface sediment samples, one field duplicate collected from the waterway, and the two samples collected from Carr Inlet. Analytical Resources, Inc. (ARI) measured total solids, grain size distribution, ammonia, and sulfide in the same samples. The analytical methods used were described in the QA Project Plan (Gries, 2006) and were consistent with the Puget Sound Estuary Protocols and Guidelines (EPA, 1986 and updates).

No substantial problems associated with results for the conventional parameters were found, and all data were found usable without qualification. There were two minor issues noted:

1. The average total solids measured by MEL and ARI differed by approximately 3%. This was probably caused by slightly different oven temperatures, and the MEL results were used in all analyses.

2. All results for field duplicate were very similar for conventional parameters except sulfide. The concentration of sulfide measured in one TRI-052 field duplicate was nearly 50% greater than the sulfide measured in the other. This was likely due to real spatial heterogeneity, so all sulfide results were deemed acceptable without qualification. Field duplicate results were averaged for all samples, conventional parameters, and analyses except for the sulfide measured for location TRI-052. Only the sulfide concentration measured in the benthic community field replicate was used for analysis of relationships between sediment characteristics and benthos.

Contaminant chemistry

MEL measured the chemicals listed in the Sediment Management Standards (SMS) (Ecology, 1995) in surface sediment samples collected from 30 Duwamish and two Carr Inlet reference samples. Table B-1, Appendix B, lists the analytical methods used. This table also cites the methods used for sample preparation, cleanup, and analysis. Finally, it provides the maximum reporting limits needed to meet Ecology's Toxics Cleanup Program data quality objectives (DQOs).

Volatile organic compounds (VOCs) and organochlorine pesticides, sometimes measured for Dredged Material Management Program projects, were not analyzed because recent remedial investigations seldom found detectable quantities of these classes of chemicals in surface sediment samples (Windward Environmental, 2005b, 2005c).

MEL measured the SMS contaminants and organotins with only two issues of note. The first was that reporting limits for N-nitrosodiphenylamine (approximately 100 µg/kg dry weight) routinely exceeded the DMMP screening level (28 µg/kg dry weight). However, all samples contained enough total organic carbon that the SQS value of 11 mg/kg organic carbon was never exceeded. The second issue concerned the % recovery of Aroclor PCBs from various quality assurance samples. Recoveries were almost always within control limits, but were often lower than what MEL has routinely achieved. For this reason, MEL elected to qualify all PCB results as estimated values. Neither issue was considered problematic for the goals of the project.

Toxicity

Sediment toxicity in the 30 test and two reference samples was assessed by Weston Solutions, Port Gamble, using two laboratory protocols common to regional sediment regulatory programs. The protocols, described in the QA Project Plan (Gries, 2006), are based on regional guidance documents (EPA, 1995) and periodic updates (DMMP, 1990-2005).

The first test measured survival of *Eohaustorius* sp. after a 10-day exposure to Lower Duwamish Waterway surface sediments, with results reported as % mortality relative to one of two Carr Inlet reference sediments.

The second toxicity test exposed *Dendraster* sp. larvae to test sediment mixed with a proportionally large volume of saline water, simulating near-bottom conditions. Larvae that were both normally and abnormally developed were counted after 48-96 hours, and the total % of dead and abnormal larvae were reported relative to the same endpoint observed in the Carr Inlet reference samples.

A third toxicity protocol commonly used in regulatory programs to assess chronic effects--the juvenile polychaete (*Neanthes arenicola*) 28-day growth test--was not conducted. Previous investigations on the Lower Duwamish Waterway site (Windward Environmental, 2005b, 2005c) rarely showed significant toxicity that was not also indicated by the other two test protocols.

Test organisms in all batches of the two toxicity tests conducted were found to be acceptably responsive to reference toxicants. In addition, water quality parameters monitored during these exposures generally met all quality assurance requirements. A few exceptions were noted during or at the conclusion of amphipod tests. Three temperatures exceeded the acceptable range ($15^{o}C \pm 1^{o}C$) but did not exceed $16.6^{o}C$. A final salinity of 31‰, that exceeded the recommended range of 28‰ ± 1‰, was recorded in five samples. These water quality exceptions were not likely to have affected test results. All toxicity test samples were grain size-matched to one of the two reference samples collected in Carr Inlet for interpretation of results.

Benthic community characteristics

Ecology collected surface sediment for analysis of the *in situ* benthic communities found at the 30 Lower Duwamish Waterway and two Carr Inlet locations. All surface sediment collected in one side of a double van Veen grab sampler was placed in a plastic tub and transferred slowly to a 1.0 mm mesh screen. A gentle stream of strained site water was then used to wash smaller particles and organisms through the screen and collect primarily the macrobenthic infaunal organisms. The larger debris and organisms were then placed in one-gallon zip-lock bags and preserved with a solution of approximately 10% formalin. Samples were transferred to Dr. Allan Fukuyama (Fukuyama/Hironaka Taxonomic & Environmental Services). He was responsible for sorting the samples into subsamples containing organisms belonging to the major taxonomic groups, and sending them to marine benthic taxonomic specialists for identification and counting.

The methods used to collect and analyze benthic community samples were generally consistent with QA Project Plan requirements (Gries, 2006) and with methods used in recent cleanup investigations (Windward Environmental, 2004). Sorting and taxonomic identifications involved some of the same benthic experts. However, samples represented a smaller surface area and volume of sediment and only those organisms retained on a 1.0 mm mesh sieve.

Established formulae and corresponding algorithms developed by the Marine Sediment Monitoring Program (Ecology, 1998) were used to calculate 15 benthic community metrics for each sampling location:

- Total abundance (total number of organisms)
- Abundance of three major taxonomic groups having regulatory relevance
  - Annelida (Polychaeta)
  - Crustacea
  - Mollusca
- Abundance of Echinodermata and miscellaneous taxa
- Total taxa richness (number of different taxa identified)
- Taxa richness for all five major groups
- Swartz Dominance Index (SDI - the minimum number of taxa needed to make up 75% of total abundance at a sampling location)
- Sample diversity (Shannon-Weiner H’)
- Sample evenness (Pielou’s J’)

The Shannon-Weiner diversity index H' was calculated as:

$$H' = -\sum_{i=1}^{s} p_i \log p_i$$

where p_i is the proportion of the assemblage that belongs to the ith taxa (number of individuals in taxonomic group "i" / total number of individuals), and s = the total number of taxa identified.

Pielou's evenness J' was important because ... It was calculated as a proportion of the maximum possible diversity for the entire data set:

$$J' = H'/\log s$$

Benthic community samples were collected from all locations except TRI-002 (as noted above). The benthic community sample collected from TRI-004 represented only the top 8.5-9 cm of sediment. Otherwise, there were notable deviations from the planned methods. First, the formalin solution used to preserve some Lower Duwamish Waterway benthic samples was prepared using freshwater instead of saline site water. This error was only discovered after the first batch of 10 was preserved and prior to preparing the second volume of formalin. In addition, the average number of days between field sample preservation and the subsequent rescreening and transfer into ethanol was 22 days (maximum 34 days), longer than the recommended agency guidance of one week.

Managing and analyzing data

Data entry and management

Data for sediment conventionals were obtained from MEL and the private vendor electronically (in approximate Environmental Information Management (EIM) format) and as printed reports. The data were manipulated as required for analysis using SEDQUAL 5.1, statistical software (Systat 11.0/12.0), and ArcView 9.2. Private vendors provided Ecology with benthic community data in an electronic format that was readily modified to meet analytical needs. All of the electronic data submittals were also modified, as needed, for entry into Ecology's EIM system. The principal investigator evaluated the accuracy of importing or transferring analytical results into spreadsheets and databases. This was done by randomly selecting 25% of the sediment samples (6) and performing a check for 100% accuracy for all data types.

Data quality and usability

The SPI experts performed a quality assurance review of SPI data (Germano and Associates, 2007) and determined that the data all met or exceeded requirements of the SPI QA Project Plan (Germano and Associates, 2006). Certain SPI parameters could not be determined or calculated for some samples or replicates, but this had little effect on analyses.

An initial review of data quality was performed by various laboratory personnel involved in the project. This was followed by a separate QA review conducted by the principal investigator, according to Gries (2006) and Ecology (2004, 2005), and with assistance from Ecology's QA officer. Results of the QA review are summarized below and in Table B-2, Appendix B. Virtually all data collected were found to be usable for the stated goals and objectives of this project.

Sediment samples were collected in a manner believed to be representative of SPI locations and results.

- The sediment survey followed the SPI survey by less than one week.
- Vessel positioning relative to final SPI coordinates was generally excellent.
- Sampling locations were chosen based on "quick look" SPI results showing homogeneous surface sediment.
- Sampling procedures generally followed those described in the QA Project plan.

Very few analytical results for sediment conventionals or contaminant chemistry required qualification, and none were deemed unusable. Substantially different results for sulfide in field duplicates could be explained by spatial variability. Reporting limits for N-nitrosodiphenyl-amine analyses exceeded the one required in the QA Project Plan but did not affect regulatory interpretation of results. All results for total Aroclor PCBs in sediment samples were qualified as estimated values by MEL but usable for analytical purposes because quality assurance sample recoveries seldom exceeded control limits.

There were no notable quality assurance exceptions or issues associated with the sediment toxicity results. Quality assurance guidelines (test protocols, exposure conditions, species sensitivity) were met, and all results were interpretable.

One batch of formalin was prepared using freshwater, and some sample exposures to the preservative exceeded recommendations. However, these potential problems did not appear to have a detrimental effect on the taxonomist's ability to identify organisms to the desired level (Table B-3, Appendix B). Information provided by the taxonomic experts about sorting benthic community samples, identifying the various taxa, and counting organisms indicated that all quality assurance requirements were met (Table B-4, Appendix B).

Data analysis

Ecology used different approaches and statistical methods to examine the relationships between different categories of data, as well as results for individual parameters (Figure 4). Most statistical analyses were performed using Systat 11.0/12 .0 (Systat Software, Inc, 2004). TerraStat Consulting Group used S-PLUS 2000, Professional Release 3, to independently conduct certain statistical analysis.

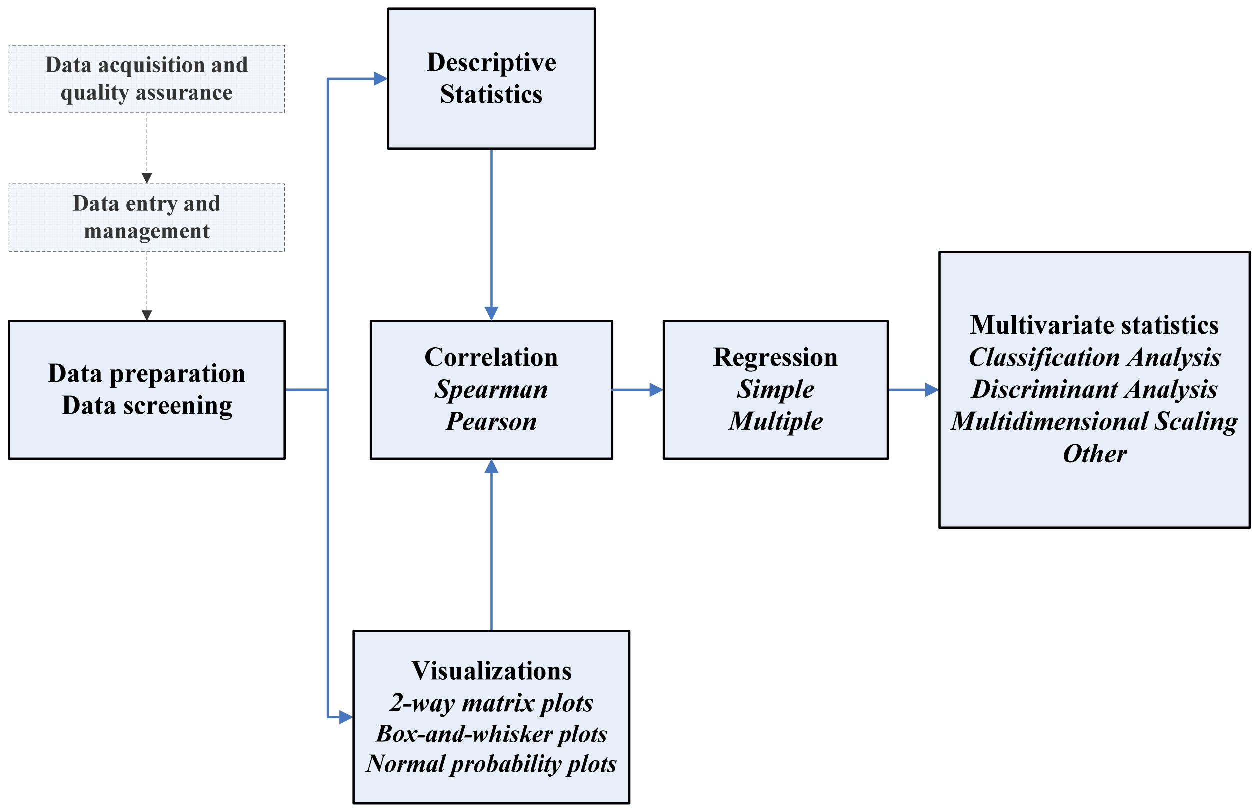


Figure 4. General scheme for preparing, screening, and analyzing SPI, sediment conventionals, and benthic community data collected for the Lower Duwamish Waterway study site.

The principal investigator carefully reviewed the Port Gamble Bay data set before conducting extensive statistical analyses (Figure 4). Potential outlier values were identified by examining:

- Descriptive statistics, Tables C-1 through C-5, Appendix C.
- Two-way matrix plots, Figures D-1, Appendix D.
- Box-and-whisker plots, Figure D-2, Appendix D.
- Normal probability plots, Figure D-3a-c, Appendix D.

Table D-1, Appendix D, summarizes potential outliers, those removed from analysis, and reasons for their removal.

Data distributions were examined using normal probability and other types of plots (Figures D-3a-c, Appendix D), as well as statistical tests for normality such as Shapiro-Wilk. Results are summarized in Table D-2, Appendix D. Variables of all types were identified that had only a limited range of values and therefore less likely to be analytically useful. Missing values and their likely analytical implications were also identified.

After screening the results, the range of values for each parameter was determined and median values were used to describe the *typical* sampling location. A description of spatial distributions, north-to-south gradients, and other obvious patterns was then prepared. These were useful for comparisons to past results, for understanding and interpreting overall results, and for planning statistical analyses.

Spearman rank correlation analysis was used to assess potential linear or nonlinear relationships between two variables. Significant correlation coefficients (rho), Table D-4, Appendix D, were one basis for reducing the list of variables used in the subsequent analyses. Regression analysis was used to probe for relationships between individual SPI parameters (independent variables), individual benthic community metrics, and sediment conventional parameters (dependent variables). Data were transformed when necessary to achieve a linear relationship, usually by means of a square root, fourth root or $\log_{10}$ transform. The lack of simple relationships between SPI and benthic community data led to the multivariate phase of analysis.

Multivariate statistical methods focused on cluster analysis and multidimensional scaling with benthic infauna results to identify related groups of sampling locations that could be considered unique benthic communities. SPI and sediment quality results were then used in discriminant analysis to identify the factors that could explain the differences between the communities. Classification trees were also explored as a means of predicting the sampling locations belonging to each benthic community identified.

Mean values for distinct groups of sampling locations were compared using box-and-whisker plots, a two-sample Student's t-test or the non-parametric Mann-Whitney test, depending on distribution of residuals.

Contaminant chemistry and toxicity results were compared to 2004-2005 results to confirm preliminary sampling strata. These comparisons took the form of contingency tables that could be evaluated using the Chi square or Kendall's coefficient of concordance.

Results

SPI survey results

Underwater digital video, plan-view, and replicate SPI images were collected at 87 sampling locations in the Lower Duwamish Waterway between July 24-26, 2006. Target coordinates and latitude and longitude values where all images were taken are presented in Germano and Associates (2007). Target coordinates at 19 of the 87 SPI sampling locations could not be attained due to the presence of an obstructing barge, boat, bridge, or pier. Positioning accuracy for the remaining 68 sampling locations was excellent, with the distance between the target and the actual coordinates averaging approximately 1.4 meters (4.6 feet).

The digital plan-view still photographs were more successful for assessing physical disturbance and homogeneity of surface sediments at each location than were the plan-view video images (Germano and Associates, 2007). The clarity of video images at the Lower Duwamish Waterway was often poor because of the native turbidity of this active waterway and residual turbidity from the instrument package contacting with the bottom.

Germano and Associates encountered no substantial difficulties taking the sediment profile images, and all data that could be derived from them were usable. Some parameters, such as RPD or feeding void depths, could not be measured or calculated for a few samples or replicates. However, this lack of certain SPI results did not hinder subsequent data analysis.

Preliminary SPI results were discussed with the principal investigator the following week, and sediment sampling locations most suitable to project goals were recommended. Images that indicated erosion processes or surface heterogeneity were generally excluded from consideration as target sediment quality sampling locations. The rest of this section summarizes SPI results for the 30 sampling locations where Ecology collected sediment quality samples, those most salient to this study. "Quick look" and final SPI results for all 87 sampling locations, together with summary interpretations and conclusions, can be found in the final SPI survey report (Germano and Associates, 2007).

Ecology collected sediment samples from 30 of the SPI locations that appeared to be depositional and superficially homogeneous, Table C-1, Appendix C. Some of the quantitative SPI parameters from the resulting subset of data--ones that could easily be summarized from triplicate images and that exhibited a good range of values--are presented in Table 1.

Median values listed in the table were used to characterize the typical SPI sampling location--one where the camera prism penetrated 16.6 cm into the surface sediment, the boundary roughness (difference between minimum and maximum penetration) was 1.35 cm, and the RPD was just under 3 cm. Locations with sediments dominated by silts were more common than sandy ones, but some locations showed layering of sands on silts. The typical location also had two small tubes and nearly 10 burrows present, with the deepest feeding voids 10.4 cm below the surface. The summed number of voids, small tubes, and burrows was 13.3. The Organism Sediment Index and Benthic Habitat Quality Index values were about 8.8 and 11.2, respectively.

The SPI vendor reported many other SPI parameters often important for characterizing the sediment, benthic habitat, and successional stage of the *in situ* community. These included grain size (minimum, maximum, and major mode), information about dynamics/physical disturbance, presence of bacterial mats, presence and state of mudclasts, bedforms, indication of low dissolved oxygen, presence of methane bubbles, presence of fecal pellets, number of large tubes (> 2mm), number of oxic voids (shallow and deep), and presence of infauna. Results for these parameters were less analytically useful because the range of values was limited or some values were missing.

Table 1. Summary of selected SPI measurements for up to 30 sampling locations in the Lower Duwamish Waterway.

	Penetration depth (cm)	Boundary roughness (cm)	RPD depth (cm)	Voids maximum depth (cm)	Number of small tubes	Number of burrows	VTB	OSI	BHQI
Minimum	11.0	0.65	0.75	3.7	0.3	3.3	6.3	5.3	8.3
Median	16.6	1.35	2.9	10.4	2.0	9.7	13.3	8.8	11.2
Mean	16.2	1.5	2.9	10.0	2.9	8.8	13.0	8.9	11.0
Maximum	20.1	3.6	5.4	16.3	10.3	12.0	18.0	11.0	13.3
Range	9.1	3.0	4.6	12.6	10.0	8.7	11.7	5.7	5.0
Sample Number	29	30	30	26	29	29	29	30	30

Boundary roughness = maximum minus minimum penetration depth for each replicate image.
RPD = redox potential discontinuity depth.
VTB = total number of voids, small tubes, and burrows per replicate.
OSI = Organism Sediment Index (See Germano and Associates, 2006).
BHQI = Benthic habitat quality index (Nilsson and Rosenberg, 1997).

The above description of a typical sample does not address any spatial patterns or grouping of sampling locations having similar SPI results. Subjective examination of SPI results for the sediment sampling locations alone revealed the following patterns or trends.

- Boundary roughness at sediment sampling locations increased slightly from north to south, but with some exceptional samples.
- 7 sampling locations--from TRI-045 through TRI-066 (Figure 5, shaded bars)--had deeper mean RPD values than all but one other location.
- Sandier sediments were observed among the most northerly locations or between river miles 2.5-2.9 (Germano and Associates, 2007).
- The number of voids declined southward from a point between TRI-066 and SPI-125.
- Mean OSI and BHQI values were generally high (8.9 and 11, respectively) with only nine SPI sampling locations having an OSI < 7 for all triplicate images.

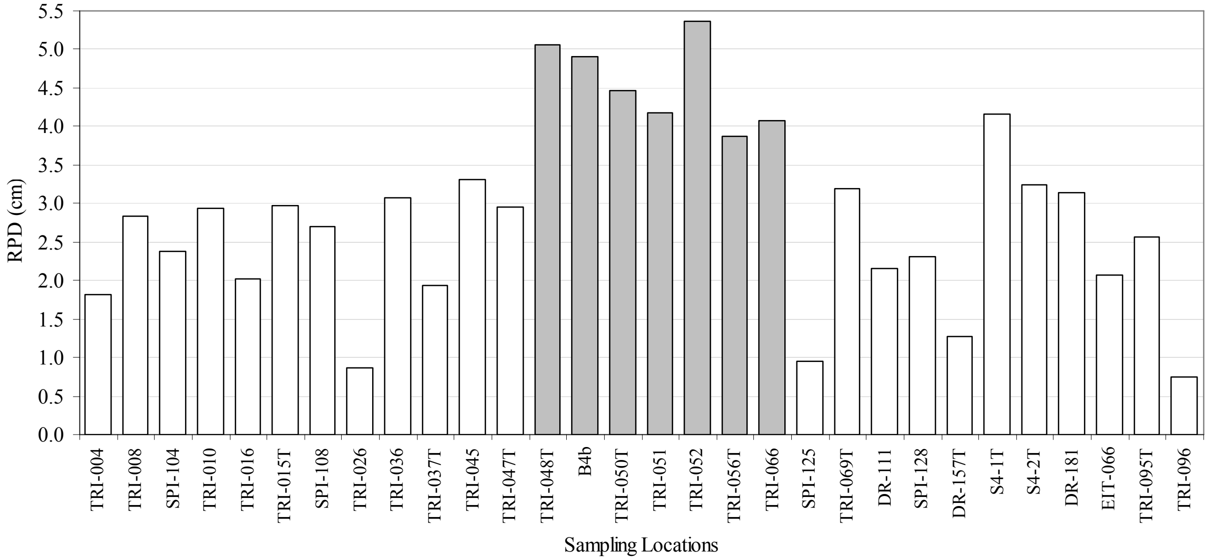


Figure 5. Mean Redox Potential Discontinuity (RPD) depth for Lower Duwamish Waterway sampling locations ordered from north (left) to south (right).

Figure 6 shows that mean values for prism penetration depth, RPD depth, number of small tubes, number of burrows, total number of voids, tubes and burrows (VTB), OSI, and BHQI all decreased from the *high* to *moderate* to *low* strata. Boundary roughness tended to decrease in the same progression. Only the number of small tubes and VTB of the *high* and *low* strata were significantly different.

SPI results for this project indicated a fairly narrow range of sediment types and structures within the study site, and do not seem to indicate benthic habitats and functions that are clearly impaired. The evidence for the latter claim includes:

- Few sampling locations had strong SPI evidence of severely depleted dissolved oxygen (shallow RPD, presence of methane bubbles, little or no bioturbation).
- Stage III organisms (Figure 2) are present and bioturbate the sediment to a reasonable depth at almost all locations that accumulate sediment.

The SPI experts identified 12 of the 30 sampling locations in this study as showing evidence of disturbance that could translate into impaired benthic communities. Seven of these locations were likely disturbed due to pollution exposures. These are listed in Germano (2007) and again in Table 11.

See Germano and Associates (2007) for detailed SPI survey results and conclusions.

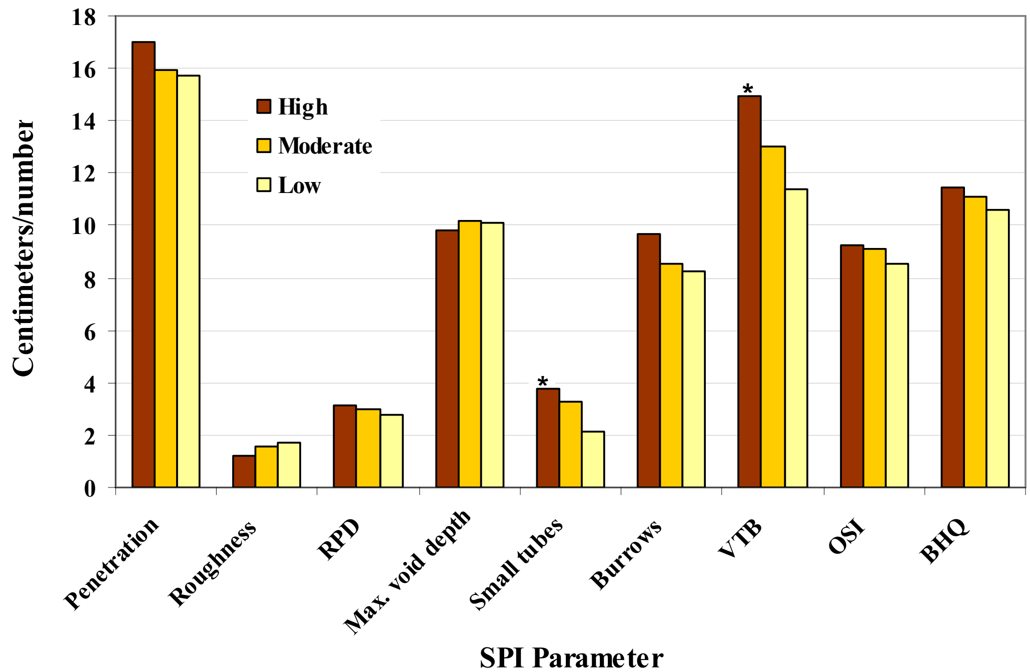


Figure 6. Mean values for selected SPI parameters, displayed by preliminary Lower Duwamish Waterway sampling strata. * = $p < 0.05$

Sediment quality survey results

Field survey

Ecology conducted the sediment quality survey of the Lower Duwamish Waterway study site on August 8-11, 2006. Weather and sea state were favorable--wind was generally from the west or west-northwest at less than 5 knots--and did not hinder vessel positioning or sampling at 30 locations. Two reference locations in Carr Inlet were sampled on August 14, also under favorable conditions. Table A-2, Appendix A, and Figure 7a-c show all target and final coordinates.

Water depth was recorded for each sampling location at the moment a grab sample was collected, in part to provide additional evidence of good positioning accuracy. Measured depth was then corrected for measured tides in Seattle and compared with the similarly tide-corrected water depth reported by the SPI survey navigator (C. Eaton, personal communication). The average difference between the two corrected depths was less than 2.4, feet greater than expected given the accuracy of positioning. This depth difference might have been real for a few samples collected in sloping areas. However, the average discrepancy was more likely due to comparing calibrated cable depths from one vessel to uncalibrated cable depths or to depth finder readings from the other vessel.

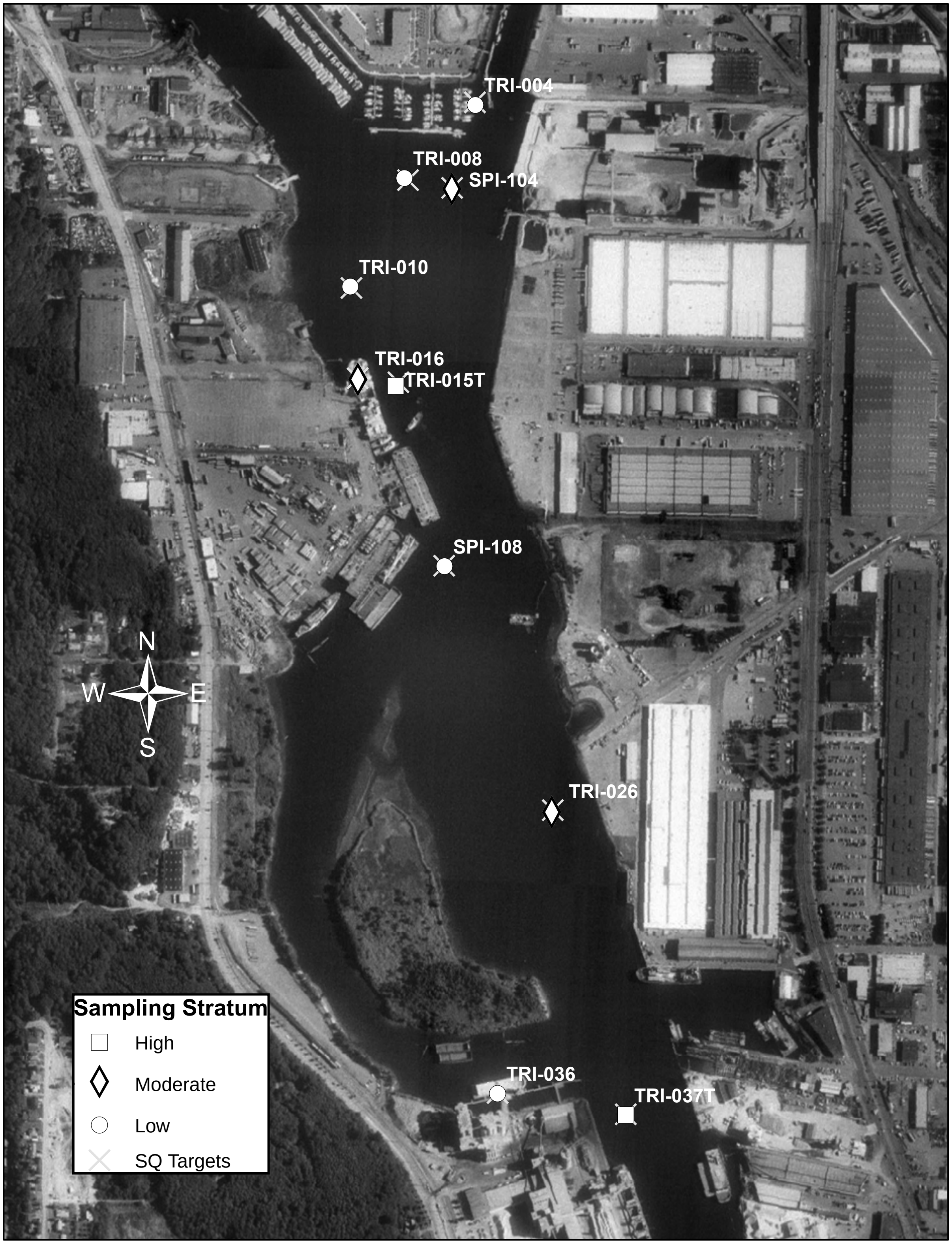


Figure 7a. Target and actual sediment quality triad sampling locations between river miles 0.0 – 1.2 (approximate) in the Lower Duwamish Waterway, SPI Feasibility Study 2006.

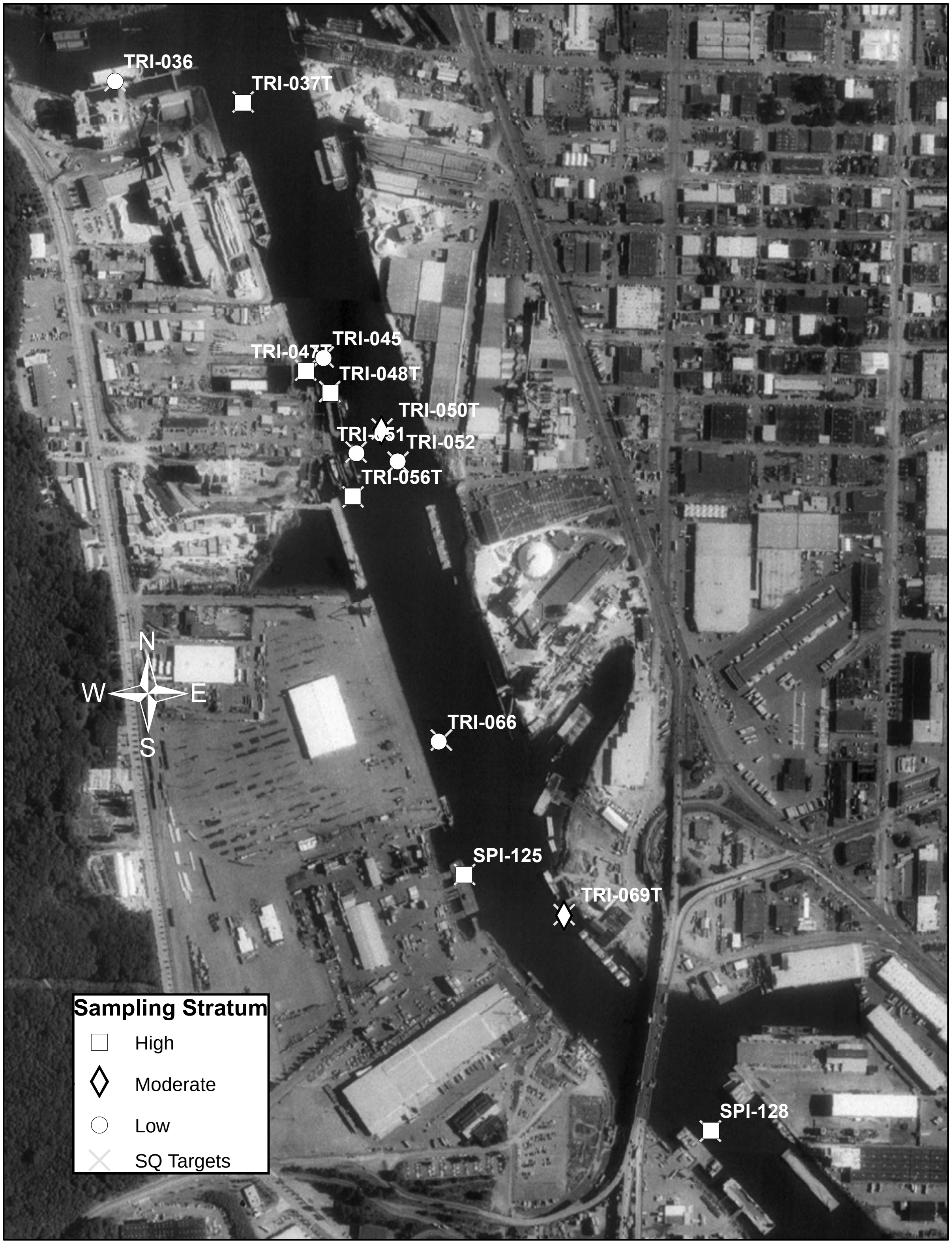


Figure 7b. Target and actual sediment quality triad sampling locations between river miles 0.9 – 2.2 (approximate) in the Lower Duwamish Waterway, SPI Feasibility Study 2006.

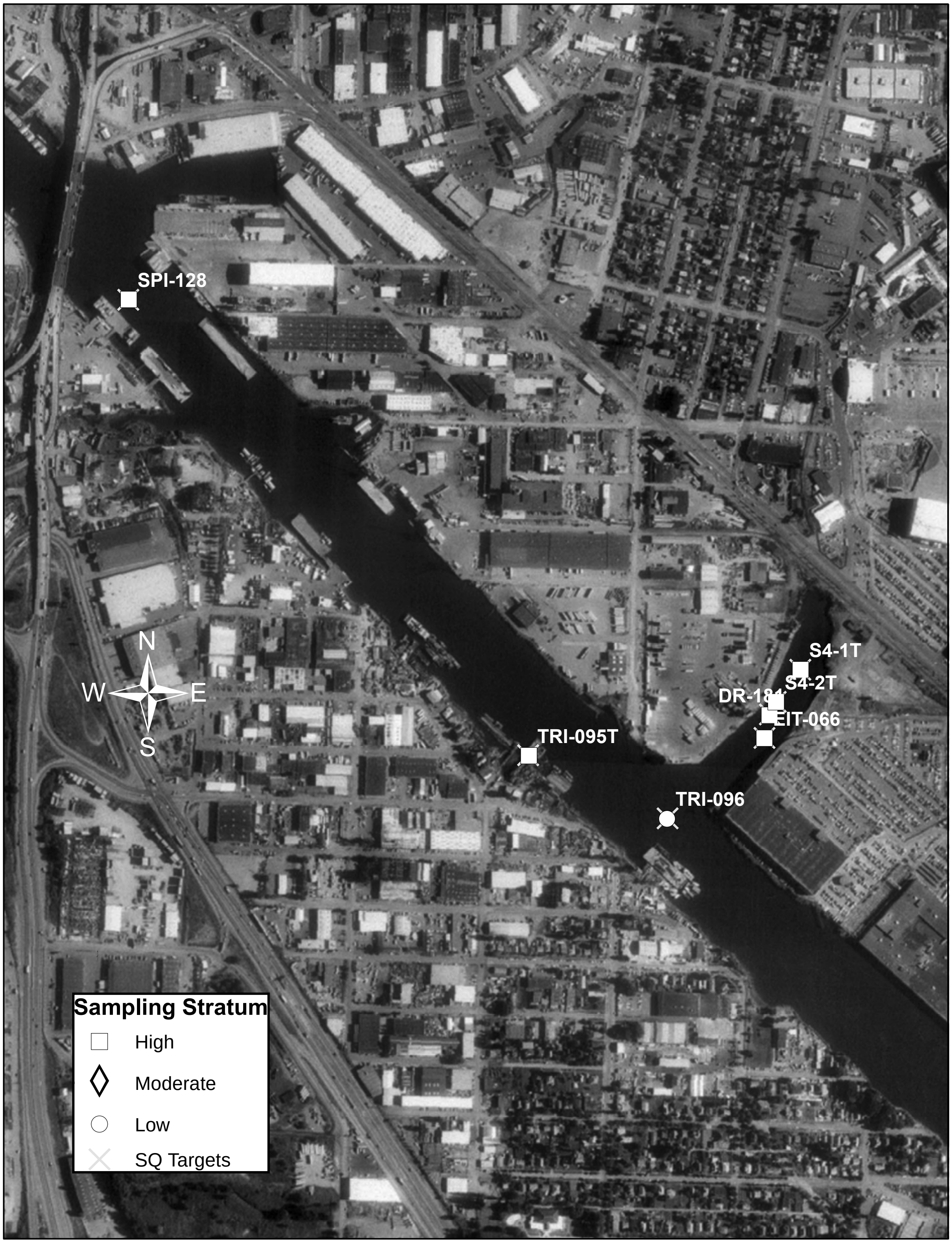


Figure 7c. Target and actual sediment quality triad sampling locations between river miles 2.0 – 3.0 (approximate) in the Lower Duwamish Waterway, SPI Feasibility Study 2006.

Field measurements and notes collected at most of these locations included water temperature, salinity, organic sheen observed, and odors detected. The water depth and salinity of sampling locations decreased slightly from north to south (upstream), while overlying water temperature remained fairly constant at 14-17^{o} C (Figure 8). A notable sheen was observed at 13 sampling locations.

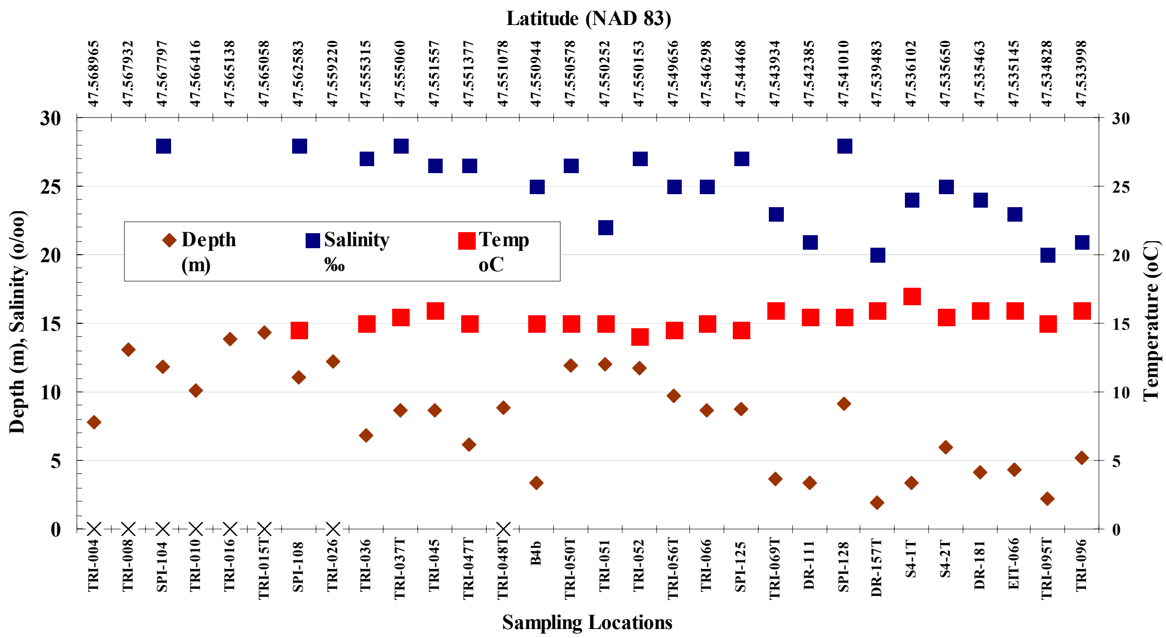


Figure 8. Sample location depth (m), bottom water salinity, and temperature in the Lower Duwamish Waterway, August 8-11, 2006. 'x' indicates a missing data point.

Sediment conventionals

Table 2 summarizes results for sediment conventional parameters, with more complete results presented in Table C-2, Appendix C. The typical sample, as characterized by the median values, had about 46% solids, 24% sand, 76% fines, 2.4% organic carbon, 15 mg/kg ammonia, and nearly 800 mg/kg sulfides. The sandiest sampling locations were SP-108, B4b, SP-128, DR-157T, and TRI-096. Organic carbon was lowest at SP-108, TRI-026, DR-157T, and TRI-96 and tracked well with % fines. Only one location had a sulfide concentration less than 200 mg/kg dry weight (TRI-056T). Sulfide concentrations were in the range of 1,000-1,500 mg/kg dry weight at locations TRI-004, TRI-008, TRI-010, TRI-36, TRI-37, SPI-125, DR-111, SPI-128, DR-157T, and EIT066, and an order of magnitude higher at location S4-1T. The only possible trend detected was in % clay, which appeared to decrease as sampling progressed upstream (north to south direction, Figure 9).

Table 2. Summary of sediment conventionals data for the Lower Duwamish Waterway study site. Complete data can be found in Appendix D.

	Total Solids (% ww)	Sand (% dw)	Silt (% dw)	Clay (% dw)	Fines (% dw)	Total Organic Carbon (% dw)	Ammonia (mg/Kg dw)	Sulfide (mg/Kg dw)
Minimum	38.2	10.5	34.5	7.0	41.5	1.55	5.6	156
Median	45.9	24.4	55.8	18.3	75.7	2.45	15.2	786
Mean	46.4	25.4	56.4	17.6	74.0	2.47	16.1	1230
Maximum	56.4	57.1	70.3	26.1	88.7	3.22	37.9	14100
Range	18.2	46.6	35.8	19.1	47.2	1.67	32.3	13944
Sample number	30	30	30	30	30	30	30	30

dw = dry weight basis, ww = wet weight basis

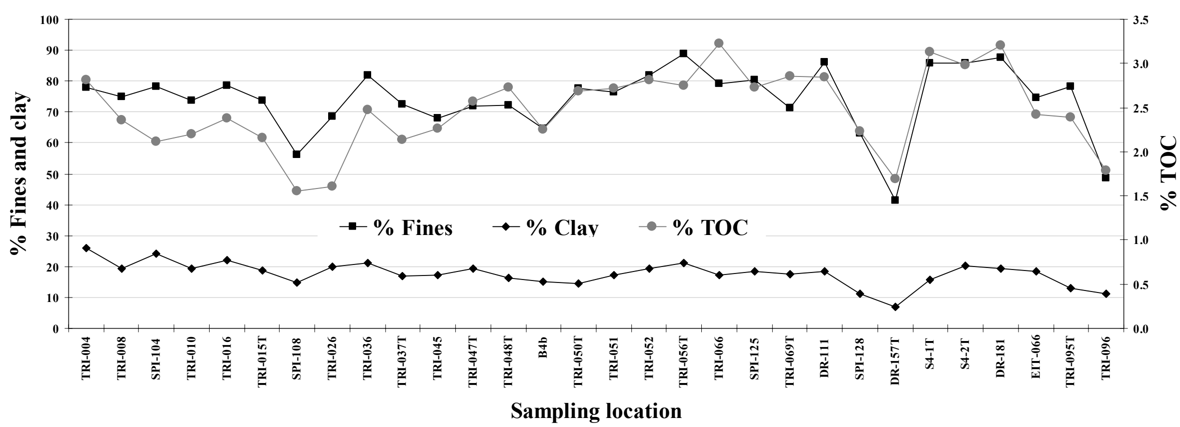


Figure 9. North-south distribution of selected conventional parameters in surface sediments of the Lower Duwamish Waterway.

Contaminant chemistry

Table 3 and Table 4 summarize concentrations of 10 trace metals, TBT, and various organic contaminants measured at the 30 sampling locations in the Lower Duwamish Waterway, along with the mean concentrations measured at two locations in Carr Inlet. A more complete summary can be found in Table C-3, and complete results are available upon request.

The typical sample from the Duwamish, as characterized by median values, did not exceed the SQS but did contain nearly 400 mg/Kg of the ten trace metals measured and 36 µg/Kg of TBT ion. Average concentrations of metals were often 2 times to more than 10 times greater than those found at reference sample locations (except for cadmium, copper and nickel).

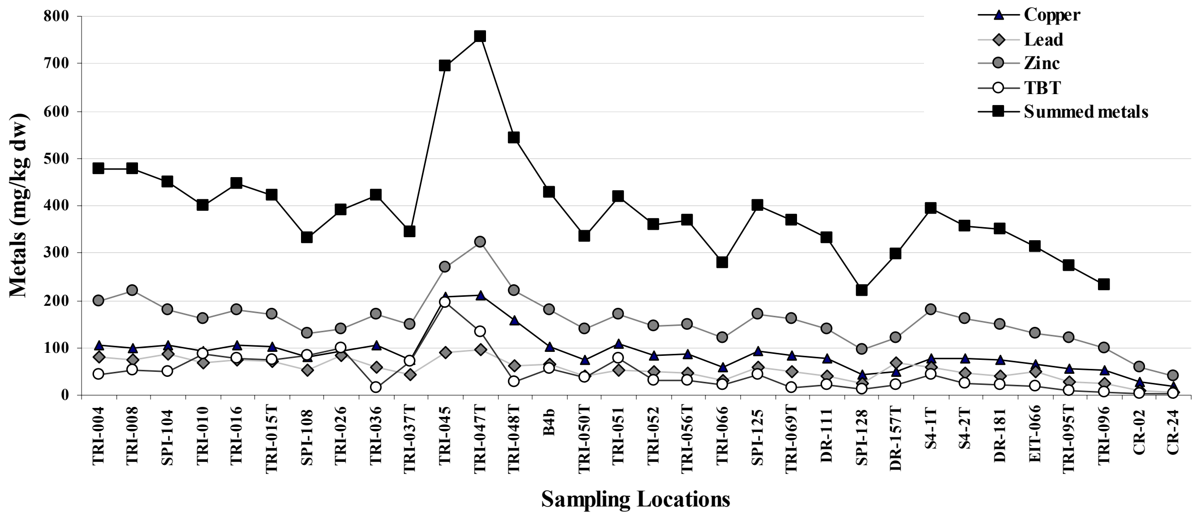
Table 3. Summary of sediment metals results for 30 samples collected from the Lower Duwamish Waterway and two reference samples collected from Carr Inlet.

	Antimony	Arsenic	Cadmium	Copper	Chromium	Lead	Mercury	Nickel	Silver	Zinc	ΣMetals	TBT+
Minimum	0.20	10.3	0.31	44.5	24.1	23.3	0.10	18.1	0.15	96.0	220	5.1
Median	0.31	14.9	0.58	86.0	36.8	55.5	0.25	26.6	0.37	160	381	36
Mean	0.74	17.3	0.59	93.4	36.0	57.2	0.28	25.6	0.43	165	396	45
Maximum	7.40	52.1	0.83	210	48.0	96.3	0.55	28.7	1.20	324	756	174
Range	7.20	41.8	0.52	166	23.9	73.0	0.46	10.6	1.05	228	536	169
Sample number	30	30	30	30	30	30	30	30	30	30	30	30
Reference mean (n=2)	0.20	4.3	0.50	22.0	30.4	7.1	0.04	33.5	0.12	50	148	2.9

Units are mg/Kg dry weight for all metals. Tributyltin ion concentration units are µg TBT+/Kg (converted from TBT chloride reported by MEL).

The average concentrations for individual metals were very similar to those reported for a much larger set of 2005 results, but the ranges were narrower (Windward Environmental, 2005b, 2005c). The average TBT ion concentration was lower than reported in 2005, but this may be an artifact of different sampling strategies.

Results of this study showed sampling locations just north of river mile 1.4 (TRI-045, TRI-047T, TRI-048T, B4b) had obviously higher concentrations of antimony, arsenic, cadmium, copper lead, silver, zinc, and the sum of all ten metals (Figure 10). Mercury concentrations at the northern-most six sampling locations (TRI-004, TRI-008, SPI-104, TRI-010, TRI-016, and TRI-015T) averaged nearly twice those found elsewhere. Except for TRI-036, concentrations of tributyltin ion (TBT+) averaged 93 ug/kg dry weight of sediment at sampling locations between River Mile 0.2 and RM 1.3 (TRI-010 to TRI-047T). This was 3 times the average concentration measured south of this portion of the waterway (29 ug/kg).



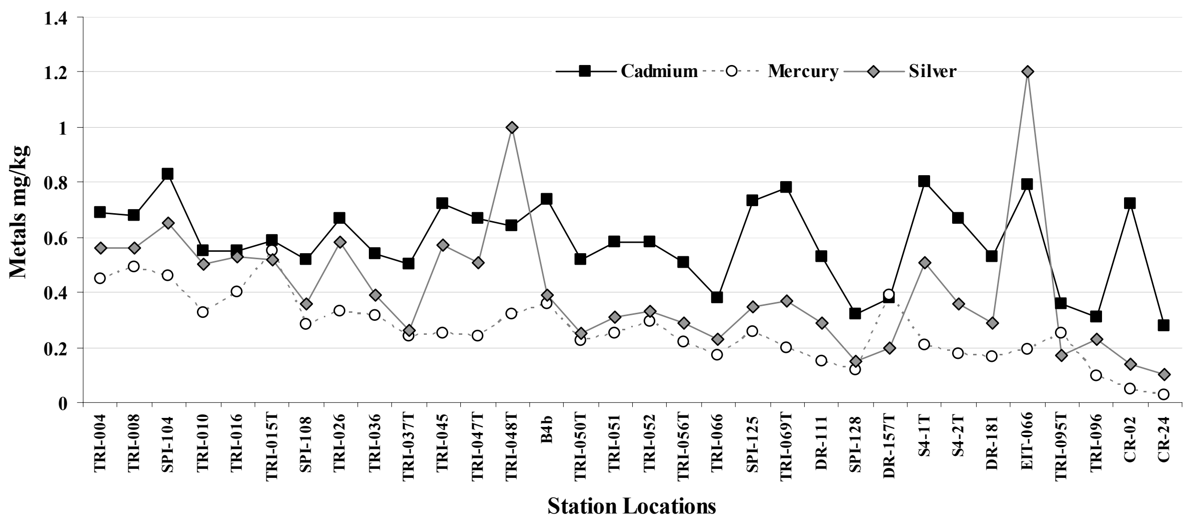


Figure 10. North-south distribution of four individual metals and the sum of ten trace metals (upper plot) as well as cadmium, mercury, and silver (lower plot) measured in the Lower Duwamish Waterway.

The typical Duwamish sample also contained 3,700 µg/Kg of total PAHs, more than 200 µg/Kg of total Aroclor PCBs, and almost 200 µg/Kg of phenol compounds (Table 4). The median value for total concentration of detected phthalates (64 ug/kg) was more uncertain because many of the individual compounds were not detected at relatively high detection levels. Median concentrations of total PAHs and PCBs in the waterway were 175 times and nearly 20 times the corresponding averages for the reference locations, respectively. The median for total phenols in the waterway was approximately 2-4 times what was found in Carr Inlet. Phthalate compounds were not detected in Carr Inlet.

Table 4. Summary of organic sediment contaminants measured in 30 samples collected from the Lower Duwamish Waterway and two Carr Inlet reference samples.

	LPAH	HPAH	TPAH	PCBs	Phthalates	Phenols	2,4-dimethyl phenol	Benzoic acid
Min	110	1000	1100	97	20	69	44	110
Median	580	3200	3700	210	64	190	52	160
Mean	850	4100	5000	410	240	250	56	160
Max	4500	13000	17000	3200	1300	760	79	280
Range	4400	12000	16000	3100	1300	690	35	170
Sample #	30	30	30	30	24	30	24	29
CR-02	u	20	20	12	u	81	u	130
CR-24	u	22	22	u	u	46	u	u

Results reported to two significant digits, u = undetected at reporting limit.

As was observed for the metals, the average concentrations for most of the summed organic contaminants were similar to those reported earlier (Windward Environmental, 2005b, 2005c). The ranges of values were again narrower. The average concentrations of some individual phenol compounds were notably different between this study and the surveys conducted in 2005. 2,4-dimethyl phenol was often measured at concentrations exceeding SQS and CSL levels in this study, but was never detected in 2005. In contrast, diethyl phenol and dimethyl phenol were not detectable in this study but were measured in 2005. The sum of all SMS phenol compounds appeared similar in both years.

Figure 11 shows that concentrations of total Aroclor PCBs were greatest at locations in or near Slip 4 (EIT-066, DR-181, S4-1T, S4-2T, DR-157T) and at one location slightly downstream (TRI-069T). Total PAHs did not show any obvious pattern of distribution, although some of the locations with the highest concentrations were near Slip 4. There was no discernable north to south trend for either phthalate or phenol compounds.

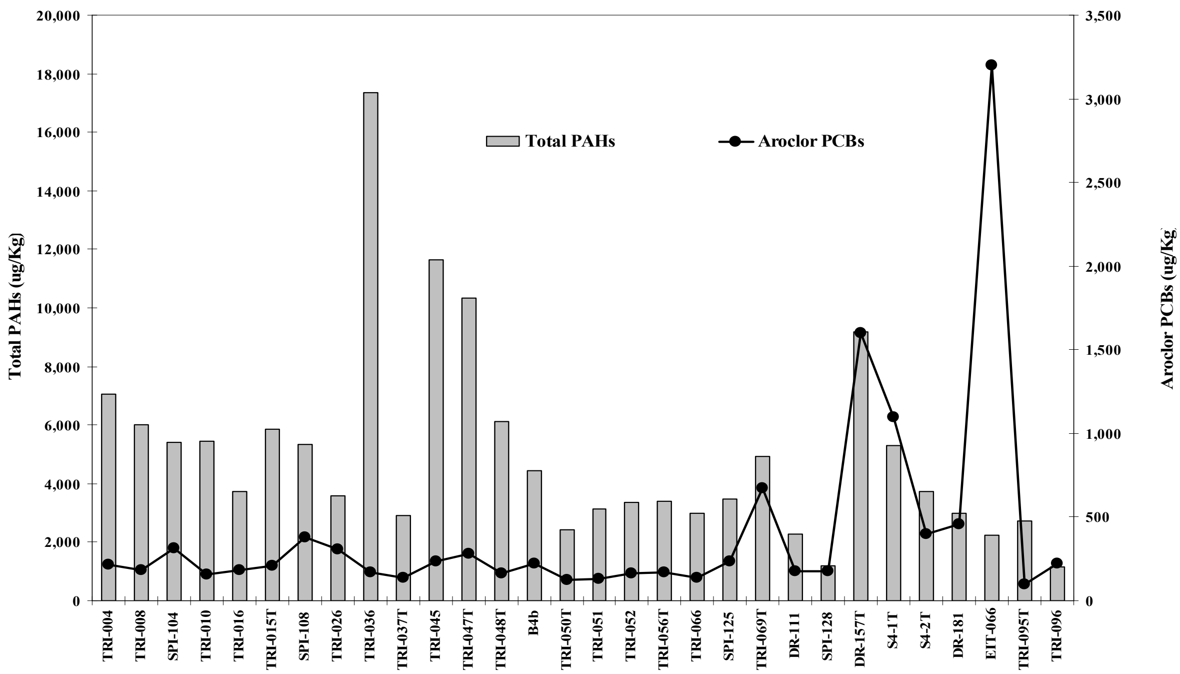


Figure 11. Summary of Total PAHs and PCBs measured in 30 samples collected from the Lower Duwamish Waterway.

Results were also interpreted relative to the SMS rule and chemical criteria. Two sampling locations exhibited concentrations of contaminants below the chemical SQS (TRI-015T, TRI-037T), another two exceeded the SQS only (TRI-026, TRI-036), and the remaining 26 exceeded at least one CSL value. The SQS values most frequently exceeded were for 2,4-dimethyl phenol (24 of 30 sampling locations), PCBs (12 sampling locations), benzyl alcohol (9 sampling locations) and mercury (4 sampling locations). TBT concentrations at six locations exceeded the bulk sediment screening value of 73 ug/kg that has occasionally been used as an interpretive endpoint. There were also single-location exceedances of the SQS values for acenaphthene, chrysene, and phenol. The CSL values most frequently exceeded were for 2,4-dimethyl phenol (24/30 sampling locations), benzyl alcohol (5/30), and PCBs (2/30).

Sediment toxicity

Weston Solutions, Inc. (now Newfields) tested sediment samples for their acute toxicity to two marine organisms. Tests were the standard 10-day test for amphipod survival, using *Eohaustorius estuarius,* and the 48-96-hour larval normal development test, using *Dendraster excentricus*. Corresponding endpoints reported were % mortality and combined % abnormality and mortality (100% – % normally developed larvae).

Test sample results, Table C-4, Appendix C, were statistically compared to one of two reference samples depending on the best matched for % fines: CR-02 (83% fines) or CR-24 (65% fines). For the first test, reference samples exhibited 7% and 2% mortality, respectively. Comparisons made according to SMS methods showed 6 of the 30 had significantly greater mortality than the matched reference sample. However, no sample had more than 15% mortality and thus did not exceed the toxicity-based SQS (25% mortality, absolute). The same test organism exhibited significant toxicity in 16 of the 48 samples tested in early 2005 (Windward Environmental, 2005b, 2005c). It should be noted, however, that only two of those sampling locations were re-occupied for this study.

Sediment larval test results showed significant toxicity and more than 15% combined abnormality and mortality (<85% normal survivorship) in only four sampling locations. Three locations (TRI-010, TRI-048T, SPI-128) had toxicity at the SQS level (all compared CR-24), and one additional sample (TRI-004) had toxicity at the CSL level (compared to CR-02). This was a lower frequency of significant larval toxicity than in 2005, when more than 40% of samples showed at least SQS-level toxicity. The limited number of sampling locations classified as toxic, together with their geographic separation, resulted in no discernable pattern of toxicity in the waterway. Plotting absolute toxicity results also failed to reveal any pattern (Figure 12).

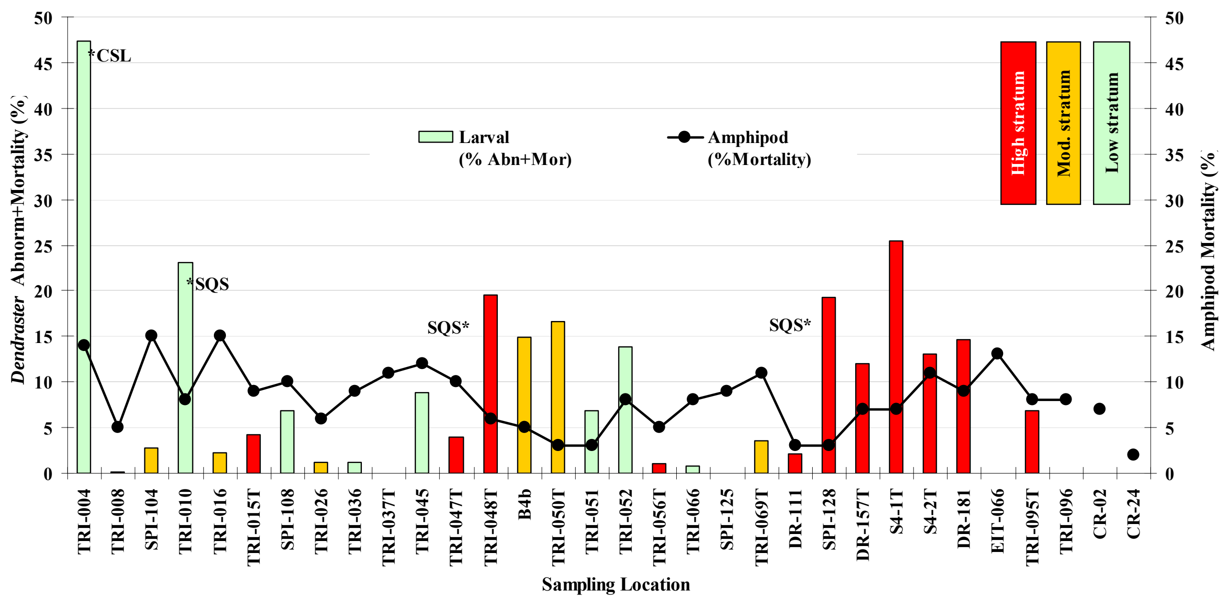


Figure 12. Sediment toxicity at 30 locations in the Lower Duwamish Waterway, in north to south order.

In general, 2006 sediment chemistry and toxicity results did not accurately confirm the assignment of target sampling locations to preliminary *High*, *Moderate,* and *Low* strata (Table 5). These sampling strata were defined by previous chemistry and toxicity results (Windward Environmental, 2005b, 2005c) and described in terms of the expected likelihood of benthic community impairment. Evidence of benthic community impairment was not considered. Observed sediment quality represented in Table 8 was based only on results of sediment chemistry and two toxicity tests. Predictions were reasonably accurate for *High* stratum samples only. The accuracy remained less than 50% overall even when the importance of exceeding criteria for 2,4-dimethyl phenol, benzyl alcohol, or both compounds, was discounted. The main effect of doing so was that prediction accuracy decreased for the *High* stratum and increased for *Moderate* and *Low* strata.

Table 5. Contingency table comparing expected and observed sediment quality.

Likelihood of impairment Expected ↓ Observed →	Observed *High*	Observed *Moderate*	Observed *Low*	Total	'Correct'
High (>CSL)	13	1	1	15	87%
Moderate (>SQS)	4	1	0	5	25%
Low (<SQS)	9	1	0	10	10%
Total samples	26	3	1	30	47%

Expected likelihood of impairment was based on 2005 results for sediment chemistry and three toxicity tests (Windward Environmental, 2005b, 2005c). Observed likelihood of impairment was based on 2006 sediment chemistry and two acute toxicity tests only.

The suite of chemicals analyzed and methods used were similar for both studies. Thus, reasons for low predictive accuracy could include:

- Small-scale spatial variability of sediment contamination in the waterway (many sampling locations were offset 10 meters from 2005 coordinates).
- Changed conditions (contaminant levels at some locations declined since 2005).
- Acute toxicity results involved a different larval test species and no chronic toxicity test.

Benthic community results

The 30 benthic community samples collected from the Lower Duwamish Waterway were evaluated by a team of taxonomists led by Fukuyama-Hirunaka Taxonomic Services. A total of 25,720 individual organisms belonging to 212 separate taxa were counted. Nine additional taxa were unique to the samples collected from the two reference locations. Detailed taxonomic results and a summary of benthic community metrics for all sampling locations are presented in Appendix C).

The relative abundance of major taxonomic groups was: Annelida (59.7%), Mollusca (32%), Crustacea (7.7%). The relative abundance of the annelids decreased from an average of 74% at locations in the preliminary *High* stratum to an average of 48% in the *Low* stratum (Figure 13). This notable shift was accompanied by a concurrent increase in the proportion of Mollusca. The Echinodermata and Miscellaneous taxa were relatively rare, comprising a combined 0.5% of total abundance. Their presence, abundance, and taxonomic identities were mainly used to help interpret results for a few of the individual samples.

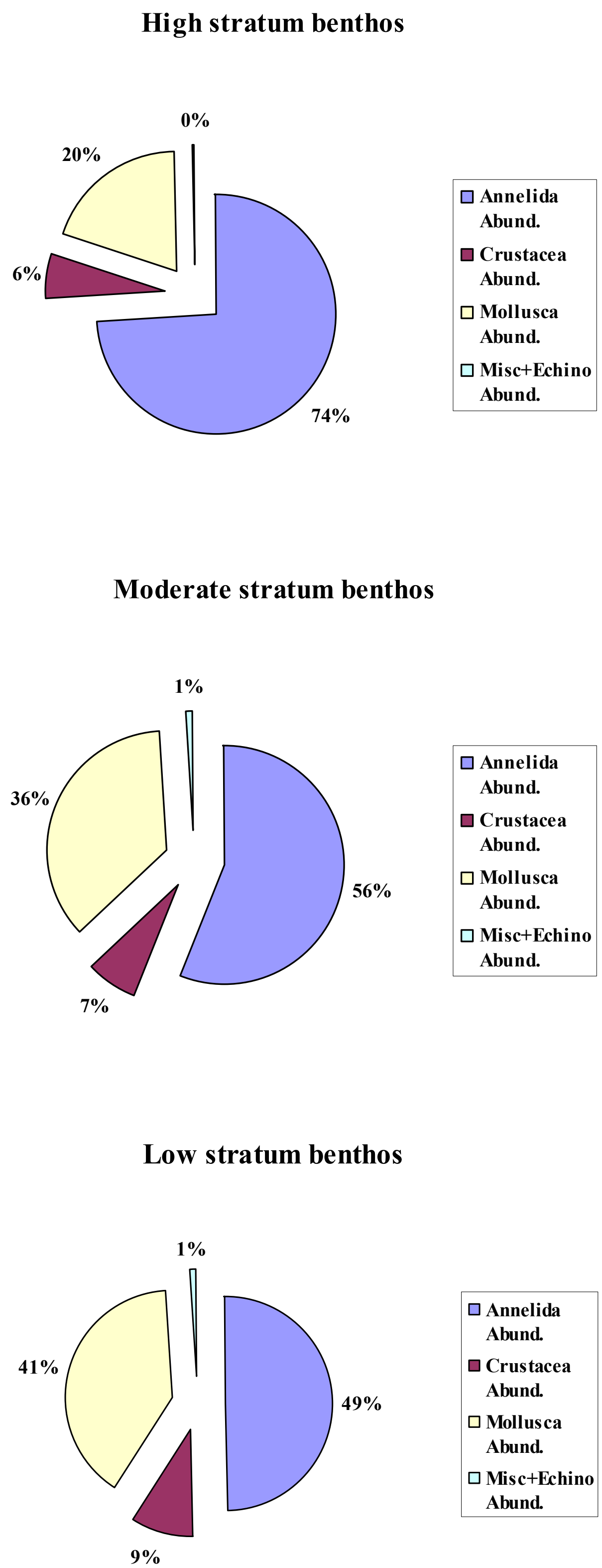


Figure 13. Benthic community composition by preliminary *High*, *Moderate*, and *Low* strata.

The 8 taxa that accounted for three-fourths of the total abundance at all locations are listed in the first column of Table 6. The top three taxa made up nearly half (47%) of all organisms counted. Three of the 8 taxa were annelids and accounted for 42% of overall total abundance, while four of the taxa were mollusks and accounted for 27.5% of the total abundance.

Labels describing tolerance to disturbance, hypoxia, and pollution were assigned to the eight most abundant taxa. This was based on peer-reviewed publications, the professional opinions of Ecology's Marine Sediment Monitoring Program staff, and regional benthic experts (Musgrove and Word, 2006). Almost all of the taxa could be assigned labels ascribing to them some level of tolerance to disturbance or pollutants.

Finally, the taxa most often identified as being among the top ten most abundant at individual sampling locations are listed in the second column.

Table 6. Benthic community taxa comprising 75% of the total number of organisms counted in 30 samples collected in the Lower Duwamish Waterway.

Taxa comprising 75% of Total Abundance Pollution Indicator Category	Count for 30 stations/ (How often in Top 10 list?)
Aphelochaeta glandaria (tolerant)	5736 (83%)
<u>Axinopsida serricata (slightly tolerant)</u>	3778 (80%)
Cossura pygodactylata	2575 (83%)
Scoletoma luti	2547 (100%)
Euphilomedes carcharodonta (slightly tolerant)	1435 (53%)
<u>Macoma carlottensis (moderately tolerant)</u>	1273 (63%)
<u>Nutricola lordi (tolerant?)</u>	1253 (70%)
<u>Parvilucina tenuisculpta (moderately tolerant)</u>	772 (50%)

Annelids are italicized, crustaceans are displayed in normal font, and mollusks are underlined.

Table 7 provides summary descriptive statistics for benthic community metrics at 30 sampling locations. The typical benthic community sample, as characterized using the median values, contained more than 878 individuals belonging to 44 separate taxa. There are 430 annelids representing 22 taxa, 32 crustaceans from 7 taxa, 224 mollusks from 11 taxa, and 4 individuals from other taxonomic groups. The typical Swartz' Dominance Index value (SDI) indicated that individuals from an average of just 6 taxa made up 75% of each sample's total abundance. Median values for Shannon Wiener diversity (H') and Pielou's evenness (J) were 1.026 and 0.625, respectively.

Table 7. Summary of benthic infaunal community indicators for 30 sampling locations in the Lower Duwamish Waterway and two potential reference locations in Carr Inlet.

	Total abundance	Annelida abundance	Crustacea abundance	Mollusca abundance	Misc. taxa abundance	Total richness	Annelid richness	Crustacea richness	Mollusca richness	Misc. taxa richness	SDI	H	J
Min	197	117	0	8.0	0	15	13	0	1	0	3	0.689	0.505
Median	878	430	32	224	4	44	22	7	11	3	6	1.026	0.625
Mean	858	512	66.	275	5	45	24	6	11	3	5.5	0.996	0.620
Max	1946	1178	305	1131	23	83	48	16	20	7	8	1.198	0.748
Range	1749	1061	305	1123	23	68	35	16	19	7	5	0.509	0.243
Count	30	30	30	30	30	30	30	30	30	30	30	30	30
CR-02	28	19	0	9	0	6	5	0	1	0	2	0.510	0.656
CR-24	612	248	95	55	214	37	20	4	8	5	7	1.085	0.692

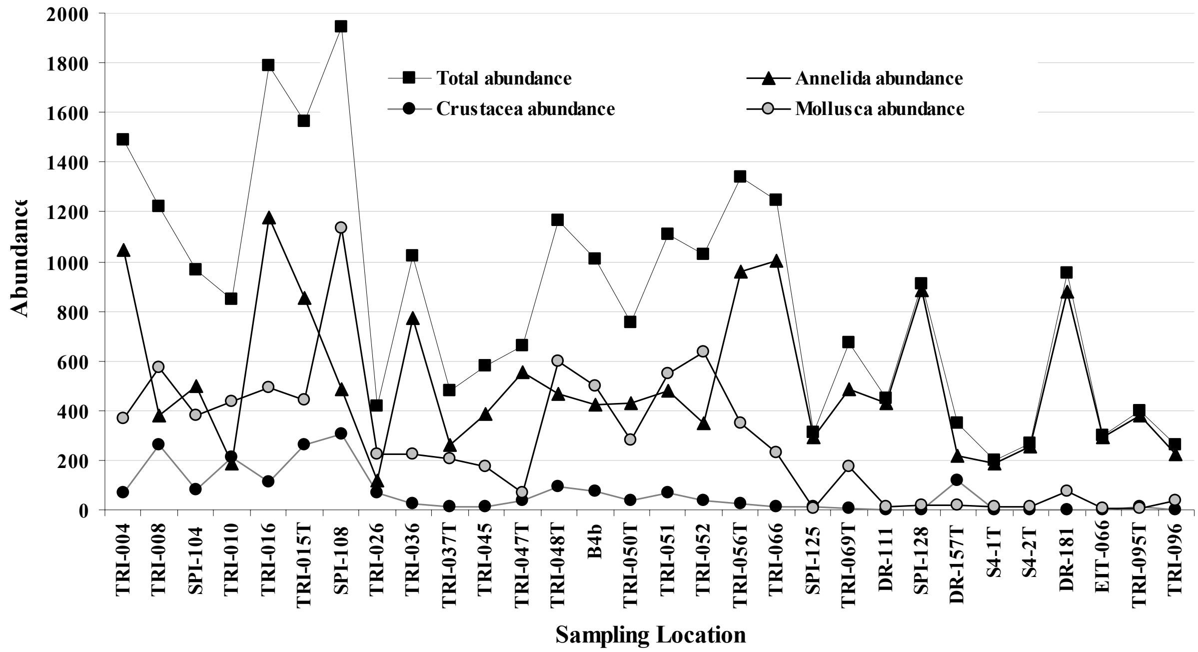
Figure 14 explores north-south trends in some important benthic community indicators. Sampling locations with the greatest total abundance were between TRI-004 and SPI-108, and between TRI-048 to TRI-066 (Figure 14, upper plot). The abundance of Annelida was more variable, but a similar pattern was noted for Mollusca. With the exception of DR-181, total abundance was lowest at locations south of SPI-128. The number of individuals in miscellaneous taxa and Echinodermata tended to be far less abundant. They decreased from north to south, with exceptions at SPI-108, B4b, TRI-051, and TRI-052.

Total taxa richness appeared to decrease from north to south, with a few notable exceptions (Figure 14, lower plot). Richness was high at location SPI-108, and between TRI-045T and TRI-066. Richness was also relatively high at TRI-069T and SPI-128. Crustacea and Mollusca richness were generally greatest in the northern portion of the study site (to RM 1.4).

Swartz' Dominance Index showed little range in values, and diversity (H) was greatest at some locations between RM 0.1 and 1.4.

The study design for this project was not intended to provide benthic community results that could be easily compared to 2005 results (Windward Environmental, 2005d). However, a few observations could be made:

- The average total abundance of organisms at the 30 sampling locations was virtually the same as at the 14 locations sampled in 2005 (when normalized to 0.1 $m^{2)}$.
- Average abundance of Annelida and Mollusca were similar, but average abundance of Crustacea appeared to be substantially lower than in 2005.
- The average total taxa richness of 45 was substantially lower than the average of 64 taxa per sampling location reported in 2005, but mostly likely due to the smaller sample volume.



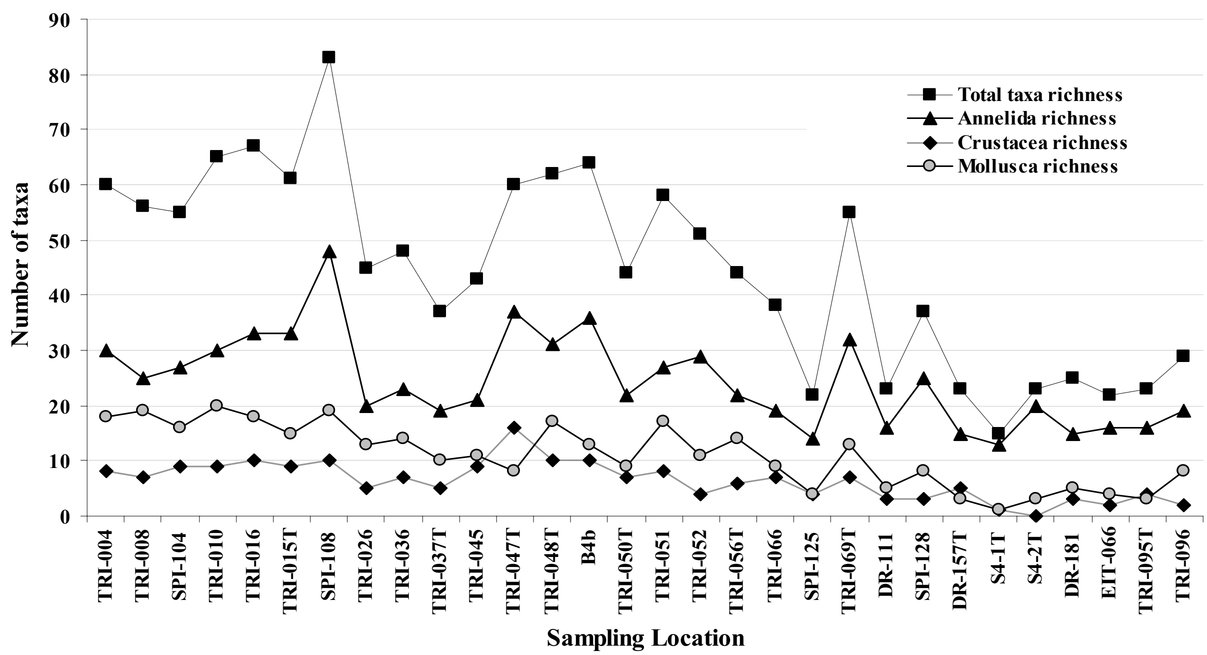


Figure 14. Benthic community abundance (upper plot) and richness (bottom plot) for 30 locations in the Lower Duwamish Waterway.

The SMS rule defines unacceptable adverse benthic effects at the SQS level as a >50% reduction in the abundance of Crustacea, Mollusca, or Polychaeta relative to the abundance in a suitable reference sample (statistically significant at $p<0.05$). The CSL level of effects is defined similarly but with 50% reduction in abundance of any two of the same major taxa.

Benthic community results could not be interpreted according to the SMS rule because the null hypothesis (*there was no significant difference between the abundance of any major taxonomic group in test and reference samples*) could not be tested.

- Results were based on a single field replicate sample instead of the recommended 3-5 replicate grabs per sampling location (Ecology, 1995 and 2003; EPA, 1986)
- One of the two reference sample locations exhibited a highly depauperate community, likely due to high concentrations of sulfide.

However, 12 sampling locations in the waterway would have exceeded the SQS and 7 would have exceeded the CSL if:

- Benthic community results based collected at location CR-24 represented an appropriate benthic reference condition.
- Greater field replication had occurred and differences in the abundance of major taxa between test and reference sampling locations were significant.

Predicting regulatory indicators of sediment quality

General conclusions based on SPI evidence were that there were few locations where benthic communities were obviously altered by chemical or organic loading, and healthy benthic infaunal functions were found throughout the waterway. These conclusions were consistent with results for most sediment conventionals and for acute toxicity that identified only 3 locations exceeding the SQS and one exceeding the CSL. The SPI conclusions were less consistent with the presence of high sulfides, elevated contaminant chemistry, and possibly significant reductions in the abundances of major benthic taxa.

Table 8 lists the 30 sediment quality sampling locations according to preliminary strata (expected level of benthic community impairment), SPI evidence for disturbance, and results for various chemical and biological indicators of sediment quality. The SPI evidence indicated 4 of the 30 sediment quality sampling locations were likely altered by chemical or organic loading (++), and another 6 locations showed slight disturbance (+). Eight of these exceeded at least one chemistry SQS, and only one showed little evidence of biological effects.

There was no SPI indication of disturbance in 18 of the remaining 20 sediment quality locations. All of these had elevated chemical concentrations, and 7 showed some evidence of biological effects.

Table 8. Summary of expected and observed sediment quality for 30 locations in the Lower Duwamish Waterway, ordered by preliminary stratum.

Sampling Location	Preliminary Stratum[a] ('Expected')	SPI Alteration[b]	Chemistry > SQS	Chemistry > CSL	Toxicity[c] > SQS	Toxicity > CSL	Major taxa abundance[d] > SQS	Major taxa abundance > CSL
DR-111	High	++	O	O				CM
DR-157T	High	++	O	O			C	
DR-181	High	-	O	O			C	
EIT-066	High	-	O	O				CM
S4-1T	High	+	O	O				CM
S4-2T	High	+	O	O				CM
SPI-125	High	+	O	O				CM
SPI-128	High	-	O	O	Larval			CM
TRI-015T	High	-	Hg/TBT					
TRI-037T	High	++					C	
TRI-047T	High	-	TBT	O			C	
TRI-048T	High	-	O	O	Larval			
TRI-056T	High	-	O	O			C	
TRI-095T	High	-	O	O				CM
B4b	Moderate	-	O	O				
SPI-104	Moderate	-	Hg/O	O				
TRI-016	Moderate	-	TBT	O				
TRI-026	Moderate	+(physical)	TBT				A	
TRI-050T	Moderate	-	O	O			C	
TRI-069T	Moderate	-	O	O			C	
SPI-108	Low	-	TBT	O				
TRI-004	Low	++	Hg/O	O		Larval		
TRI-008	Low	+	HgO	O				
TRI-010	Low	+	TBT	O	Larval			
TRI-036	Low	-	O				C	
TRI-045	Low	+	TBT	O			C	
TRI-051	Low	-	TBT	O				
TRI-052	Low	-	O	O			C	
TRI-066	Low	-	O	O			C	
TRI-096	Low	+(other)	O	O			C	

a Level of expected impairment *High* = chemistry or toxicity > CSL, *Moderate* = chemistry or toxicity > SQS, *Low* = chemistry or toxicity < SQS.
b SPI evidence for alteration from Germano and Associates (2007).
++ = strong SPI evidence for disturbance, + = some SPI evidence for disturbance
c Toxicity based on two acute tests only, Larval = *Dendraster* normal development.
d Benthic community results based on single field replicates and one reference sample.
A = Annelida, C = Crustacea, Hg = mercury, M = Mollusca, O = organic contaminant(s)
TBT = tributyltin ion (>73 µg TBT+/Kg).

Data analysis

The general scheme for acquiring, assuring quality, managing, preparing, and statistically analyzing environmental data collected for this project is shown in the Methods section of this report (Figure 4). The following section summarizes preliminary observations, data preparation and screening, and exploratory data analysis. Analytical questions are then addressed by appropriate statistical procedures. More detailed results are presented in Appendices C and D.

Preparing and screening data

Numerous potential outlier values were identified but few were removed from the data set prior to analysis, Table D-1, Appendix D. The sulfide concentration at S4-1T (14,100 mg/Kg dry weight) was one that was consistently removed. Although likely real, it was a full order of magnitude greater than the next greatest sulfide concentration measured and appeared to have undue influence on results.

The greatest number of potential outlier results was associated with location DR-157T. This was an unusually sandy location that had the poorest camera penetration and the highest number of tubes and burrows, yet had concentrations of organic contaminants among the highest measured. SPI-108 was also unusually sandy, with the lowest boundary roughness, and had the highest total, crustacean, mollusk, and miscellaneous taxa abundance. Annelid abundance was relatively low but annelid richness was the highest of any location. Locations TRI-045 and TRI-047T had potential outlier values for metals and PAHs. Many of these results were removed for exploratory analysis of distributions, correlations, and regressions, but may not have been removed prior to multivariate analyses.

Data distributions for variables measured at the 30 sampling locations are summarized in Table D-2. As is often the case with many environmental parameters, results for many parameters not normally distributed. Those results were transformed, usually using square root, fourth root or $\log_{10}$ transforms, prior to any analysis that assumed a normal data distribution.

Continuous variables with a limited range of results included the following SPI parameters: boundary roughness, RPD depths, minimum and maximum grain size, number of voids per replicate, number of mudclasts, number of large tubes, few burrows per replicate, and number of oxic voids. This was also true for % gravel. These variables were assumed to have limited utility for statistical purposes.

Categorical variables that either had a limited range of results or an unequal number of results included boundary roughness type, SPI grain size results, presence or absence variables (methane bubbles, low dissolved oxygen, bacterial mats, bedforms, fecal pellets, infauna), infaunal successional stage and successional stage ranks, mudclast number and state, dynamics, and physical disturbance. These variables were not used in statistical analysis, despite their importance for understanding the structure and function of the sediment and benthic community at a specific sampling location.

Variables having a substantial number of missing values, and their likely importance, were identified prior to statistical analysis. For example, minimum and maximum depths of feeding voids (six missing values) were often not used because the sample size and utility of other data would have been reduced.

Correlation analysis

After removing outlier values and variables lacking range, a matrix of Spearman rank correlation rho values (Zar, 1984) was tabulated for different combinations of SPI, conventional, and benthic variables. These correlations did not assume data distributions were uniform or normal, or that the relationships were linear or positive. Table 9 shows the various parameters that were most often significantly correlated with important benthic community metrics such as total abundance and richness, abundance and richness of major taxa, SDI, diversity H', and evenness J'. Table D-4 lists the Spearman rho values only for correlations between selected SPI parameters and benthic community metrics.

Table 9. SPI parameters, sediment conventionals, and sediment quality indicators most often found significantly correlated with 13 benthic community metrics (Spearman rho, $p<0.05$).

Category of results	Benthic community results
SPI parameters	Penetration depth, boundary roughness, BHQI (OSI)
Sediment conventionals	Total solids, % silt, sulfides
Contaminant chemistry	Sb, Cu, Cr, Hg, Ni, ΣMetals, TBT LPAH, PAH No. chemicals > SQS, CSL
Toxicity	None

Sb = antimony, Cu = copper, Cr = chromium Hg = mercury, ΣMetals = total concentration all trace metals measure, TBT = tributyltin ion, LPAH = low molecular weight polynuclear aromatic hydrocarbons.

Regression analysis

Ecology explored simple and multiple linear regressions of potential use to regulatory programs, guided by the frequency and magnitude of Spearman correlations (e.g., Table D-4, Appendix D). Simple, least squares linear regression analysis resulted in a few correlations between SPI variables and sediment quality-related parameters that might be of use to regulators.

Spearman rank correlation analysis indicated that multiple independent variables might improve prediction of certain dependent variables. For this reason, multiple regression analyses were conducted using Systat software. This was done to answer the question: "Are simple linear combinations of relatively few SPI parameters, sediment conventionals, or SPI parameters and conventional parameters in combination, able to predict key indicators of benthic community health?"

In general, results were similar to those found for the Port Gamble Bay study site (Gries, 2007). Much of the variability exhibited by certain benthic metrics could be explained using multiple untransformed sediment quality variables. However, most multiple regressions that involved few (3-4) independent variables had a corrected multiple r^2 on the order of 0.4-0.6. A greater number of predictors was usually required to account for a higher percentage of the total variability. This rendered the utility of the multiple regression approach somewhat questionable.

Multivariate statistical analysis

Because SPI results did not appear able to easily predict sediment quality indicators (Table 8), possible relationships were explored using multivariate statistical methods. The first question asked was: How many distinct benthic communities are present at the Lower Duwamish Waterway study site?

The two multivariate methods used to address this question were exploratory cluster analysis and multidimensional scaling (MDS).

Numerous hierarchical and agglomerative cluster analyses were conducted. Benthic community results for a single sample were used as a starting point, and then the sample with the most similar benthic results was identified. This was done using any of several measures of distance or similarity. The next closest case was linked to the first two cases using one of many linking algorithms. Euclidian distance (the shortest between two points) and complete linkages were generally used to group sampling locations for the analyses presented in this report. In general, other measures of distance or similarity, and other linkages, did not produce substantially different results.

Figure 15 shows an example result of a cluster analysis based on the benthic community results for 30 sampling locations in the Lower Duwamish Waterway. It shows that benthic data can be grouped into at least three distinct clusters or communities. The first group (green, top) is comprised of eight sampling locations (TRI-016, TRI-004, TRI-056, TRI-066, TRI-015T, TRI-036, DR-181, and SPI-128) from various preliminary sampling strata. The benthic communities at these locations had the highest average total and annelid abundance, coupled with the lowest average SDI, diversity, and evenness. These locations were also characterized by having the lowest average boundary roughness, number of mudclasts, number of tubes, concentrations of several individual and total metals, TBT, phthalates, and phenols, but the highest fines, TOC,
and PAHs.

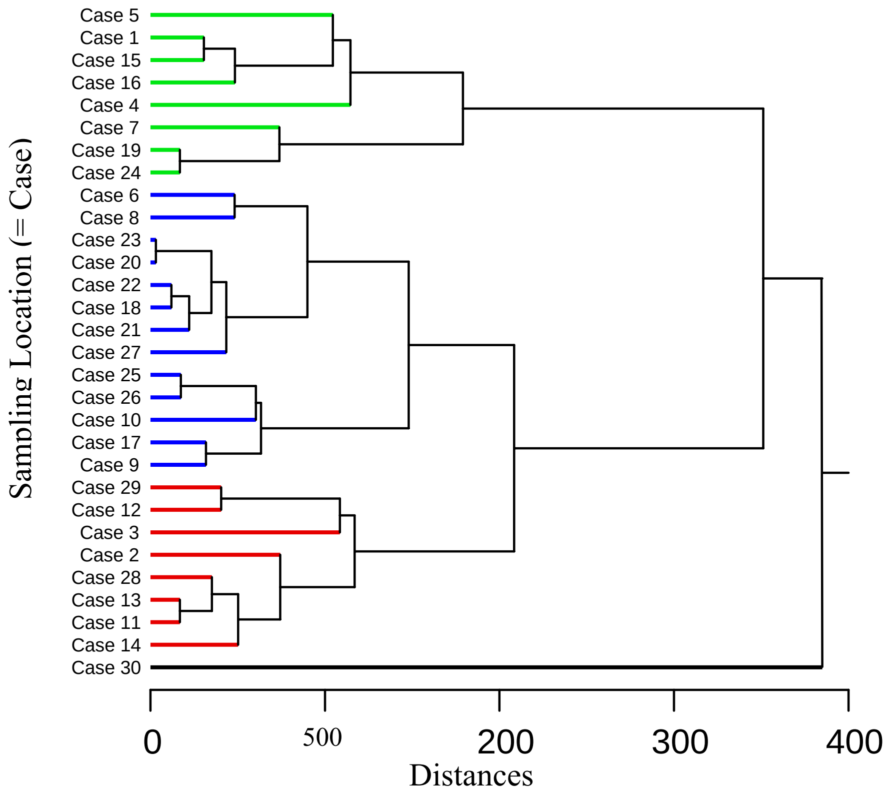


Figure 15. Benthic infaunal communities in the Lower Duwamish Waterway identified by cluster analysis using 11 metrics for 30 sampling locations.

Benthic community metrics used were total, annelid, crustacean and mollusk abundance, and richness, along with SDI, diversity (H'), and evenness (J'). Clustering used Euclidian distance and complete linkages. Table A-2 can be used to convert case numbers to sampling locations in Figures 7a - 7c.

The second group includes 13 sampling locations (TRI-026, TRI-037T, SPI-125, EIT-066, S4-2T, TRI-096, S4-1T, DR-157T, TRI-095T, DR-111, TRI-047T, TRI-069T, and TRI-045) with 9 (70%) from the preliminary *High* stratum. As a group, these benthic communities had the lowest average for total and major taxa abundance, as well as the lowest total and major group taxa richness values. The sampling locations had the lowest average camera penetration depth, RPD depth, number of voids, burrow count, number of oxic voids, BHQI, and OSI. These locations also had the highest average boundary roughness and some of the highest contaminant concentrations relative to SQS values.

The third group is formed by 8 sampling locations (SPI-104, TRI-050T, TRI-010, TRI-008, B4b, TRI-051, TRI-048T, and TRI-052) with only one belonging to the preliminary *High* stratum. As a group, these locations had the highest abundance of Crustacea, Mollusca, and Miscellaneous taxa, total and major group richness (except Annelida), and highest average SDI value. These locations also exhibited the highest camera penetration depth, RPD depth, number of voids, maximum depth of feeding voids, OSI, BHQI, copper, ΣMetals, but the lowest average sulfides and PCBs.

Sampling location SPI-108 (Case 30) is the most unlike the other locations based on these benthic metrics. It has the highest (or nearly highest) values for total, major taxa and miscellaneous taxa abundance and richness, as well as diversity. It is one of the sandiest samples and has low values for boundary roughness, number of voids, maximum depth of voids, and TOC.

Independent cluster analyses were conducted by the TerraStat Consulting Group (results not shown) and generally confirmed the result shown in Figure 16. One analysis was based on the same methods but 10 benthic metrics (not J') yielded almost identical results, with only location TRI-050T becoming associated with the second group. A second cluster analysis based on the same methods but using trimmed benthic results (taxa comprising 95% of total abundance, Table C-6, Appendix C) also yielded very similar results, with sampling locations SPI-104 and TRI-016T no longer being associated with any group. A divisive cluster analysis, where all sampling locations began as a single group and then split, also yielded similar results when based on 10 benthic metrics.

Multidimensional scaling (MDS), in contrast to cluster analysis, displays information contained in a data set as points in space, with the distance between points reflecting complex empirical relationships. MDS results help visualize similarities between different sampling locations based on multiple variables in two (or more) dimensions. It is used extensively to help understand relationships between benthic (or other) communities, habitats, and environmental stressors.

Figure 16 illustrates the power of MDS. It shows at three distinct benthic community groups identified by the similarities among 11 benthic metrics (abundance and richness of four major taxa, SDI, H' and J') in the 30 sampling locations. The two parameters that are the strongest correlates in the combined components are annelid and mollusk abundance. The first of these communities is comprised of 11 sampling locations (TRI-47T, SPI-125, DR-111, SPI-128, DR-157T, S4-1T, S4-2T, DR-181, EIT-066, TRI-095T, and TRI-096) most of which are near Slip 4. The second group contains at least 12 locations that are more distributed throughout the study site. The last group has six sampling locations in the northern portion of the study site, with three of them around River Mile 1.4. The proportion of total variance explained by this analysis and configuration of sampling locations is 94%.

There are numerous significant differences between the three groups ($p<0.05$). Group 1 has significantly greater boundary roughness, fewer total and deep oxic voids, fewer burrows, and lower BHQI values than Group 2, as well as several SPI parameters that significantly differ from those of Group 3. Groups 2 and 3 also have SPI parameter mean values that significantly differ from each other. There are exceedingly few differences between the three groups relative to conventionals, contaminant chemistry, or toxicity.

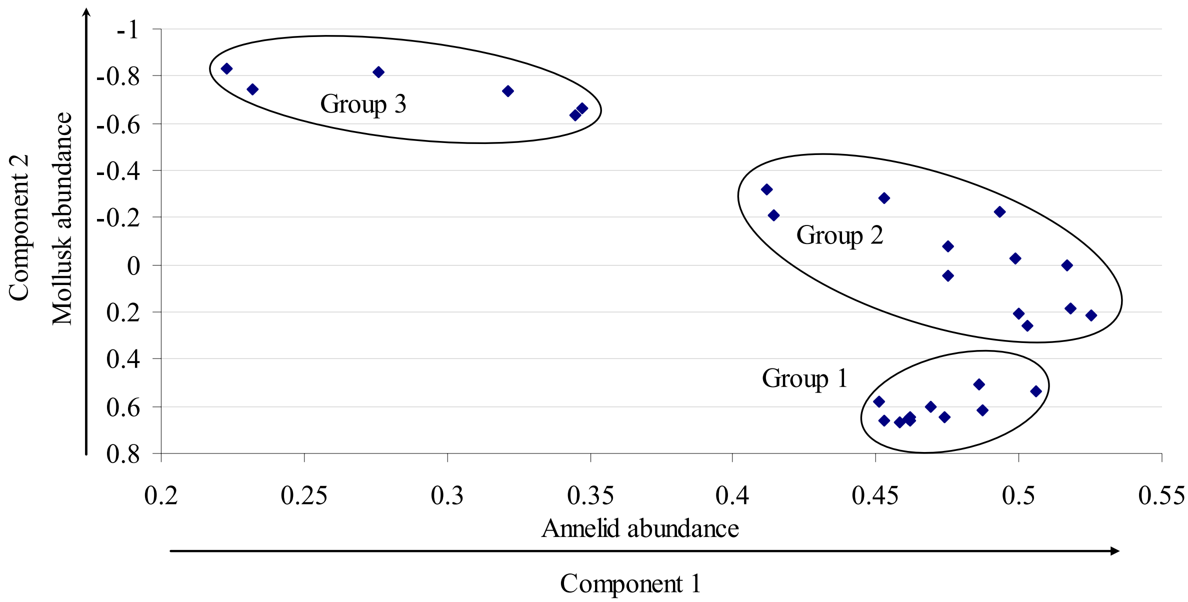


Figure 16. Non-metric MDS based on 11 benthic metrics for 30 sampling locations in the Lower Duwamish Waterway.

Figure 17 shows results of an independent MDS analysis that explains 98% of the variability between the sampling locations (TerraStat Consulting Group, personal communication). In this case, slightly different MDS methods using 10 benthic metrics contribute to a somewhat different result. Group 1 sampling locations in Figure 17 are similar to, but a subset of, Group 3 in Figure 16. Group 3 in Figure 17 is very similar to Group 2 in Figure 16. This reinforces the importance of using identical statistical methods, algorithms, input data, and software to duplicate results.

Figure 18 shows an MDS plot that uses the same trimmed benthic community results as was used for some cluster analyses. It also uses a different measure of distance between points (Bray Curtis instead of Euclidian distance). The two clusters that are apparent, one cluster of 9 sampling locations being almost all from the preliminary *High* stratum and near Slip 4, accounts for 56% of the variability between the points displayed.

The groups of sampling locations identified by these examples of cluster analyses and MDS (and others not shown) are assumed to represent distinct benthic infaunal communities within the waterway because they are based on benthic results alone. Relative to the main goal of this study, there is a logical next question: Can SPI parameters be used to distinguish between or predict the sampling locations associated with different benthic communities?

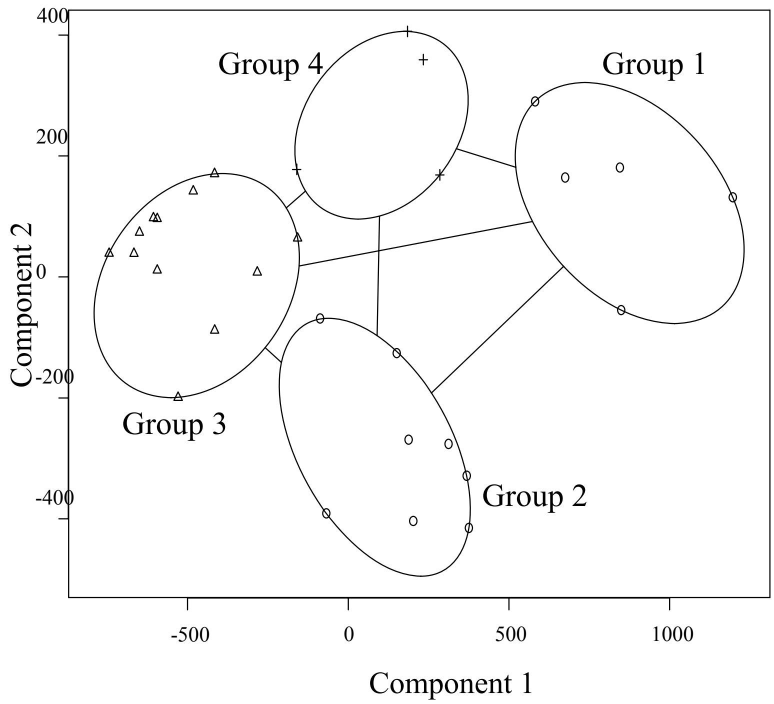


Figure 17. MDS plot using total, annelid, crustacean and mollusk abundance and richness, SDI, and H' for 30 sampling locations in the Lower Duwamish Waterway.

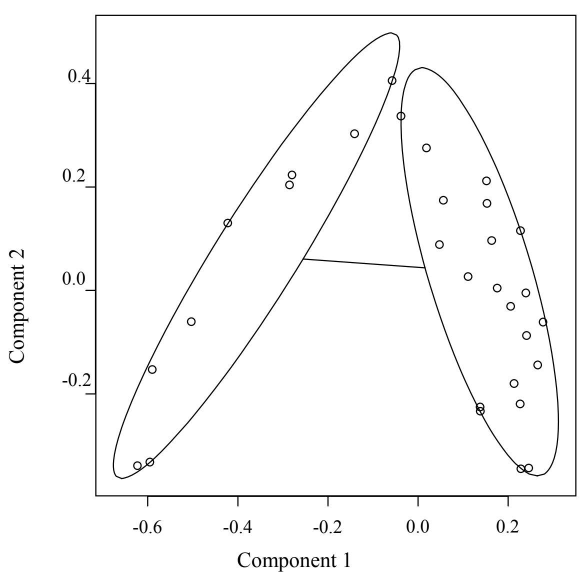


Figure 18. MDS plot using trimmed benthic abundance results (the most abundant taxa comprising 90% of the total) for 30 sampling locations in the Lower Duwamish Waterway.

The main methods used to address this question were:

- Discriminant analysis of the groupings identified by cluster analysis or MDS.
- Regression trees that used SPI and sediment quality results to classify sampling locations into the groupings identified by the cluster analysis or MDS results.

The first of these, discriminant analysis, helps identify combinations of factors that are major sources of variance explaining the observed groupings of results. Discriminant analyses were conducted using the distinct groupings (benthic communities) identified by both cluster analysis and MDS. Results can be shown in plots of canonical means that show confidence envelopes containing all or nearly all of the sampling locations for each group. One example of such a plot is shown in Figure 19.

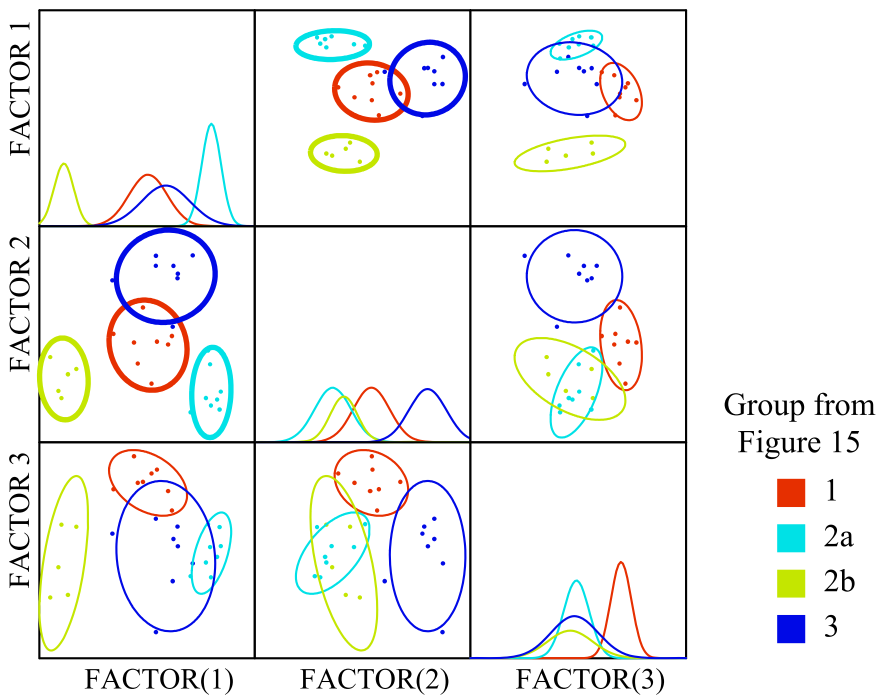


Figure 19. Canonical means plots for benthic community groups identified in Figure 15 (Group 2 split into 2a and 2b), using water depth, SPI, conventionals, and contaminant chemistry as components of three discriminant factors.

In this example, the known groups are taken from Figure 15, but with Group 2 split into two separate groups joined at a distance of approximately 150. The result is four benthic communities instead of the three. Parameters used in the discriminant analysis include water depth, 7 SPI parameters, % sand and sulfides, and several metals and organic contaminants. The result indicates that Factors 1 and 2 alone can distinguish between all four groups (second plot in top row and first plot in the middle row). Important SPI parameters in these two factors include penetration depth, number of burrows, BHQI, and, to a lesser extent, boundary roughness and RPD depth. A matrix shows 100% correct classification of the sampling locations from this study (not presented), but whether this accuracy would be sustained with new sampling results is unknown.

Classification trees were also used to assign sampling locations to the groups defined by cluster analysis or MDS. This was done using sediment quality results. The plot of such a tree shows branches that should be balanced at each node (so that the branch is level). The variable and value defining the split at each node is indicated. Several of such trees were developed whereby sampling locations are assigned to the categorical variable, such as preliminary stratum, using SPI and sediment quality results.

An example of a tree is shown in Figure 20. This tree used only SPI results to classify sampling locations into the benthic communities defined by the cluster analysis presented in Figure 15.

Figure 20 uses average RPD depth as the first branch or node to classify five sampling locations into Group 3. Those five locations belong to Group 3 shown in Figure 16. Thus, the accuracy of classification for this group is 5/8. The next branch classifies another 23 sampling locations using the SPI boundary roughness parameter. Three sampling locations are accurately classified into Group 1 (3 of 8 locations), and 12 sampling locations are accurately classified into Group 2 (12 of 13 locations). The overall accuracy of classifying locations by this method, and using only SPI parameters to do so, is 20/29 or 69%. But 86% of the sampling locations in the preliminary *High* stratum were correctly assigned to their benthic community group. The number of burrows can split Group 2 into 2a and 2b (described in discriminant analysis).

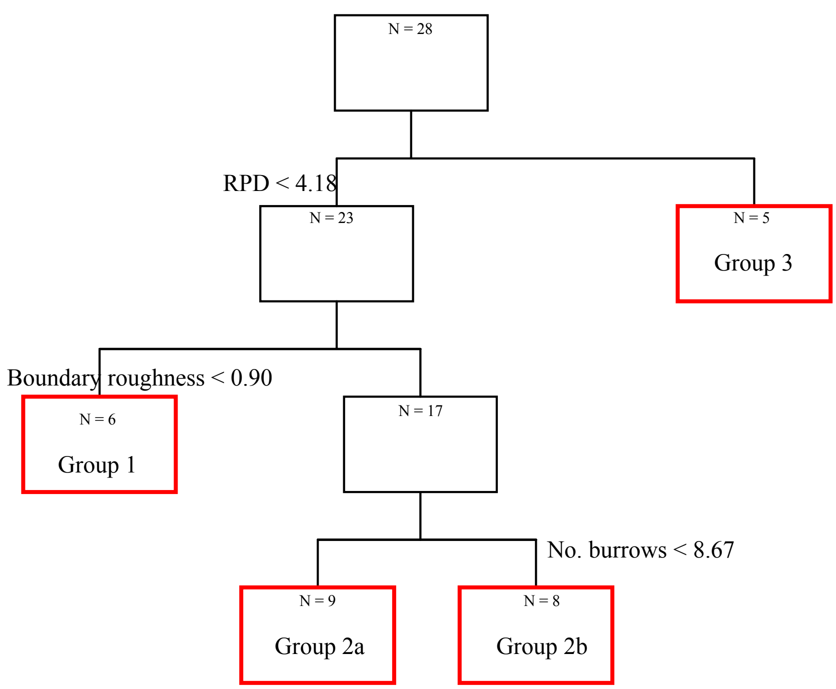


Figure 20. Regression tree for benthic community groups identified as a result of the cluster analysis shown in Figure 15.

The accuracy of classifying sampling locations into the benthic communities identified in Figure 18, ranged from 63% to 73%, depending on whether the SPI, conventionals, chemistry parameters, or combinations of them, were used. Classification of sampling locations into the benthic communities identified by other MDS analyses yielded accuracy of at least 90%, again depending on parameters used in the tree analysis (TerraStat Consulting, 2007, personal communication).

Project costs

Table 10 indicates that conducting a preliminary SPI survey of a cleanup site could be quite cost-effective if it resulted in fewer locations being sampled for detailed evaluation of sediment quality. The total cost associated with obtaining SPI survey results for this study was approximately $460 per sample. The cost to obtain the sediment quality results for this study was approximately $2,400 per sample, or about 5 times as much. And the sediment quality results did not fully comply with the SMS (Ecology, 1995; EPA, 1986-2003).

The cost to just obtain sediment quality results that fully comply with the SMS would be approximately $2,600 per sample. That cost would include results for sediment conventionals, SMS contaminant chemistry, and biological effects using three standard toxicity tests (no benthic community analysis). The cost for sediment quality evaluation that included benthic community analysis as one indicator of biological effects would be approximately $4,400 - $6,500 per sample. Thus, the cost to obtain traditional sediment quality results, not including vessel costs or staff time, would be at least 5 times and perhaps more than 10 times the cost of a SPI survey conducted for a study of similar scale.

Table 10. Costs associated with SPI and sediment quality surveys conducted for this study.

Total and itemized costs	SPI survey costs (3 field days, 87 locations)	Sediment quality survey costs (6 field days, 32 locations)
Total costs	$37,000	$85,700
Total costs per sampling location	$460	$2,635
Conventionals	--	$190
Contaminants	--	$810
Toxicity (2 tests)	--	$925
Benthic infaunal community (1 field replicate)	--	$710
Toxicity (3 tests, estimate)	--	$1,600
Benthic infaunal community (5 field replicates, estimate)	--	$2,500 - $3,600

SPI costs include planning, vessel time, navigation support, analysis and all reporting.
Sediment quality survey costs shown for this study do not include vessel costs or any staff time.

Conclusions

The major goal of this study was to determine the feasibility of SPI survey results to streamline and reduce costs associated with investigations of contaminated sediment cleanup sites. Results indicated that individual SPI parameters were not likely to be predictive of SMS indicators of sediment quality at this study site.

However, non-SMS methods identified distinct benthic infaunal communities at the site, and SPI results could accurately classify sampling locations associated with each. This finding could be useful to regulators if the new methods for identifying benthic communities were accepted and if at least one of the communities was determined to be unacceptably impaired. In addition, there are other reasons not particularly related to this study that SPI should be useful for sediment cleanup investigations.

1. Relationships between SPI and sediment quality results

The ability of SPI survey results to predict the regulatory indicators of benthic community health at this study site is uncertain but promising. A definitive interpretation of sediment quality is not possible from current results for two reasons. First, chronic toxicity was not measured. Second, benthic community results were based on single field replicates so differences from in major taxa abundance at reference locations could not be statistically tested for significance.

This study does show that distinct benthic communities can be identified in the waterway using methods not described in the SMS. If regulators use the latest scientific knowledge policy to identify communities that are unacceptably impaired, then the study also shows SPI parameters can help identify or predict where those impaired communities occur.

- Overall, results from the Lower Duwamish Waterway SPI survey show that benthic community functions at the study site did not appear to be adversely affected by major sources of disturbance.
- Sediment quality results showed the following:
  - Exceedances of chemical SQS and CSL were ubiquitous for two contaminants (2,4-dimethyl phenol and benzyl alcohol).
  - 14 of the 30 sampling locations still exceeded a chemical SQS even when exceedances of 2,4-dimethyl phenol and benzyl alcohol are discounted.
  - Exceedances of acute toxicity SQS and CSL were rare.
  - Not surprisingly, SPI appeared unable to predict sampling locations that would have exceeded the abundance-based benthic community SQS or CSL had there been adequate replication and consensus on acceptable benthic community reference samples.
- Statistical analyses revealed few individual SPI results were highly correlated with chemistry or toxicity indicators of sediment quality. Regression analysis using SPI results to predict these indicators did not yield promising results.

- Multivariate statistical methods appeared to be essential for identifying relationships between biological variables (detailed benthic results, taxa richness, dominance, diversity) and complex environmental or habitat variables (SPI and sediment chemistry results).
  - Cluster analysis and multidimensional scaling both successfully identified different subtidal benthic infaunal communities within the study area (Figures 16-18).
  - Other multivariate methods were able to (1) identify SPI (and sediment quality parameters) that explained much of the variability in those communities or (2) assign sampling locations to each community with good accuracy (Figures 19-20).
  - If regulators determined that one of these communities was unacceptably altered or impaired, then SPI could be a promising tool for predicting sediment quality.

Based on a greater understanding of SPI capabilities and limitations that relate to sediment quality, not necessarily to results of this study, SPI results constitute a meaningful, separate line of evidence for evaluating sediment quality and benthic community health. SPI results have a well-published record of providing information on:

- Sediment structure (sediment grain size mode and layering).
- Sediment stability (visual evidence of physical disturbance).
- Benthic habitats (sediment grain size mode, estimated % wood waste, thickness of sediments most likely to be oxic).
- Apparent functional complexity of benthic infaunal communities (successional stage).
- Biological modification of the sediment column functions (type, depth, and degree of bioturbation).

In combination, these SPI results help identify areas of disturbance due to organic loading, contaminant loading, or physical factors such as periodic scouring. The results also help determine how well benthic communities and functions have recovered from or adapted to such disturbances. This explains why SPI survey results are routinely used by dredging and monitoring programs to make other regulatory decisions about sediment quality. Finally, the addition of SPI results as a line of evidence pertinent to benthic habitat quality and community functions could benefit decision makers when other lines of evidence appear to be in conflict.

2. Do SPI results fill data gaps?

Results from this study supplement existing information in several ways.

- Prior to this study, few SPI images had been collected in the Lower Duwamish Waterway.
- SPI results are useful for understanding the fate and transport of contaminants because they provide extensive new information about the stability and structure of these waterway sediments.
- SPI results also provide extensive new information about benthic habitats (grain size major mode, surface roughness, apparent depth of oxic zone) and biological functions (surface colonization, depth, and type of bioturbation).

- Sediment chemistry and toxicity results for 2004 sampling stations that were intentionally reoccupied for this study could represent more current conditions and effectively replace earlier results.
- Other sediment chemistry and toxicity results from this study represent conditions at new locations: those intentionally offset 10 m from 2004 sampling stations.
- Benthic community results from the 30 locations sampled for this study constitute a substantial addition to benthic results from the approximately 16 subtidal locations sampled previously.

3. Can SPI results help define *baseline* conditions?

This study presents SPI, sediment conventionals, contaminant chemistry, toxicity, and benthic community results that represent recent conditions. As such, future monitoring results could be compared to these *baseline* conditions, especially if no more active cleanup actions are taken. The spatial coverage, sampling density, and types of information provided by the SPI survey should make SPI results clearly related to sediment stability and biological functions very appealing as a possible basis for future, cost-effective monitoring.

Other conclusions

Conducting separate SPI and sediment quality surveys, as closely as possible in time and space, appears to be an effective approach for investigating relationships between the two types of results.

SPI results for this study, by themselves, do not indicate that benthic habitats and functions are clearly impaired. The evidence for the latter claim includes:

- There is little indication that sediments have been impaired by low dissolved oxygen. This is probably due to relatively strong circulation in the bay, evident from SPI photographs and other images of surface sediments at various locations.
- Stage III organisms (see Figure 2) are present and bioturbate the sediment to a reasonable depth at almost all depositional locations (e.g., ones that accumulate sediment).

Recommendations

The major recommendations from this study are:

1. Conduct additional confirmatory analysis and peer review.
2. Conduct similar studies at other sediment cleanup sites.
3. Conduct SPI surveys more often as part of initial cleanup site investigations.
4. Interpret benthic infaunal community results using standardized multivariate statistical methods, not just abundance-based metrics.

1. Conduct more confirmatory analysis and peer review

An independent statistician conducted confirmatory statistical analysis using this data set. The statistician's multidimensional scaling results were generally consistent with Ecology's, but the effort was very limited. Additional independent analysis might:

- Confirm individual results.
- Identify analytical errors.
- Apply more optimal or entirely new statistical methods (detrended correspondence analysis, multivariate regression, path analysis).
- Result in new findings.
- Identify "standard operating procedures" for multivariate statistical methods.

An independent expert on benthic infaunal communities in Puget Sound should also review findings of this study. This review would likely lead to a better understanding of:

- The detailed ecology of the benthic communities that were identified.
- The extent to which organic loading, chemical contamination, physical disturbance, and other factors might explain the distribution of communities and important individual taxa.
- How the observed benthic communities might differ in the absence of such disturbances.

2. Conduct similar studies at other sediment cleanup sites

Similar studies of other cleanup sites should be planned. This may be especially true for sites that have sharper contaminant gradients. Reasons for this recommendation include:

- Concentrations of many chemical contaminants in much of the Lower Duwamish Waterway do not exhibit a large range or high variability.
- Greater statistical power (more samples) may be needed to clearly distinguish different benthic infaunal communities and identify the factors influencing their distribution.

- A more extensive sediment quality database that includes synoptic SPI results could help identify other relationships useful to regulators.

Future studies should involve sediment quality triad sampling and analysis according to SMS requirements and should use SPI as a fourth line of evidence. An *a posteriori* analysis might reveal if SPI results could eliminate the need to collect any other line of evidence or provide other valuable information (physical or water quality disturbances).

3. Conduct more SPI surveys as part of initial investigations

Sediment cleanup programs should consider conducting a preliminary SPI survey as a cost-effective part of early-phase cleanup site investigations. The potential benefits of conducting a preliminary SPI survey at other cleanup sites are that SPI could:

- Augment studies of the "fate and transport" of sediment.
- Fill data gaps for "nature and extent" investigations.
- Identify and distinguish between areas disturbed by physical actions (erosion), areas disturbed by organic loading, areas possibly disturbed by contaminant loading, and areas which show no evidence of disturbance.
- Provide additional lines of evidence that could help in weight-of-evidence decision-making at a cleanup site.
    - High likelihood of anoxia and poorly developed benthic communities, indicated by SPI results, could spur action when other sediment quality evidence is not clear.
    - SPI evidence of physical disturbance could focus cleanup investigations on areas where a poorly developed benthic community is more likely due to organic or contaminant loading.
- Provide a basis for cost-effective, long-term monitoring of cleanup sites after remedial actions have occurred.

4. Use multivariate statistical methods to identify distinct benthic communities

This study showed that cluster analysis and multidimensional scaling can identify different benthic communities within one cleanup site. At least two statistical methods used SPI results to distinguish between those benthic communities or to identify sampling locations belonging to each community. Therefore, this study also indicated that SPI survey results might accurately predict the occurrence of different benthic infaunal communities. This might streamline cleanup investigations and reduce associated costs if latest science policy in the SMS was used to clarify the characteristics of an unacceptably impaired benthic community.

Other recommendations and "lessons learned"

A design feature of this study was sequencing the SPI and sediment surveys to collect what should be truly synoptic data. Accurate vessel positioning was one of several ways Ecology minimized uncertainties about how representative sediment samples were of SPI sampling locations. The following measures would reduce such uncertainties further:

- The offset between the vessel's GPS receiver and the end of the boom that lowers sampling devices should be eliminated or minimized.
- Either the same vessel should be used for both surveys or the meter wheels on both vessels should be recently calibrated (so tide-corrected depths for both surveys better match).
- Field crews should be certain to record water depth from both the meter wheel and the vessel's depth finder.

Characterizing benthic communities at a cleanup site, because of spatial variability, should involve more than a single replicate grab sample. This recommendation is consistent with current regional guidance (Ecology 2003, EPA, 1987), but does have substantial costs associated with it. Therefore, Ecology should explore the advantages and disadvantages of (1) collecting benthic community data using reduced sample volume (smaller surface area or shallower depth) or (2) identifying benthic infaunal organisms only at a higher taxonomic level (Ferraro and Cole, 2004).

Regulators should use the latest scientific knowledge (Ecology, 1995, Section 130) in a multiple lines-of-evidence approach for evaluating sediment quality (SETAC, 2002). Such an approach might:

- Focus more on direct assessment of benthic communities instead of surrogate indicators.
- Include more than abundance-based measures to define significant benthic community effects (Ecology, 1996, 1999). Areas of organic enrichment or other disturbance often exhibit increased abundances and are relatively more likely to pass the current SQS and CSL, but often have poor diversity, taxa richness, or surface sediment processing.
- Use standardized multivariate methods to identify different benthic infaunal communities that could be compared to new standards or interpretive guidelines.

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Appendices

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Appendix A - Background and Vessel Positioning

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Table A-1. Applications of SPI technology to regulatory programs and marine sediment sites in the Pacific Northwest.

Program/project name	Application/purpose	References
PSDDA and DMMP, WA Regional dredging program	Identify and monitor open-water dredged material disposal sites.	Cooper Consultants, 1986 PSDDA, 1988 PSDDA/ DMMP, 1990-2006
Eagle Harbor (Seattle), WA Sediment cleanup site	Map areas capped with clean dredged material or sand.	USACE, 1994 SAIC, 1996 and 1998 Striplin Environmental Associates, 2000
Hylebos Waterway (Tacoma), WA *Sediment cleanup site with wood waste component*	Determine likely causes of impaired benthic communities. Map areas of wood waste.	Striplin Environmental Associates, 2001
Denny Way CSO (Seattle), WA Sediment cleanup/restoration cap	Map sediment cap and recovery of benthic community.	Striplin Environmental Associates, et al, 1996
Port Angeles Harbor, WA *Sediment cleanup site*	Survey nature and extent of wood waste in harbor, areas of high oxygen demand, apparent health of benthic communities.	SAIC, 1999
Coos Bay, OR Navigation dredging program	Identify and monitor open-water dredged material disposal sites.	Striplin Environmental Associates, 2000
Puget Sound Naval Shipyard (Bremerton), WA Cleanup and navigation site	Map distribution of recent dredged material and sand near confined aquatic disposal site	Germano and Associates, 2002
Port Gamble Bay, WA *Sediment cleanup site*	Map distribution of wood waste. Characterize sediment and benthic communities.	Parametrix, 2004 Anchor Environmental, 2006
West Hylebos log storage facility Tacoma, WA	Survey nature and extent of wood waste at the site	Gerrmano and Associates, 2004
Mouth of Columbia River, OR Regional dredging program	Identify open-water dredged material disposal sites. Characterize beneficial use site.	SAIC and Weston Solutions, 2006
Alaska Pulp Corp., (Sitka) AK	Fate and effects of wood waste.	Foster Wheeler, 1998
Thorne Bay and Ward Cove, AK *Ketchikan Pulp Co.* *Sediment cleanup and 303(d) sites*	Survey sediments, benthic habitats, and benthic communities.	Germano and Browning, 2006
Woodard Bay (Olympia), WA *Habitat restoration site*	Map distribution of wood waste	Germano and Associates, 2005

Wood waste sites are shown in italics.

Table A-2. Target and actual sampling coordinates (NAD 1983) for the sediment quality survey of the Lower Duwamish Waterway, August 2006. Potential reference locations are shown in italics.

Sampling Location ID	Statistical Analysis ID	Chemistry Lab ID	Sediment Quality Survey Target Latitude	Sediment Quality Survey Target Longitude	Sediment Quality Survey Actual Latitude	Sediment Quality Survey Actual Longitude	Water Depth (m) (tide corrected, relative to Mean Lower Low Water)
TRI-004	1	324231	47.568998	122.346568	47.568965	122.346559	7.9
TRI-008	2	324232	47.567902	122.347895	47.567932	122.347971	11.6
TRI-010	3	324233	47.566395	122.348997	47.566416	122.349023	8.0
TRI-015T	4	324234	47.565108	122.347997	47.565058	122.348051	11.6
TRI-016	5	324235	47.565150	122.348828	47.565138	122.348827	10.6
TRI-026	6	324236	47.559247	122.344645	47.559220	122.344662	8.8
TRI-036	7	324237	47.555327	122.345645	47.555315	122.345633	7.6
TRI-037T	8	324238	47.555068	122.343010	47.555060	122.343011	9.3
TRI-045	9	324239	47.551570	122.341252	47.551557	122.341248	8.5
TRI-047T	10	324240	47.551385	122.341605	47.551377	122.341598	5.1
TRI-048T	11	324241	47.551095	122.341107	47.551078	122.341090	7.1
TRI-050T	12	324242	47.550595	122.340017	47.550578	122.340034	9.7
TRI-051	13	324243	47.550268	122.340540	47.550252	122.340531	9.2
TRI-052	14	324244	47.550143	122.339678	47.550153	122.339689	8.5
TRI-056T	15	324245	47.549648	122.340582	47.549656	122.340590	10.3
TRI-066	16	324246	47.546318	122.338662	47.546298	122.338717	9.4
TRI-069T	17	324247	47.543945	122.336077	47.543934	122.336080	4.2
TRI-096	18	324248	47.534002	122.321747	47.533998	122.321760	4.8
DR-181	19	324249	47.535473	122.319710	47.535463	122.319718	3.3
EIT-066	20	324250	47.535147	122.319812	47.535145	122.319811	2.7
S4-1T	21	324251	47.536103	122.319112	47.536102	122.319106	1.1
S4-2T	22	324252	47.535648	122.319598	47.535650	122.319591	3.1
SPI-125	23	324253	47.544467	122.338125	47.544468	122.338134	5.2
SPI-128	24	324254	47.541003	122.332992	47.541010	122.332978	5.8
TRI-095T	25	324255	47.534832	122.324622	47.534828	122.324608	2.8

Sampling Location ID	Statistical Analysis ID	Chemistry Lab ID	Sediment Quality Survey Target Latitude	Sediment Quality Survey Target Longitude	Sediment Quality Survey Actual Latitude	Sediment Quality Survey Actual Longitude	Water Depth (m) (tide corrected, relative to Mean Lower Low Water)
DR-111	26	324256	47.542397	122.333225	47.542385	122.333230	3.8
DR-157T	27	324257	47.539490	122.331752	47.539483	122.331750	2.1
B4b	28	324258	47.550943	122.339590	47.550944	122.339585	3.1
SPI-104	29	324259	47.567810	122.346995	47.567797	122.346998	10.1
SPI-108	30	324260	47.562588	122.346978	47.562583	122.346968	10.2
CR-02	*31*	*334130*	*47.335833*	*122.664238*	*47.335838*	*122.664215*	*18.0*
CR-24	*32*	*334131*	*47.333300*	*122.673600*	*47.333298*	*122.673614*	*16.5*

Most SPI sampling locations were named using the prefix “SPI” followed by a sequential number, such as SPI-104. Target sampling locations intended to reoccupy or be near historic ones were named in a manner preserving a portion of the historic name. Examples of location names related to recent remedial investigations (Windward Environmental, 2004 and 2005) include “TRI-004” (Ecology’s triad sampling of Windward station 004), “B4b” (subtidal benthic station 4), “S4-1T” (Slip 4, Station 1), and “DR-111” (Duwamish River station 111). Locations with a “T” suffix indicate they were intentionally offset by approximately 10 meters from an historic location.

Appendix B - Analytical Methods and Quality Assurance

Table B-1. Sample preparation methods, cleanup methods, analytical methods, and detection limits for sediments collected from the Lower Duwamish Waterway.

Chemical	Sample Preparation Methods[a]	Sample Cleanup Methods[b]	Analytical Methods[c]	Reporting Limits[d, e] (µg/kg dry wt)
Metals				
Antimony	SW 846	--	SW 846	50,000
Arsenic	3050	--	6010/6020	19,000
Cadmium	3050	--	6010/6020	1,700
Chromium	3050	--	6010/6020	87,000
Copper	3050	--	6010/6020	130,000
Lead	3050	--	6010/6020	150,000
Mercury	--[f]	--	7471	140
Nickel	3050		6010/6020	47,000
Silver	3050	--	6010/6020	2,000
Zinc	3050	--	6010/6020	137,000
Non-ionizable Organic Compounds				
LPAH Compounds				
Naphthalene	3541 or 3545	3630 or 3640	8270/1625	700
Acenaphthylene	3541 or 3545	3630 or 3640	8270/1625	430
Acenaphthene	3541 or 3545	3630 or 3640	8270/1625	170
Fluorene	3541 or 3545	3630 or 3640	8270/1625	180
Phenanthrene	3541 or 3545	3630 or 3640	8270/1625	500
Anthracene	3541 or 3545	3630 or 3640	8270/1625	320
2-Methylnaphthalene	3541 or 3545	3630 or 3640	8270/1625	220
HPAH Compounds				
Fluoranthene	3541 or 3545	3630 or 3640	8270/1625	570
Pyrene	3541 or 3545	3630 or 3640	8270/1625	870
Benz[a]anthracene	3541 or 3545	3630 or 3640	8270/1625	430
Chrysene	3541 or 3545	3630 or 3640	8270/1625	470
Total benzofluoranthene[g]	3541 or 3545	3630 or 3640	8270/1625	1070
Benzo[a]pyrene	3541 or 3545	3630 or 3640	8270/1625	530
Indeno[1,2,3-cd]pyrene	3541 or 3545	3630 or 3640	8270/1625	200
Dibenz[a,h]anthracene	3541 or 3545	3630 or 3640	8270/1625	80
Benzo[ghi]perylene	3541 or 3545	3630 or 3640	8270/1625	220
Chlorinated Benzenes				
1,2-Dichlorobenzene	3541 or 3545	3630 or 3640	8270	35
1,3-Dichlorobenzene	3541 or 3545	3630 or 3640	8270	55
1,4-Dichlorobenzene	3541 or 3545	3630 or 3640	8270	35
1,2,4-Trichlorobenzene	3541 or 3545	3630 or 3640	8270	30
Hexachlorobenzene	3541 or 3545	3630 or 3640	8270	20
Phthalate Esters				
Dimethyl phthalate	3541 or 3545	3630 or 3640	8270	25
Diethyl phthalate	3541 or 3545	3630 or 3640	8270	65
Di-n-butyl phthalate	3541 or 3545	3630 or 3640	8270	470
Butyl benzyl phthalate	3541 or 3545	3630 or 3640	8270	20
Bis[2-ethylhexyl]phthalate	3541 or 3545	3630 or 3640	8270	430
Di-n-octyl phthalate	3541 or 3545	3630 or 3640	8270	2070
Miscellaneous Extractable Compounds				
Dibenzofuran	3541 or 3545	3630 or 3640	8270	180
Hexachlorobutadiene	3541 or 3545	3630 or 3640	8270	10

Chemical	Sample Preparation Methods[a]	Sample Cleanup Methods[b]	Analytical Methods[c]	Reporting Limits[d, e] (µg/kg dry wt)
Hexachloroethane	3541 or 3545	3630 or 3640	8270	45
N-nitrosodiphenylamine	3541 or 3545	3630 or 3640	8270	25
PCBs				
PCB Aroclors®	3541 or 3545	3630 or 3640	8082	5
Ionizable Organic Compounds				
Phenol	3541 or 3545	3630 or 3640	8270	140
2-Methylphenol	3541 or 3545	3630 or 3640	8270	60
4-Methylphenol	3541 or 3545	3630 or 3640	8270	220
2,4-Dimethylphenol	3541 or 3545	3630 or 3640	8270	25
Pentachlorophenol	3541 or 3545	3630 or 3640	8270	120
Benzyl alcohol	3541 or 3545	3630 or 3640	8270	55
Benzoic acid	3541 or 3545	3630 or 3640	8270	210

[a] Recommended methods include the 3500 series from SW-846 (EPA, 1996 and updates. Test Methods for Evaluating Solid Waste, Physical/Chemical Methods. (Contains 1000 – 9000 series methods.) EPA Publication SW-846, Fourth Edition, December 1996. www.epa.gov/epaoswer/hazwaste/test/main.htm.
[b] Method 3630 (Silica Gel Cleanup) is recommended. Other sample cleanup methods that may be used include 3640 (Gel Preparation Chromatography), 3660 (sulfur cleanup), 3620 (florisil column cleanup for all PCB extracts) or others (EPA, 1996 and updates. Test Methods for Evaluating Solid Waste, Physical/Chemical Methods. (Contains 1000 – 9000 series methods.) EPA Publication SW-846, Fourth Edition, December 1996. www.epa.gov/epaoswer/hazwaste/test/main.htm.
[c] Recommended analytical methods include 1624C/1625C – isotope dilution, and the 6000, 7000, 8000, and 9000 series from publication SW-846 ((EPA, 1996 and updates. Test Methods for Evaluating Solid Waste, Physical/Chemical Methods. (Contains 1000 – 9000 series methods.) EPA Publication SW-846, Fourth Edition, December 1996. www.epa.gov/epaoswer/hazwaste/test/main.htm.
[d] To achieve reporting limits for some BNA compounds, it may be necessary to reduce the water content of the sample, use an additional sample cleanup step to reduce interference, use a smaller extract volume for gas chromatography/mass spectrometry analyses (0.5 mL), or use a larger sample size (Ecology 2003). Limits shown are on a dry-weight basis unless otherwise indicated. Analysis of low-TOC sediments for contaminants with TOC-normalized criteria may require lower reporting limits.
[e] Limits based on one-third the 1988 dry weight lowest apparent effects threshold value (LAET, Barrick, et al, 1988) except for 1,2-dichlorobenzene, 1,2,4-trichlorobenzene, hexachlorobenzene, hexachlorobutadiene, n-nitrosodiphenylamine, 2-methylphenol, 2,4-dimethylphenol, and benzyl alcohol. Limits for these compounds are equal to the value of the 1988 dry weight LAET.
[f] The sample digestion method for mercury is described in the analytical method (Method 7471, EPA SW-846 (US EPA, 1986 and updates).
[g] Total benzofluoranthenes represent the sum of the b, j, and k isomers.

Table B-2. Summary of quality assurance review findings for Lower Duwamish Waterway sediment quality-related results.

QA review element → Parameter ↓		Methods	Holding/ handling	Calibrations/	Blanks	RLs	RPD/ RSD	LCS	Matrix spike recovery/MSD	Distance to target (mean)	Decision
Positioning		Per QAPP								± 4.6'	Acceptable, Representative
Sampling		Per QAPP	Per QAPP								Acceptable
Conventionals	Total Solids	Per QAPP	Per QAPP	Acceptable	<0.01%	0.01%	RPD < 1%				Acceptable
	Grain size	Per QAPP	Per QAPP	Acceptable	<1%	1%	RSD < 5%				Acceptable
	TOC (%)	Per QAPP	Per QAPP	Acceptable	<0.1 <0.1	0.1 0.1	RSD < 5%	< ±20%			Acceptable
	Ammonia (mg/Kg)	Per QAPP	Per QAPP	Acceptable	<0.1	0.1	RSD 1-12 %	99-101%	89-101%		Acceptable
	Sulfide (mg/Kg)	Per QAPP	Per QAPP	Acceptable	<0.05	0.05	RSD 2-4%	92-105%	55%, 79%, 170%		Acceptable, some results qualified
Chemistry	Metals (mg/Kg)	Per QAPP	Per QAPP	Acceptable	< RLs	Per QAPP	Some > control limits	95-114%	Sb < 20%, some others > control limits		Acceptable, some results qualified
	TBT (µg/Kg)	Per QAPP	Per QAPP	Acceptable	< 2.0	Per QAPP	RPD 8.6%	CRM 63-82%	MSD 3.3%-24.3%		Acceptable
	BNAs (µg/Kg)	Per QAPP	Per QAPP	Some responses outside	<RLs, some exceptions	Per QAPP, some	<40%, some exceptions	Acceptable, except benzoic	Some low recoveries		Acceptable, some results

QA review element → Parameter ↓		Methods	Holding/ handling	Calibrations/	Blanks	RLs	RPD/ RSD	LCS	Matrix spike recovery/MSD	Distance to target (mean)	Decision
				acceptable range		exceptions		acid			qualified as estimates
	PCBs (µg/Kg)	Per QAPP	Per QAPP	Acceptable	<RLs	7-13	10%	43-57%	40-60% MSD 27-33%		Acceptable, all results qualified as estimates (biased low)
		Methods	Holding/ handling	Test conditions, water quality	Control performance	Reference sample performance					
Toxicity	Amphipod	Per QAPP	Per QAPP	Minor deviations	OK	OK					Acceptable
	Larval	Per QAPP	Per QAPP	Minor deviations	OK	OK					Acceptable
Benthic Community		Minor deviations	Minor deviations	Formalin for Batch #1 prepared using freshwater (see text). Batches held too long between sampling and rescreening (see text).							Acceptable

RLs = reporting limits
RPD/RSD = relative percent difference (duplicates)/relative standard deviation (triplicates)
LCS = laboratory control sample
MSD = matrix spike duplicates
CRM = certified reference material
QAPP = Quality Assurance Project Plan
TOC = total organic carbon
TBT = tributyl tin
PAHs = polycyclic aromatic hydrocarbon compounds
PCBs = polychlorinated biphenyls
As, Cu, Hg, Pb, Zn etc. = symbol for metallic elements (consult periodic table)
(See Glossary for definition of other acronyms.)

Table B-3. Analysis of condition of benthic community samples to assess potential negative effects from excessive exposures to formalin preservative.

Taxonomic Group	Percent Total Abundance	Percent Annelida taxa with juvenile individuals only	Maximum percent damaged individuals	Percent taxa noted in poor condition	Total taxa	Percent taxa identified > genus	Percent taxa identified > species
Annelida	59.7	< 0.1	Not provided	Not provided	107	2.8	16.8
Crustacea	7.7	0.0	Not provided	Not provided	43	0.0	20.9
Mollusca	32.0	0.15	Not provided	Not provided	36	0.0	11.1
All other taxa	0.5	0.0	Not provided	Not provided	26	0.0	38.5
Total	100.0	0.1	Not provided	Not provided	212	1.4	19.3

Table B-4. Quality assurance summary for sorting benthic macroinvertebrates into major taxonomic groups prior to community analysis. Sort efficiency equals [1- (QA x 4)/Total]*100.

Taxa and Sort Data: Station ID ↓	Annelida	Mollusca	Crustacea	Misc	Total	QA	Sort Efficiency	QA Status
TRI-004	1046	366	72	3	1487	18	95.4	Pass
TRI-008	381	572	265	2	1220	3	99.0	Pass
SPI-104	499	378	85	1	963	3	98.8	Pass
TRI-010	188	438	219	2	847	3	98.6	Pass
TRI-016	1178	492	115	4	1789	3	99.3	Pass
TRI-015T	852	442	270	1	1565	6	98.5	Pass
SPI-108	487	1131	321	8	1947	3	99.4	Pass
TRI-026	117	223	71	2	413	0	100.0	Pass
TRI-036	772	225	23		1020	5	98.1	Pass
TRI-037T	240	196	15	2	453	2	98.3	Pass
TRI-045	367	173	17		557	4	97.2	Pass
TRI-047T	557	69	36	3	665	2	98.8	Pass
TRI-048T	470	597	95	4	1166	4	98.6	Pass
B4b	421	499	90	2	1012	3	98.8	Pass
TRI-050T	427	280	43	3	753	2	98.9	Pass
TRI-051	481	551	75	4	1111	2	99.3	Pass
TRI-052	349	633	43	3	1028	0	100.0	Pass
TRI-056T	961	343	29	1	1334	0	100.0	Pass
TRI-066	1001	233	11	1	1246	0	100.0	Pass
SPI-125	294	9	11		314	0	100.0	Pass
TRI-069T	489	172	12		673	5	97.1	Pass
DR-111	433	13	3	1	450	2	98.3	Pass
SPI-128	884	21	3	1	909	2	99.1	Pass
DR-157T	216	16	112		344	1	98.9	Pass
S4-1T	184	12	2		198	2	96.1	Pass
S4-2T	254	15			269	2	97.1	Pass
DR-181	875	73	4	1	953	2	99.2	Pass
EIT-066	287	9	2		298	1	98.7	Pass
TRI-095T	379	8	13		400	0	100.0	Pass

Taxa and Sort Data: Station ID ↓	Annelida	Mollusca	Crustacea	Misc	Total	QA	Sort Efficiency	QA Status
TRI-096	223	35	2	1	261	0	100.0	Pass
CR-02	19	9			28	0	100.0	Pass
CR-24	248	53	298	13	612	0	100.0	Pass

Appendix C - SPI and Triad Survey Results

Table C-1. Summary and descriptive statistics for selected SPI results from the Lower Duwamish Waterway.

Results listed represent the mean of three replicates. Complete results can be found in Germano and Associates (2007).

Sampling location	Preliminary stratum	Penetration depth (cm)	Boundary roughness (cm)	RPD (mean depth cm)	Voids (total number)	Voids (max. depth cm)	Number of mudclasts	Small tubes (total)	Burrows (total number)	Number of oxic voids	Total number of voids + tubes + burrows	Organism Sediment Index	Benthic Habitat Quality Index
TRI-004	L	13.7	0.7	1.8	0.33	3.7	0.3	3.3	11.3	0.3	15.00	7.33	9.67
TRI-008	L	17.2	0.6	2.8	1.33	11.2	0.3	2.0	9.7	1.0	13.00	8.33	11.67
SPI-104	M	16.6	0.8	2.4	3.00	9.8	3.3	1.3	10.7	3.0	15.00	8.67	11.33
TRI-010	L	17.5	0.8	2.9	2.00	12.2	1.3	2.0	8.0	2.0	12.00	9.67	12.00
TRI-016	M	14.0	0.8	2.0	0.67	8.7	0.7	1.0	10.3	0.7	12.00	8.00	10.33
TRI-015T	H	16.9	1.4	3.0	0.33	8.2	1.0	2.0	9.3	0.3	11.67	8.67	10.33
SPI-108	L	16.3	0.8	2.7	0.50	5.9	0.0	5.0	7.5	0.5	13.00	9.00	11.50
TRI-026	M	11.0	2.7	0.9	0.33	8.1	2.3	3.5	6.5	0.3	10.33	7.00	9.00
TRI-036	L	16.6	0.8	3.1	2.33	11.3	0.0	1.3	10.0	2.3	13.67	9.67	12.00
TRI-037T	H	15.8	0.9	1.9	1.00	8.1	0.0	5.0	10.0	1.0	16.00	7.67	11.67
TRI-045	L	17.7	1.5	3.3	1.00	10.4	1.0	3.3	12.0	1.0	16.33	9.67	11.67
TRI-047T	H	18.2	2.2	3.0	2.00	16.3	0.3	1.0	7.7	2.0	10.67	9.33	11.33
TRI-048T	H	20.1	1.9	5.1	0.33	12.6	1.0	2.0	9.7	0.3	12.00	11.00	12.33
B4b	M	18.4	1.4	4.9	1.33	10.4	7.3	6.0	10.7	1.3	18.00	11.00	13.33
TRI-050T	M	18.9	2.4	4.5	2.00	13.7	2.7	5.7	5.3	2.0	13.00	10.33	13.00
TRI-051	L	19.1	0.9	4.2	2.00	7.7	2.3	4.7	10.7	2.0	17.33	10.67	13.00
TRI-052	L	19.6	1.4	5.4	2.00	12.2	3.3	2.3	9.7	2.0	14.00	11.00	13.00
TRI-056T	H	15.8	1.3	3.9	4.33	11.4	1.5	2.7	10.0	4.3	17.00	10.33	12.67
TRI-066	L	18.5	1.3	4.1	2.33	13.7	1.7	3.7	11.0	2.3	17.00	10.67	12.00
SPI-125	H	14.1	2.5	1.0	0.00	--	0.7	2.0	3.3	0.0	5.33	5.33	8.33
TRI-069T	M	16.6	1.3	3.2	0.00	--	4.0	2.0	7.7	0.0	9.67	9.67	9.67
DR-111	H	16.6	1.2	2.2	0.67	13.6	5.0	2.7	11.0	0.7	14.33	8.67	10.33

Sampling location	Preliminary stratum	Penetration depth (cm)	Boundary roughness (cm)	RPD (mean depth cm)	Voids (total number)	Voids (max. depth cm)	Number of mudclasts	Small tubes (total)	Burrows (total number)	Number of oxic voids	Total number of voids + tubes + burrows	Organism Sediment Index	Benthic Habitat Quality Index
SPI-128	H	13.7	1.4	2.3	1.00	6.5	0.0	4.0	8.67	1.0	13.67	8.67	11.00
DR-157T	H	8.5	1.0	1.3	0.00	7.2	0.0	>40	16.3	0.3	>56.3	6.33	9.33
S4-1T	H	15.9	3.6	4.2	1.00	5.5	0.0	1.0	5.0	1.0	7.00	10.00	11.00
S4-2T	H	14.8	1.2	3.2	0.67	14.5	1.3	1.0	6.3	0.7	8.00	8.67	10.00
DR-181	H	15.4	1.7	3.1	0.33	13.9	0.0	0.3	9.7	0.3	10.33	9.00	10.33
EIT-066	H	13.3	1.7	2.1	0.00	--	2.5	2.0	6.0	0.0	8.00	7.50	9.50
TRI-095T	H	14.0	1.5	2.6	0.67	3.8	2.0	1.7	11.0	0.7	13.33	8.67	10.33
TRI-096	L	14.2	3.1	0.8	0.00	--	1.7	10.3	6.7	0.0	17.00	6.67	8.33
CR-02	R	--	--	--	--	--	--	--	--	--	--	--	--
CR-24	R	--	--	--	--	--	--	--	--	--	--	--	--
Count		30	30	30	30	26	30	29	30	30	30	30	30
Minimum		8.5	0.7	0.7	0.0	3.7	0.0	0.3	3.3	0.0	5.3	5.3	8.3
Median		16.4	1.4	2.9	0.8	10.4	1.2	2.0	9.7	0.8	13.2	8.8	11.2
Mean		16.0	1.5	2.9	1.1	10.0	1.6	2.9	9.1	1.1	14.3	8.9	11.0
Maximum		20.1	3.6	5.4	4.3	16.3	7.3	10.3	16.3	4.3	18.0	11.0	13.3
Range		11.6	3.0	4.6	4.3	12.6	7.3	10.0	13.0	4.3	12.7	5.7	5.0
25th percentile		14.1	0.9	2.1	0.3	7.8	0.3	1.7	7.5	0.3	10.7	8.1	10.1
75th percentile		17.6	1.6	3.7	2.0	12.5	2.3	3.7	10.7	2.0	15.0	9.9	12.0
Interquartile range (IQR)		3.5	0.7	1.6	1.7	4.6	2.0	2.0	3.1	1.7	4.3	1.8	1.9
25th percentile +1.5*IQR		10.7	0.2	0.5	-1.3	3.2	-1.7	-0.3	4.4	-1.3	6.3	6.3	8.2
75th percentile +1.5*IQR		21.1	2.4	5.4	3.7	17.1	4.3	5.7	13.8	3.7	19.3	11.8	13.9
Stand. Dev. (s)		2.6	0.7	1.2	1.0	3.4	1.7	2.1	2.6	1.0	3.3	1.5	1.4
Mean - 2.5s		9.6	-0.4	-0.1	-1.5	1.5	-2.7	-2.3	2.6	-1.5	6.1	5.2	7.5
Mean + 2.5s		22.3	3.4	6.0	3.7	18.5	5.9	8.1	15.5	3.7	22.6	12.6	14.5

Table C-2. Summary and descriptive statistics for sediment conventionals at 30 sampling locations in the Lower Duwamish Waterway and two potential reference sample locations in Carr Inlet.

Sampling Location = Station ID	Preliminary stratum	Temperature (ºC)	Salinity (ppt)	Total Solids (% dry wt.)	Sand (% dry wt.)	Silt (% dry wt.)	Clay (% dry wt.)	Fines (% dry wt.)	TOC (% dry wt.)	Ammonia (mg/Kg dry wt.)	Sulfide (mg/Kg dry wt.)
TRI-004	L	-	-	46	20.8	51.7	26.1	77.8	2.81	21.2	1490
TRI-008	L	-	-	47.3	25.1	55.8	19.2	75	2.36	13.3	1500
SPI-104	M	-	28	48.8	21.7	54.2	24.1	78.3	2.11	10.7	250
TRI-010	L	-	-	49.0	26.3	54.5	19.2	73.7	2.20	5.6	1090
TRI-016	M	-	-	48.4	21.3	56.7	22.0	78.7	2.38	26.9	870
TRI-015T	H	-	-	47.6	25.6	55	18.7	73.7	2.16	9.1	697
SPI-108	L	14.5	28	56.4	43.4	41.4	14.9	56.3	1.55	11.3	487
TRI-026	M	-	-	56.0	31.1	48.6	20.0	68.6	1.61	5.8	838
TRI-036	L	15	27	43.2	17.0	60.9	21.0	81.9	2.47	20.2	1130
TRI-037T	H	15.5	28	50.1	27.1	55.6	17.0	72.6	2.14	9.3	1150
TRI-045	L	16	26.5	47.6	30.7	50.8	17.1	67.9	2.26	14.6	445
TRI-047T	H	15	26.5	47.4	25.6	52.6	19.2	71.8	2.57	14.2	448
TRI-048T	H	-	-	45.2	27.0	55.8	16.3	72.1	2.73	37.9	262
B4b	M	15	25	47.2	34.2	49.6	15.1	64.7	2.25	24.0	532
TRI-050T	M	15	26.5	45.2	20.1	63	14.5	77.5	2.69	22.7	233
TRI-051	L	15	22	45.3	23.6	59.1	17.2	76.3	2.72	9.8	266
TRI-052	L	14	27	45.8	18.2	62.4	19.4	81.8	2.81	11.1	268
TRI-056T	H	14.5	25	43.2	10.5	67.7	21.0	88.7	2.75	16.1	156
TRI-066	L	15	25	42.5	20.7	62.2	17.1	79.3	3.22	16.3	606
SPI-125	H	14.5	27	44.7	17.4	61.9	18.4	80.3	2.73	18.8	1610
TRI-069T	M	16	23	45.0	28.5	53.8	17.4	71.2	2.85	17.2	711
DR-111	H	15.5	21	53.3	13.8	67.9	18.3	86.2	2.84	17.2	1440
SPI-128	H	15.5	28	48.8	36.8	51.8	11.3	63.1	2.23	15.6	1110
DR-157T	H	16	20	38.2	57.1	34.5	7.0	41.5	1.69	8.8	1020
S4-1T	H	17	24	38.3	14.2	70.3	15.6	85.9	3.13	14.7	14100

Sampling Location = Station ID	Preliminary stratum	Temperature (°C)	Salinity (ppt)	Total Solids (% dry wt.)	Sand (% dry wt.)	Silt (% dry wt.)	Clay (% dry wt.)	Fines (% dry wt.)	TOC (% dry wt.)	Ammonia (mg/Kg dry wt.)	Sulfide (mg/Kg dry wt.)
S4-2T	H	15.5	25	39.2	14.0	65.6	20.3	85.9	2.98	23.8	734
DR-181	H	16	24	39.5	12.4	68.4	19.2	87.6	3.20	30.5	946
EIT-066	H	16	23	44.4	25.6	56.2	18.3	74.5	2.42	15.7	1060
TRI-095T	H	15	20	43.7	21.8	65.1	13.1	78.2	2.39	10.4	655
TRI-096	L	16	21	54.1	50.3	37.4	11.3	48.7	1.79	10.9	844
CR-02	R	12.8	30	40.1	16	67.9	15.9	83.8	1.34	27.1	479
CR-24	R	12.7	32	62.1	34.8	58.8	6.2	65	0.62	6.8	27
Count		22	23	30	30	30	30	30	30	30	30
Minimum		14.0	20.0	38.2	10.5	34.5	7.0	41.5	1.55	5.6	156
Median		15.3	25.0	45.9	24.4	55.8	18.3	75.7	2.45	15.2	786
Mean		15.3	24.8	46.4	25.4	56.4	17.6	74.0	2.47	16.1	1232
Maximum		17.0	28.0	56.4	57.1	70.3	26.1	88.7	3.22	37.9	14100
Range		3.0	8.0	18.2	46.6	35.8	19.1	47.2	1.67	32.3	13944
25th percentile				43.9	18.7	52.0	15.8	71.4	2.21	10.8	457.8
75th percentile				48.7	28.2	62.4	19.4	80.1	2.80	19.9	1105.0
Interquartile range (IQR)				4.8	9.5	10.4	3.6	8.7	0.59	9.1	647.3
25th percentile + 1.5*IQR				39.1	9.2	41.7	12.2	62.7	1.62	1.7	-189.5
75th percentile + 1.5*IQR				53.5	37.6	72.7	22.9	88.8	3.38	29.0	1752.3
Stand. Dev. (s)				4.7	10.7	8.7	3.8	10.9	0.45	7.4	2465.5
Mean - 2.5s				34.7	-1.3	34.5	8.0	46.9	1.34	-2.3	-4932.3
Mean + 2.5s				58.0	52.1	78.2	27.2	101.1	3.59	34.5	7395.5

Table C-3. Summary and descriptive statistics for contaminant chemistry measured at 30 sampling locations in the Lower Duwamish Waterway and two potential reference sample locations in Carr Inlet.

Complete results, including those for other individual SMS organic contaminants of concern and relevant sample reporting limits, are available upon request. "u" = not detected at reporting limit. Dry weight normalized reporting limits were below the SQS for all contaminants except for N-nitrosodiphenylamine (which never exceeded the SQS when normalized to organic carbon).

Sampling Location = Station ID	Preliminary stratum	Antimony	Arsenic	Cadmium	Copper	Chromium	Lead	Mercury	Nickel	Silver	Zinc	∑Metals	TBT-Cl	TBT+	2,4-dimethylphenol	Benzoic acid	∑LPAH	∑HPAH	∑PAH	∑PCBS	∑Phthalates	∑Phenols
TRI-004	L	0.56	21.4	0.69	104	43.6	79.8	0.451	26.7	0.56	200	478	43	38	50	174	930	6110	7040	216	58	328
TRI-008	L	0.62	13.8	0.68	100	41.4	74.8	0.491	26.6	0.56	220	479	53	48	52	158	1049	4974	6023	183	173	351
SPI-104	M	0.20	12.1	0.83	105	37.7	85.9	0.461	27.5	0.65	180	450	50	44	77	108	730	4666	5396	313	795	464
TRI-010	L	0.78	12.2	0.55	93.6	39.6	66.7	0.324	26.6	0.50	160	401	85	76	45	139	963	4493	5456	159	53	181
TRI-016	M	0.57	16.2	0.55	105	41.7	74.6	0.401	28.4	0.53	180	448	78	70	44	136	606	3130	3736	185	62	755
TRI-015T	H	0.44	13.6	0.59	101	36.7	71.8	0.551	27.0	0.52	170	422	75	67	u	151	1053	4791	5844	207	63	84
SPI-108	L	0.22	10.6	0.52	79.5	32.2	53.5	0.285	24.3	0.36	130	331	85	76	52	u	901	4431	5332	380	u	372
TRI-026	M	0.43	10.3	0.67	91.6	38.3	84.5	0.331	24.9	0.58	140	392	98	87	u	125	654	2919	3573	304	47	258
TRI-036	L	0.33	18.8	0.54	106	39.0	59.7	0.313	25.6	0.39	170	421	15	13	u	166	4485	12852	17337	173	190	90
TRI-037T	H	0.38	12	0.50	75.0	35.6	44.3	0.24	26.1	0.26	150	344	70	63	u	133	520	2375	2895	140	83	69
TRI-045	L	7.4	52.1	0.72	207	40.5	89.0	0.251	27.3	0.57	269	694	196	174	45	145	1785	9872	11657	233	32	409
TRI-047T	H	5.1	44	0.67	210	48.0	96.3	0.242	27.2	0.51	324	756	134	119	52	241	2185	8165	10350	283	40	502
TRI-048T	H	0.73	28	0.64	158	41.0	63.4	0.318	28.0	1.00	220	541	28	25	49	158	1025	5111	6136	165	112	156
B4b	M	0.20	14	0.74	103	36.9	66.5	0.358	26.4	0.39	180	428	55	49	65	126	617	3807	4424	223	675	363
TRI-050T	M	0.3	15.2	0.52	73.2	37.1	39.0	0.222	28.7	0.25	140	334	38	34	47	164	380	2058	2438	126	64	195
TRI-051	L	0.66	18.7	0.58	110	38.7	52.7	0.252	28	0.31	170	420	77	69	46	150	509	2611	3120	132	35	189
TRI-052	L	0.41	15.9	0.58	83.4	38.25	48.6	0.2945	27.2	0.33	145	360	32	28	46	158	543	2829	3372	162	80	189
TRI-056T	H	0.4	18.4	0.51	88.3	37.6	45	0.217	27.9	0.29	150	369	32	29	49	173	562	2849	3411	170	48	147
TRI-066	L	0.26	13.7	0.38	60.2	29.8	31.7	0.171	22.8	0.23	120	279	22	20	49	178	475	2509	2984	134	56	148
SPI-125	H	0.20	15.4	0.73	94.0	33.0	58.4	0.257	27.0	0.35	170	399	44	39	64	140	378	3090	3468	237	27	152
TRI-069T	M	0.31	14.6	0.78	83.6	35.4	49.6	0.197	24.9	0.37	160	370	17	15	49	165	965	3942	4907	670	102	158
DR-111	H	0.20	15.1	0.53	76.2	33.0	40.9	0.152	25.3	0.29	140	332	23	21	54	118	277	2016	2293	176	u	109

Sampling Location = Station ID	Preliminary stratum	Antimony	Arsenic	Cadmium	Copper	Chromium	Lead	Mercury	Nickel	Silver	Zinc	∑Metals	TBT-Cl	TBT+	2,4-dimethylphenol	Benzoic acid	∑LPAH	∑HPAH	∑PAH	∑PCBS	∑Phthalates	∑Phenols
SPI-128	H	0.20	10.5	0.32	44.5	24.1	23.7	0.115	20.9	0.15	96	220	13	12	58	126	146	1061	1207	174	20	170
DR-157T	H	0.20	11.1	0.38	50.4	28.6	69.5	0.389	18.1	0.2	120	299	22	20	u	278	1718	7457	9175	1600	u	348
S4-1T	H	0.20	17.8	0.80	76.8	34.8	57.5	0.21	25.2	0.51	180	394	45	40	79	199	535	4765	5300	1100	1299	244
S4-2T	H	0.20	15.3	0.67	76.8	32.3	47.8	0.178	23.9	0.36	160	358	24	21	77	205	369	3368	3737	400	917	336
DR-181	H	0.21	19.6	0.53	73.8	36.7	41.6	0.167	27.4	0.29	150	350	20	u	U	189	360	2638	2998	458	712	139
EIT-066	H	0.20	14.5	0.79	64.7	32.6	48.1	0.191	22.0	1.20	130	314	20	17	68	124	246	1989	2235	3200	u	294
TRI-095T	H	0.20	12.8	0.36	54.5	30.6	26.4	0.251	26.8	0.17	120	272	8.1	7	64	114	425	2313	2738	97	u	284
TRI-096	L	0.20	10.3	0.31	53.8	25.7	23.3	0.0952	18.7	0.23	100	233	5.7	5	52	180	112	1032	1144	221	u	145
CR-02	R	0.20	5.3	0.72	26.9	33.6	9.35	0.047	34.7	0.14	58	169	4.2	4	U	128	u	20	20	12	u	81
CR-24	R	0.20	3.3	0.28	17.2	27.1	4.9	0.029	32.2	0.10	41	126	2.3	2	U	u	u	22	22	u	u	46
Count		30	30	30	30	30	30	30	30	30	30	30	25	29	24	30	30	30	24	30	25	29
Minimum		0	10	0.31	45	24	23	0.10	18	0	96	220	18	108	44	1032	1144	97	20	69	18	108
Median		0	15	0.58	86	37	56	0.25	27	0	160	381	52	158	52	3249	3737	212	63.5	192	52	158
Mean		1	17	0.59	93	36	57	0.28	26	0	165	396	54	159	56	4141	4991	407	239	254	54	159
Maximum		7	52	0.83	210	48	96	0.55	29	1	324	756	79	278	79	12852	17337	3200	1299	755	79	278
Range		7	42	0.52	166	24	73	0.46	11	1	228	536	61	170	35	11820	16193	3103	1279	686	61	170
25th percentile		0.2	12.4	0.52	74.1	32.7	44.5	0.20	24.9	0.29	140.0	332.4	47.0	133.0	48.5	2534.5	2987.5	166.3	47.8	149.0	47.0	133.0
75th percentile		0.5	18.3	0.69	103.8	38.9	71.2	0.33	27.3	0.53	180.0	426.9	64.0	174.0	64.0	4784.5	5747.0	310.8	177.3	345.0	64.0	174.0
Interquartile range (IQR)		0.3	5.9	0.17	29.7	6.2	26.8	0.13	2.4	0.24	40.0	94.5	17.0	41.0	15.5	2250.0	2759.5	144.5	129.5	196.0	17.0	41.0
25th percentile - 1.5*IQR		-0.1	6.5	0.35	44.5	26.5	17.7	0.07	22.5	0.05	100.0	237.8	30.0	92.0	33.0	284.5	228.0	21.8	-81.8	-47.0	30.0	92.0
75th percentile + 1.5*IQR		0.9	24.2	0.86	133.4	45.2	98.0	0.46	29.7	0.77	220.0	521.5	81.0	215.0	79.5	7034	8506	455.3	306.8	541.0	81.0	215.0
Stand. Dev. (s)		1.5	9.2	0.14	38.7	5.2	19.6	0.11	2.7	0.23	47.3	115.3	13.0	37.8	10.9	2605.3	3401	613.4	353.9	149.9	13.0	37.8
Mean - 2.5s		-3.1	-5.9	0.23	-3.2	23.0	8.1	0.00	18.8	-0.14	46.5	108.2	21.4	64.8	28.3	-2372	-3511	-1126	-646	-120	21.4	64.8
Mean + 2.5s		4.6	40.4	0.95	190.1	49.0	106.2	0.56	32.3	1.00	283.1	684.4	86.6	253.8	82.8	10654	13493	1940.8	1124	629.1	86.6	253.8

Table C-4. Summary of acute sediment toxicity testing results for 30 sampling locations in the Lower Duwamish Waterway and two reference sample locations in Carr Inlet.

Complete results from final toxicity report (Weston Solutions, 2006) available on request.

Sampling Location	Amphipod mortality vs. CR-02	Amphipod mortality vs. CR-24	Amphipod "Hit"?	Larval combined abnormality + mortality vs. CR-02	Larval combined abnormality + mortality vs. CR-24	Larval "Hit"?	SMS toxicity[a]
TRI-004	14	na	--	47.4	na	CSL	CSL
TRI-008	5	5	--	0.1	0.1	--	--
SPI-104	15	na	--	2.8	na	--	--
TRI-010	8	8	--	23.1	23.1	SQS[c]	SQS
TRI-016	15	na	--	2.2	na	--	--
TRI-015T	9	9	--	4.2	4.2	--	--
SPI-108	na	10	--	na	6.9	--	--
TRI-026	na	6	--	na	1.2	--	--
TRI-036	9	na	--	1.2	na	--	--
TRI-037T	na	11	--	na	0.0	--	--
TRI-045	na	12	--	na	8.9	--	--
TRI-047T	na	10	--	na	4.0	--	--
TRI-048T	na	6	--	na	19.5	SQS	SQS
B4b	na	5	--	na	14.9	--	--
TRI-050T	3	na	--	16.6	na	--[b]	--
TRI-051	3	na	--	6.8	na	--	--
TRI-052	8	na	--	13.8	na	--	--
TRI-056T	5	na	--	1.1	na	--	--
TRI-066	8	na	--	0.8	na	--	--
SPI-125	9	na	--	0.0	na	--	--
TRI-069T	na	11	--	na	3.6	--	--
DR-111	3	na	--	2.1	na	--	--
SPI-128	na	3	--	na	19.2	SQS[c]	SQS
DR-157T	na	7	--	na	12.0	--	--
S4-1T	7	na	--	25.4	na	--[b]	--
S4-2T	11	na	--	13.1	na	--	--

Sampling Location	Amphipod mortality vs. CR-02	Amphipod mortality vs. CR-24	Amphipod "Hit"?	Larval combined abnormality + mortality vs. CR-02	Larval combined abnormality + mortality vs. CR-24	Larval "Hit"?	SMS toxicity[a]
DR-181	9	na	--	14.6	na	--	--
EIT-066	13	13	--	0.0	0.0	--	--
TRI-095T	8	na	--	6.9	na	--	--
TRI-096	na	8	--	na	0.0	--	--
CR-02	(7)	(7)	na	na	na	na	--
CR-24	(2)	(2)	na	na	na	na	--

a = overall toxicity status based on acute tests only.
b = significant toxicity at SQS level if compared to alternate reference sample (not preferred based on grain size match).
c = no significant toxicity at SQS level if compared to alternate reference sample (not preferred based on grain size match).

-- = sample did not exhibit significant toxicity at SQS level.
na = not applicable. Reference sample grain size was not best match with test sample or the interpretation was not appropriate.

Note: Grain size (% fines) at 4 sampling locations (TRI-008, TRI-010, TRI-015T, and EIT-066) was considered equally matched to either reference sample.

Table C-5. Summary and descriptive statistics for selected benthic community metrics representing 30 Lower Duwamish Waterway sediment sampling locations and two potential reference sampling locations in Carr Inlet.

Sampling Location = Station ID	Preliminary stratum	Total abundance	Annelida abundance	Crustacea abundance	Mollusca abundance	Miscellaneous taxa abundance	Echinodermata abundance	Miscellaneous taxa + Echinodermata abundance	Total richness	Annelida richness	Crustacea richness	Mollusca richness	SDI	Diversity H'	Evenness J'
TRI-004	L	1489	1046	71	366	5	1	6	60	30	8	18	7	1.0267	0.5774
TRI-008	L	1223	381	262	572	5	3	8	56	25	7	19	7	1.1468	0.6560
SPI-104	M	963	499	80	378	1	5	6	55	27	9	16	6	1.0471	0.6017
TRI-010	L	848	188	213	438	3	6	9	65	30	9	20	7	1.1500	0.6343
TRI-016	M	1791	1178	114	492	6	1	7	67	33	10	18	5	0.9226	0.5053
TRI-015T	H	1566	852	264	442	2	6	8	61	33	9	15	7	1.0870	0.6088
SPI-108	L	1946	487	305	1131	7	16	23	83	48	10	19	6	1.1981	0.6243
TRI-026	M	417	117	66	224	5	5	10	45	20	5	13	8	1.1785	0.7128
TRI-036	L	1023	772	22	225	3	1	4	48	23	7	14	4	0.8895	0.5291
TRI-037T	H	482	259	13	206	2	2	4	37	19	5	10	6	1.0246	0.6533
TRI-045	L	578	388	15	173	0	2	2	43	21	9	11	7	1.0852	0.6643
TRI-047T	H	662	557	36	69	2	0	2	60	37	16	8	6	1.0566	0.5942
TRI-048T	H	1167	470	94	597	5	1	6	62	31	10	17	7	1.1393	0.6356
B4b	M	1012	421	77	499	2	13	15	64	36	10	13	8	1.1947	0.6614
TRI-050T	M	754	427	40	280	4	3	7	44	22	7	9	6	1.0815	0.6581
TRI-051	L	1110	481	70	551	5	5	10	58	27	8	17	7	1.1555	0.6552
TRI-052	L	1029	349	37	633	4	6	10	51	29	4	11	6	1.0292	0.6027
TRI-056T	H	1342	961	28	351	1	1	2	44	22	6	14	4	0.9323	0.5673
TRI-066	L	1248	1001	11	233	3	0	3	38	19	7	9	4	0.8416	0.5327
SPI-125	H	314	294	11	9	0	0	0	22	14	4	4	3	0.7692	0.5730
TRI-069T	M	672	488	8	172	0	4	4	55	32	7	13	6	1.0837	0.6227
DR-111	H	448	433	3	13	0	0	0	23	16	3	5	6	1.0189	0.7482
SPI-128	H	909	884	3	21	1	0	1	37	25	3	8	3	0.8325	0.5309
DR-157T	H	349	216	117	16	0	0	0	23	15	5	3	5	0.9622	0.7066

Sampling Location = Station ID	Preliminary stratum	Total abundance	Annelida abundance	Crustacea abundance	Mollusca abundance	Miscellaneous taxa abundance	Echinodermata abundance	Miscellaneous taxa + Echinodermata abundance	Total richness	Annelida richness	Crustacea richness	Mollusca richness	SDI	Diversity H'	Evenness J'
S4-1T	H	197	184	2	11	0	0	0	15	13	1	1	4	0.8356	0.7105
S4-2T	H	269	254	0	15	0	0	0	23	20	0	3	4	0.8530	0.6264
DR-181	H	955	877	3	73	1	1	2	25	15	3	5	4	0.7790	0.5572
EIT-066	H	302	291	2	9	0	0	0	22	16	2	4	3	0.6890	0.5132
TRI-095T	H	400	379	13	8	0	0	0	23	16	4	3	5	0.8897	0.6534
TRI-096	L	260	222	2	35	0	0	0	29	19	2	8	5	0.9815	0.6711
CR-02	R	28	19	0	9	0	0	0	6	5	0	1	2	0.5104	0.6559
CR-24	R	612	248	95	55	14	200	214	37	20	4	8	7	1.0847	0.6917
Count		30	30	30	30	30	30	30	30	30	30	30	30	30	30
Minimum		197.0	117.0	0.0	8.0	0.0	0.0	0.0	15.0	13.0	0.0	1.0	3.0	0.6890	0.5053
Median		878.5	430.0	32.0	224.5	2.0	1.0	4.0	44.5	22.5	7.0	11.0	6.0	1.0257	0.6254
Mean		857.5	511.9	66.1	274.7	2.2	2.7	5.0	44.6	24.4	6.3	10.9	5.5	0.9960	0.6196
Maximum		1946	1178	305	1131	7.0	16	23	83	48	16	20	8.0	1.1981	0.7482
Range		1749	1061	305	1123	7.0	16	23	68	35	16	19	5.0	0.5091	0.2430
25th %ile		424.8	291.8	8.8	24.5	0.0	0.0	0.3	26.0	19.0	4.0	5.8	4.0	0.8896	0.5741
75th %ile		1152.8	718.3	79.3	441.0	4.0	4.8	7.8	59.5	30.0	9.0	15.8	7.0	1.0865	0.6576
Interquartile range (IQR)		728.0	426.5	70.5	416.5	4.0	4.8	7.5	33.5	11.0	5.0	10.0	3.0	0.1970	0.0834
25th %ile - 1.5*IQR		-303.3	-134.8	-61.8	-392.0	-4.0	-4.8	-7.3	-7.5	8.0	-1.0	-4.3	1.0	0.6926	0.4907
75th %ile - 1.5*IQR		1880.8	1144.8	149.8	857.5	8.0	9.5	15.3	93.0	41.0	14.0	25.8	10.0	1.2835	0.7410
StdDev		477.7	293.4	86.0	264.5	2.2	3.9	5.3	17.6	8.3	3.4	5.7	1.5	0.1402	0.0628
Mean - 2.5*StdDev		-336.7	-221.6	-148.9	-386.6	-3.2	-6.9	-8.2	0.7	3.8	-2.3	-3.4	1.8	0.6456	0.4626
Mean + 2.5*StdDev		2051.7	1245.3	281.0	936.0	7.7	12.4	18.1	88.5	45.1	15.0	25.2	9.2	1.3465	0.7766

Table C-6. Summary of most abundant benthic community taxa found at subtidal 30 locations in the Lower Duwamish Waterway.

Taxa	Major group	Total abundance	Total abundance rank	Percent of total abundance	Total abundance Cumulative %
Aphelochaeta glandaria	A	5736	1	22.3	22.3
Axinopsida serricata	MB	3778	2	14.7	37.0
Cossura pygodactylata	A	2575	3	10.0	47.0
Scoletoma luti	A	2547	4	9.9	56.9
Euphilomedes carcharodonta	C	1435	5	5.6	62.5
Macoma carlottensis	MB	1273	6	4.9	67.4
Nutricola lordi	MB	1253	7	4.9	72.3
Parvilucina tenuisculpta	MB	772	8	3.0	75.3
Heteromastus filobranchus	A	508	9	2.0	77.3
Chaetozone sp N1	A	494	10	1.9	79.2
Rochefortia tumida	MB	372	11	1.4	80.6
Capitella capitata Cmplx	A	338	12	1.3	81.9
Polydora cornuta	A	313	13	1.2	83.1
Euchone limnicola	A	284	14	1.1	84.3
Turbonilla sp.	MG	267	15	1.0	85.3
Prionospio steenstrupi	A	234	16	0.9	86.2
Pseudopolydora kempi	A	222	17	0.9	87.1
Lanassa venusta	A	204	18	0.8	87.9
Euchone incolor	A	161	19	0.6	88.5
Monticellina sp N1	A	152	20	0.6	89.1
Oligochaeta	A	147	21	0.6	89.6
Macoma nasuta	MB	143	22	0.6	90.2
Nephtys cornuta	A	121	23	0.5	90.7
Americorophium salmonis	C	111	24	0.4	91.1
Mediomastus californiensis	A	102	25	0.4	91.5
Eudorella pacifica	C	91	26	0.4	91.8
Macoma yoldiformis	MB	85	27	0.3	92.2
Eochelidium sp.	C	84	28	0.3	92.5
Armandia brevis	A	81	29	0.3	92.8
Artacama coniferi	A	76	30	0.3	93.1

Taxa	Major group	Total abundance	Total abundance rank	Percent of total abundance	Total abundance Cumulative %
Polycirrus sp I (Banse, 1980)	A	74	31	0.3	93.4
Monticellina serratiseta	A	61	32	0.2	93.6
Hobsonia florida	A	54	33	0.2	93.9
Sphaerodoropsis sphaerulifer	A	52	34	0.2	94.1
Aricidea lopezi	A	51	35	0.2	94.3
Barleeia subtenuis	MG	46	36	0.2	94.4
Paraprionospio pinnata	A	45	37	0.2	94.6
Exogone molesta	A	45	38	0.2	94.8
Glycera nana	A	44	39	0.2	95.0

A = Annelida, C = Crustacea, MB = Mollusca/Bivalvia, MG = Mollusca/Gastropoda

Table C-7. Benthic community data for 30 sample locations in the Lower Duwamish Waterway and two potential reference sample locations in Carr Inlet.

Results were reformatted by Ecology staff from raw data provided by Allan Fukuyama (FHTS). "P" values that were reported, indicating presence of a specific taxon, were reassigned the number 1.

Sampling Location→ Taxon ↓	TRI-004	TRI-008	SP-104	TRI-010	TRI-016	TRI-015T	SP-108	TRI-026	TRI-036	TRI-037T	TRI-045T	TRI-047T	TRI-048T	B4b	TRI-050T	TRI-051	TRI-052	TRI-056T	TRI-066	SP-128	TRI-069T	DR-111	SP-125	TRI-157T	S4-1T	S4-2T	DR-181	EIT-066	TRI-095T	TRI-096	CR-02	CR-24
Abarenicola sp.																								1					1			
Acila castrensis															1																	
Alvania compacta	2	2	1		12		8	5	3		1	4		1						1	1											
Amage anops				1																												
Americhelidium shoemakeri		1	1	3	3	5	2		1						1		1															
Americorophium salmonis												3	1	2										103					2			
Americorophium spinicorne												2						1									1					
Ampharete acutifrons								2																								
Ampharete labrops											1	1			1					4		1						1				
Ampharete nr crassiseta					1																											
Amphiodia sp.		3	3	3		2	13	1			1		1	5		2	3				2											
Amphiodia urtica/periercta				2			2	1		2				7	2	2	2				1											200
Ampithoe valida																		1														
Anobothrus gracilis	1		1	1						1		1	1																	3		
Aoroides inermis		1			1			2				1																				
Aphelochaeta glandaria	656	179	328	26	956	546	74	15	483	83	175	280	10	5	138	114	17	445	202	335	38	94	154			43	288	45	7			5
Aphelochaeta monilaris	3	7	1		4	6	7		1			1			1		1				4					2	2					
Aricidea lopezi	1	3	1	1	4	7	2		3				2	4	4	9	4	4	1		1											
Armandia brevis	7								6			4		31					1	10	6	7		2	1				5	1		
Artacama coniferi		3	2	3	2	8	4	2	4	11			6	1	1	1	15	8	2			1	2									

Sampling Location→ Taxon ↓	TRI-004	TRI-008	SP-104	TRI-010	TRI-016	TRI-015T	SP-108	TRI-026	TRI-036	TRI-037T	TRI-045T	TRI-047T	TRI-048T	B4b	TRI-050T	TRI-051	TRI-052	TRI-056T	TRI-066	SP-128	TRI-069T	DR-111	SP-125	TRI-157T	S4-1T	S4-2T	DR-181	EIT-066	TRI-095T	TRI-096	CR-02	CR-24
Astyris gausapata	1	1		1	2	5	4	2																								2
Axinopsida serricata	169	203	170	210	129	183	359	113	94	144	40	37	304	263	112	261	429	215	173	7	107	2	3			8	36	4	1	2		5
Balanus sp.	7				8																											
Barantolla nr americana							1																									
Barentsia benedeni		1		1																												
Barleeia subtenuis	4	6		2	9	1			3		4				3	4	5	4			1											
Bathyleberis sp.					2		2					1	3						1													
Boccardiella hamata											2	2																				
Bowerbankia gracilis	1				1				1																							
Bugula cf. pacifica																			1													
Bugula pacifica															1																	
Buskia nitens		1			1	1	1	1	1																							
Cancer oregonensis			1										1																			
Capitella capitata complex	37	1	2		3	1			3		2	12		1	1			1	3	3	1	22		45	27		9		158	6	1	
Celleporella hyalina	1	1						1					1																			
Cerebratulus albifrons													1																			
Chaetoderma sp.					1																											
Chaetozone nr setosa					1	2	1		5				2	1		2	2		3													
Chaetozone sp.												3			1										3							
Chaetozone sp N1	3										7	14						2		44	5	33	3	2		44	132	93	35	77		
Cirratulus spectabilis									1		2	5				1					1	6										
Clinocardium sp. juv.																					2											
Clymenura gracilis				2			3																									
Compsomyax subdiaphana		1	1	3		2	16	2		1			4			1		1														

Sampling Location→ Taxon ↓	TRI-004	TRI-008	SP-104	TRI-010	TRI-016	TRI-015T	SP-108	TRI-026	TRI-036	TRI-037T	TRI-045T	TRI-047T	TRI-048T	B4b	TRI-050T	TRI-051	TRI-052	TRI-056T	TRI-066	SP-128	TRI-069T	DR-111	SP-125	TRI-157T	S4-1T	S4-2T	DR-181	EIT-066	TRI-095T	TRI-096	CR-02	CR-24
Corambe pacifica																																2
Cossura pygodactylata	115	25	44	7	42	50	11	6	149	42	54	57	57	74	130	80	88	289	434	255	123	51	29	1	2	51	259	10	32	8		
Crangon alaskensis	1										2	1		2	1				1		1		1									
Crangon sp.											1			2		1		1		1									1			
Crustacea megalopa												1				2						1										3
Crustacea zoeae												1																				
Cylichna attonsa													1																			2
Diastylis santamariensis	1		1	1	6	2		1		1	2				2				1		1		2									
Dipolydora cardalia				4																1												
Dipolydora caulleryi																												1				
Dipolydora quadrilobata												1																				
Dipolydora socialis		1					2						1		1																	
Dorvillea (Schistomeringos) sp.																1																
Drilonereis longa							1							1																		
Dyopedos sp.				1							1								1													
Edwardsia sipunculoides							5	2						1			1															
Ennucula tenuis				2		1	1	1					1			3		1			1	1										
Eochelidium sp.	3	3	2	1	8	12	3	8	11		1	4	5	1	4	1	3	1	1	1	2	1	7							1		
Eogammarus confervicolus												2				1																
Eteone leptotes																				1												
Eteone sp.	1															1		1		3	1											
Eteone spilotus											2	3		2										3								
Euchone incolor	12	2	3	3	14	10	17	6	7	2		7	9	3		4	6	41	15													
Euchone limnicola	7	3		1		2		3	9	3	23	9	9	8	15	13	9	8	27	51	19	21	30			1	4	1	2	6		
Euclymene cf																																2

Sampling Location→ Taxon ↓	TRI-004	TRI-008	SP-104	TRI-010	TRI-016	TRI-015T	SP-108	TRI-026	TRI-036	TRI-037T	TRI-045T	TRI-047T	TRI-048T	B4b	TRI-050T	TRI-051	TRI-052	TRI-056T	TRI-066	SP-128	TRI-069T	DR-111	SP-125	TRI-157T	S4-1T	S4-2T	DR-181	EIT-066	TRI-095T	TRI-096	CR-02	CR-24
zonalis																																
Euclymeninae		1		3	2		2					1	2	1																		
Eudorella pacifica	7	11	1	4	13	18	8				1	3	7	1	3	3	7	3	1													1
Euphilomedes carcharodonta	49	242	71	197	59	215	280	53	3	9	5	11	48	53	28	57	26	21	5		1		1	1								
Euphilomedes producta		3	1	4		3	4																									
Euphysa ruthae				1	2												1															
Exogone lourei	10	3	1		8	1	2				1																					
Exogone molesta	7	1		4	3	2	4			1		1	1	3		5	2	1		1	9											
Glycera americana					2		1				1				1											1	1	2				1
Glycera nana	1	3	5	5	3	4	5	3		1	1	1	3	1	2	2	2									2						3
Glycinde armigera						1	1			1											2				1							3
Glycinde picta									1			2	2			2								2					2	1		
Gnorimosphaeroma insulare																								1				1				
Grandidierella japonica									1					12										2					1	1		
Halcampa decemtentaculata																																1
Harpacticoida sp.												1																				
Heteromastus filobranchus	23	35	19	23	32	46	17	12	3	21	19	31	47	26	17	31	37	17	13	6	19		8			3	1		2		1	23
Heteromastus sp.			11								3																1					
Hippolytidae sp.												1																				
Hobsonia florida																								51	3							
Hoplonemertea sp.							1									1																
Hydroida sp.								1																								
Kaburakia excelsa																1																
Lanassa nordenskioeldi							3															29										
Lanassa sp.							3																									
Lanassa venusta	1					3	5		1	1	35	5	13	10	23	9	16	3	5	25	25	15	1			1				7		
Laonice cirrata								1								1	1															
Lasaea adansoni																																1

Sampling Location→ Taxon ↓	TRI-004	TRI-008	SP-104	TRI-010	TRI-016	TRI-015T	SP-108	TRI-026	TRI-036	TRI-037T	TRI-045T	TRI-047T	TRI-048T	B4b	TRI-050T	TRI-051	TRI-052	TRI-056T	TRI-066	SP-128	TRI-069T	DR-111	SP-125	TRI-157T	S4-1T	S4-2T	DR-181	EIT-066	TRI-095T	TRI-096	CR-02	CR-24
Leitoscoloplos pugettensis																														1		2
Lepidasthenia berkeleyae																																8
Leptochelia dubia		1							1			1									1											
Leucon subnasica					1																											
Levinsenia gracilis				2		1	1		1				1				1															
Lineidae sp.		2	1		1	1						2	3		1	2																10
Lophopanopeus bellus													1																			
Lucinoma annulatum		2	1	1	1	1	4		2				1	2		1	2															
Lumbrineris californiensis	3					3	1	1																								
Lyonsia californica	2	2	5	5	3		5				1		2	1	2	1	1	1				2	1									
Macoma carlottensis	35	128	93	94	141	61	236	28	32	22	60	16	57	23	41	55	33	59	32	1	10	5	2				7		1	1		
Macoma elimata				1			2																									
Macoma nasuta	20	4	8	6	27	2	1	2	4		1	1	5	11		3		5	2	3	5			7	11	3	3	1	6	2		
Macoma sp. juv.					6					1								2		1												
Macoma yoldiformis	12	13	8	8	5	8	5	3		1	2	1	1	6		1	3		3	2	1									2		2
Malmgreniella liei													1				2	4		1	1											
Malmgreniella macginitiei																			1									1				
Mayerella banksia				1																												
Mediomastus californiensis	13	5	9	4	8	8	9	2	4	4		5	3	3		9	3	1		7						1		1	3			
Megayoldia montereyensis																1																
Melinna elisabethae							1																									
Melita sp.												1																				
Micronereis nanaimoensis								1																								

Sampling Location→ Taxon ↓	TRI-004	TRI-008	SP-104	TRI-010	TRI-016	TRI-015T	SP-108	TRI-026	TRI-036	TRI-037T	TRI-045T	TRI-047T	TRI-048T	B4b	TRI-050T	TRI-051	TRI-052	TRI-056T	TRI-066	SP-128	TRI-069T	DR-111	SP-125	TRI-157T	S4-1T	S4-2T	DR-181	EIT-066	TRI-095T	TRI-096	CR-02	CR-24
Micropodarke dubia																											1					
Monocorophium acherusicum														1																		
Monocorophium insidiosum						1			2												1											
Monticellina serratiseta		14				42			2												2									1		
Monticellina sp N1							152																									
Monticellina tesselata					1																											
Mytilus sp.	1								1																							
Neaeromya rugifera					1																											
Nematoda																														1		
Nemocardium centifilosum	1	1			3	1																										
Nephtys cornuta	4	11	2		4	6	4	1	2	2	1	8	9	5	1	9	7	14	21	2	4		1			1	1	1				
Nephtys ferruginea		1		4	1		4	1				1			2		1				1									1		2
Nereididae juv																										1						
Nereis procera	2											1																				
Nippoleucon hinumensis			1			1			3					2								1		10	2		1	1	9			
Notomastus hemipodus			5	9			9																									
Notomastus lineatus							8																									
Notomastus sp.					1																											
Nutricola lordi	20	50	22	32	26	41	303	26	8	18	56	2	140	113	90	113	44	49	5	4	24	3	3	8		4	25	1		23		
Obelia sp.									1							1	1		1													
Oligochaeta	58						2		5			2	1	5										3	60				11			23
Ophelina acuminata	4		3	2	2			1			2	1	4				6		2		2		1									
Ophiurida sp.	1		2	1	1	4	1	3	1		1			1	1	1	1	1			1						1					
Orchomene pinguis													25																			

Sampling Location→ Taxon ↓	TRI-004	TRI-008	SP-104	TRI-010	TRI-016	TRI-015T	SP-108	TRI-026	TRI-036	TRI-037T	TRI-045T	TRI-047T	TRI-048T	B4b	TRI-050T	TRI-051	TRI-052	TRI-056T	TRI-066	SP-128	TRI-069T	DR-111	SP-125	TRI-157T	S4-1T	S4-2T	DR-181	EIT-066	TRI-095T	TRI-096	CR-02	CR-24
Pandora filosa	1			1								1																				
Paraprionospio pinnata		3	1	5	3	3	7	3	3	3		2	1		1	1	1	2	2	2	1						1				1	5
Parvilucina tenuisculpta	46	77	46	54	31	83	138	34	7	13	3	7	39	32	17	70	60	1	4		10										9	5
Pectinaria californiensis																		1														3
Pennatulacea sp.																																1(1)
Pholoe minuta						1	3					1	5	3				2		1										1		
Pholoe sp N1																5	4		2		2											46
Pholoides asperus	1																															
Photis brevipes			1				2																									
Phyllodoce hartmanae					1		1				3	2		1									1							2		
Pilargis maculata					2	1										1	1															1
Pinnixa schmitti														1		3																23
Pinnixa sp.										1																						
Pista percyi						1							1																			
Pista wui					1																											1
Platynereis bicanaliculata					1			1				1		1																		
Pleurogonium rubicundum																					1											
Pleusymtes subglaber	2						1				1		1		1																	
Podarkeopsis glabrus						2									1		2	1			3				1	1		2	1			
Polinices pallidus			1																													
Polycirrus californiensis						1										1																
Polycirrus sp. complex			1	1		4	8					1	4	4							1					1		1				
Polycirrus sp I (Banse, 1980)		1	1			2	1		4				6			3	8	40	1	2	1	1				1		2				
Polycirrus sp juv					7															2			1									

Sampling Location→ Taxon ↓	TRI-004	TRI-008	SP-104	TRI-010	TRI-016	TRI-015T	SP-108	TRI-026	TRI-036	TRI-037T	TRI-045T	TRI-047T	TRI-048T	B4b	TRI-050T	TRI-051	TRI-052	TRI-056T	TRI-066	SP-128	TRI-069T	DR-111	SP-125	TRI-157T	S4-1T	S4-2T	DR-181	EIT-066	TRI-095T	TRI-096	CR-02	CR-24
Polydora cornuta	1											1		33						3	3	104	6	33	24	3	5	2	37	58		
Pontogeneia rostrata												2																				
Praxillella gracilis		1					4							1																		
Praxillella pacifica				1																												20
Praxillella sp.							2																									
Priapulus caudatus										1										1							1					
Prionospio lighti						1					3			1			2				1			1		1						2
Prionospio multibranchiata	4		1									1		2						4												
Prionospio steenstrupi	8	5	13	12	32	29	20	15		8	5	6	23	14	2	16	3	6		1	10		3		2					1	1	12
Protomedeia grandimana				1			1			1			2			2																
Pseudopolydora kempi														4						9	2	28		42	49	5	5	1	66	11		
Pseudopolydora paucibranchiata																								2								
Pygospio elegans														1								1		24	1				1	2		
Rhepoxynius boreovariatus																																71
Rhodine bitorquata			2	3			4																									
Rochefortia tumida	15	41	14	10	7	33	17	3	39	3			33	41	11	31	54	3	3		6						2	3		3		36
Saxidomus gigantea	1		1				2						1																			
Scoletoma luti	57	67	35	45	31	55	55	40	73	70	46	82	233	158	82	153	102	70	263	111	197	19	54	4	10	90	167	127	16	35		24
Scoloplos acmeceps					1									4																		
Scoloplos sp juv				1																												
Sigambra nr bassi																															15	62
Sinelobus stanfordi										1																	1					
Solamen columbianum	2	1	2	3	1		7						2	3				1														
Solen sicarius				1		1		3	1	1	1		2	1	3	1	1	1			1									1		
Sphaerodoropsis	4	3	1	5	3	1	5		2	1			9	5	1	5	3		3		1											

Sampling Location→ Taxon ↓	TRI-004	TRI-008	SP-104	TRI-010	TRI-016	TRI-015T	SP-108	TRI-026	TRI-036	TRI-037T	TRI-045T	TRI-047T	TRI-048T	B4b	TRI-050T	TRI-051	TRI-052	TRI-056T	TRI-066	SP-128	TRI-069T	DR-111	SP-125	TRI-157T	S4-1T	S4-2T	DR-181	EIT-066	TRI-095T	TRI-096	CR-02	CR-24
sphaerulifer																																
Sphaerosyllis ranunculus							1	1						2							1											
Spiochaetopterus pottsi			1	4	1		3																									
Spiophanes berkeleyorum	1		3	3	1		2			2		1	2	1							1					1						
Sthenelais berkeleyi				3																												
Streblosoma bairdi							2																									
Tellina modesta	1	2							1				1			1			1													
Terebellides californica	1	3	3			2	9			2			2	1	1	2	3															
Thecata sp.														1																		
Thracia trapezoides							1																									
Thyasira flexuosa		2		1			3									2								1						1		
Thysanocardia nigra	3			1																												
Tritella pilimana											1									1												
Tubulanus pellucidus					1												1	1	1													
Tubulanus polymorphus										1																						1
Tubulanus sp.															1																	1
Turbonilla sp.	33	35	4	2	87	19	19	2	29	2	4		3	2		2	1	8	10	2	3											
Typosyllis cornuta							3																									
Virgularia sp.															1																	
Westwoodilla caecula	1				13	7	2	2																								
Yoldia seminuda		1	1	1					1																							

Appendix D - Data Preparation and Screening

Table D-1. Screening for potential outlier results in SPI, sediment conventionals, and benthic community Lower Duwamish Waterway data sets.

Parameter	Potential Outlier	Why?	Excluded?	Reason(s) for excluding from some analyses
Penetration depth	DR-157T	c,d	Yes	Magnitude of difference. Failed test for statistical outliers.
Boundary Roughness	5 locations	a-c	No	
Voids	TRI-056T	a,b,d	No	Limited range variable, not used for that reason.
Mudclasts	B4b, DR-111	a-d	No	Limited range variable, not used for that reason.
Number of small tubes	B4b, DR-157T, TRI-096	a-d	DR-157T	Value reported for DR-157T was text (>40), not a number, and much greater than all other sample results.
Burrows	DR-157T	a-c	No	
Oxic voids	TRI-056T	a,b,d	No	Limited range variable, not used for that reason.
VTB	DR-157T, SPI-125	a-c	DR-157T	See comment for number of small tubes.
Total solids	5 locations	a	No	
% sand, silt, fines	SPI-108, DR-157T, TRI-096	a-d	No	
% clay	5 locations	a-c	No	
% TOC	SPI-108	a	No	
Ammonia	DR-181, TRI-048T	a-d	No	
Sulfide	S4-1T	a-d	Yes	Likely real value but an order of magnitude greater than next highest concentration and failed several screening criteria.
Sb, Ar, Cu, Hg, Ni, Ag, Zn, TBT	8 locations, esp. TRI-045, TRI-047T, TRI-048T	a-d	None	
Total metals	TRI-047T, TRI-048T	a-d	No	
PAHs	TRI-036, TRI-045, TRI-047T, DR-157T	a-d	No	
PCBs	TRI-069T, DR-157T, S4-1T, DR-181,	a-d	No	

Parameter	Potential Outlier	Why?	Excluded?	Reason(s) for excluding from some analyses
	EIT-066			
Phenols	TRI-016	a-d	No	
Larval toxicity	TRI-004	a-c	No	
Abundance indicators	TRI-008, TRI-010, TRI-015T, TRI-016, SPI-108	a-d	No	
Richness indicators	SPI-108, TRI-047T	a-c	No	
H' and J	DR-111, EIT-066	a	No	

a = < 25th percentile value - 1.5*interquartile range or
> 75th percentile value + 1.5*interquartile range
b = outside the mean value ± 2.5*standard deviation
c = box plot outlier
d = identified as outlier using Dixon's equations

VTB = Total number of voids, small tubes, and burrows

Table D-2. Distributional analysis of results for 30 sampling locations in the Lower Duwamish Waterway.

SPI Parameters	Normal?	Conventionals Contaminants SMS Exceeds Toxicity	Normal?	Benthic Community Metrics	Normal?
Penetration depth	√	Total Solids	√	Total abundance	√
Boundary roughness	X	% Sand	X	Annelid abundance	X
RPD depth (mean)	√	% Silt	√	Crustacea abundance	X
Total Voids	X	% Clay	√	Mollusca abundance	X
Voids (Max Depth)	√	% Fines	X	Miscellaneous + Echinoderm. abundance	X
Successional stage	X	% TOC	√	Total richness	√
Small tubes (total number)	X	Cd, Cr, Hg, Pb	√	Annelid richness	√
Burrows (total number)	√	Other metals	X	Crustacea richness	√
VTB = Number of voids+tubes+burrows	X	Organics	X	Mollusca richness	√
OSI	√	Mean/Maximum SQS EF	√	SDI	X
BHQI	√	Other variables related to chemical SQS/CSL	√	H'	√
Others	X	*Eohaustorius* mortality	X	J	√
		Dendraster (abnormality+mortality)	X		

√ = normal distribution ($p < 0.05$)
X = not normal distribution

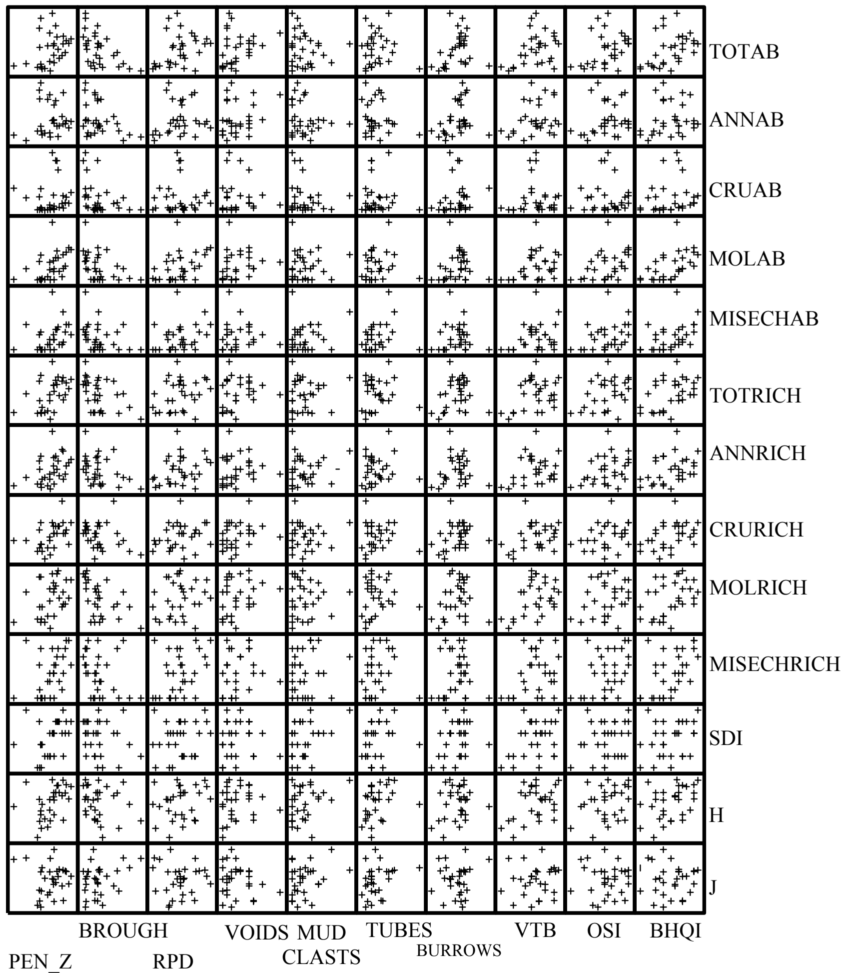

Figure D-1. Matrix of two-way plots of SPI parameters (as independent variable x) and benthic metrics (as dependent variable y) at 30 sampling locations in the Lower Duwamish Waterway, having removed several potential outlier results.

ANNAB = Annelida abundance, CRUAB = Crustacea abundance, MOLAB = Mollusca abundance, MISECHAB = abundance of miscellaneous taxa and Echinodermata, TOTRICH = total richness, ANNRICH = Annelida richness, CRURICH = Crustacea richness, MOLRICH = Mollusca richness, MISECHRICH = richness of miscellaneous taxa and Echinodermata, SDI = Swartz dominance index, H' = Shannon Wiener diversity index.

PEN_Z = prism penetration depth (cm), BROUGH = surface boundary roughness (cm), RPD = redox discontinuity depth (cm), VOIDS = number of feeding voids, BURROWS = number of infaunal burrows, VTB = total number of voids, small tubes and burrows per replicate, OSI organism sediment index = , BHQI = benthic habitat quality index.

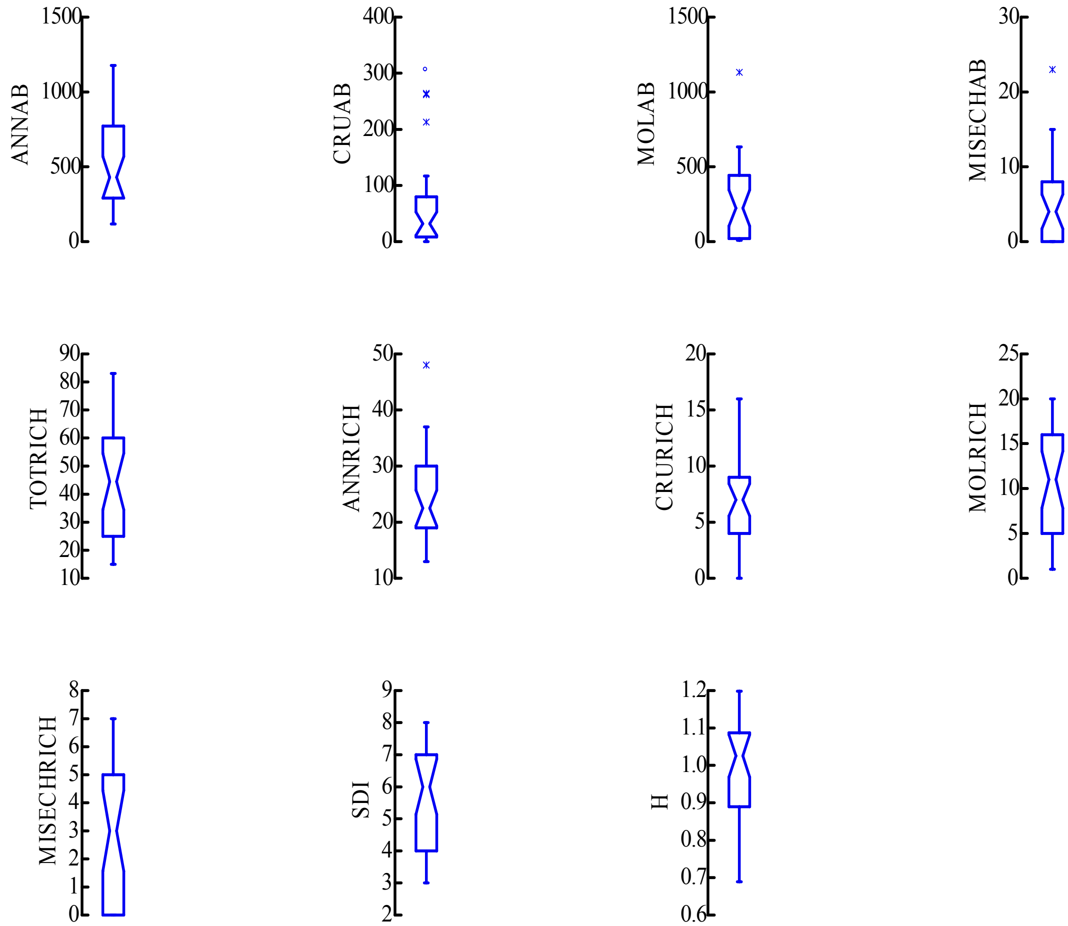

Figure D-2. Box plots identifying potential outlier values for 11 example benthic community metrics for 30 sampling locations in the Lower Duwamish Waterway.

ANNAB = Annelida abundance
CRUAB = Crustacea abundance
MOLAB = Mollusca abundance
MISECHAB = abundance of miscellaneous taxa and Echinodermata
TOTRICH = total richness
ANNRICH = Annelida richness
CRURICH = Crustacea richness
MOLRICH = Mollusca richness
MISECHRICH = richness of miscellaneous taxa and Echinodermata
SDI = Swartz dominance index
H' = Shannon Wiener diversity index

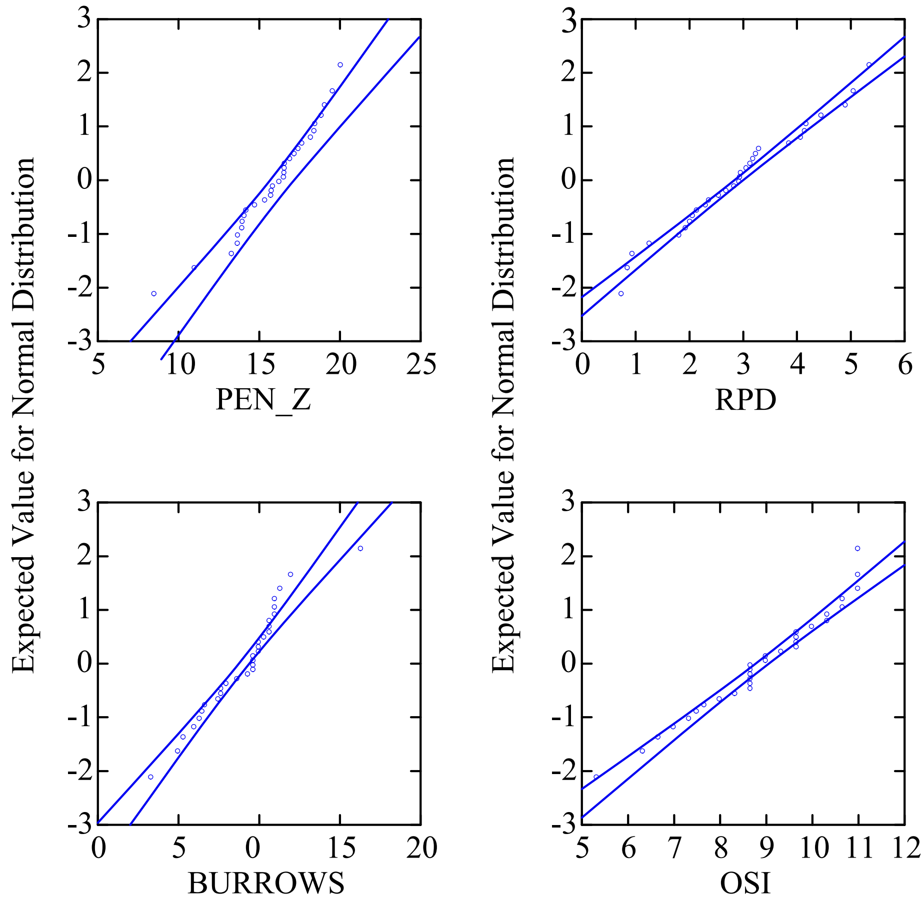

Figure D-3. Normal probability plots for example SPI parameters, sediment conventionals and contaminant chemistry results, and benthic community metrics.

Figure D-3a. Normal probability plots for example SPI parameters for 30 sampling locations in the Lower Duwamish Waterway.

PEN_Z = prism penetration depth (cm)
RPD = redox potential discontinuity depth (cm)
BURROWS = number of benthic infaunal burrows per replicate image
OSI = organism sediment index

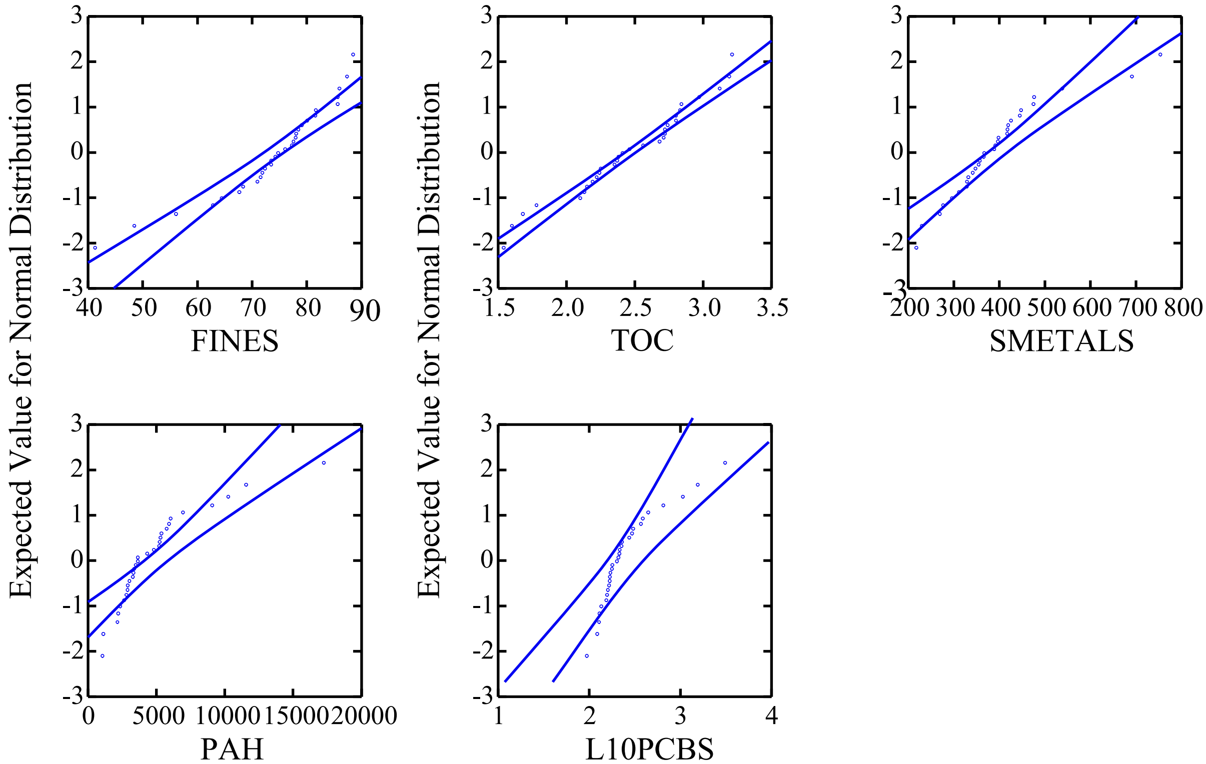

Figure D-3b. Normal probability plots for example sediment conventionals and contaminant chemistry results 30 sampling locations in the Lower Duwamish Waterway.

FINES = % fines
TOC = % total organic carbon.
SMETALS = sum of detected concentrations of all trace metals (mg/Kg dry weight).
PAH = sum of all detected concentrations of polynuclear aromatic hydrocarbons (μg/Kg dry wt).
L10PCBS = log10 of the concentration of total Aroclor PCBs.

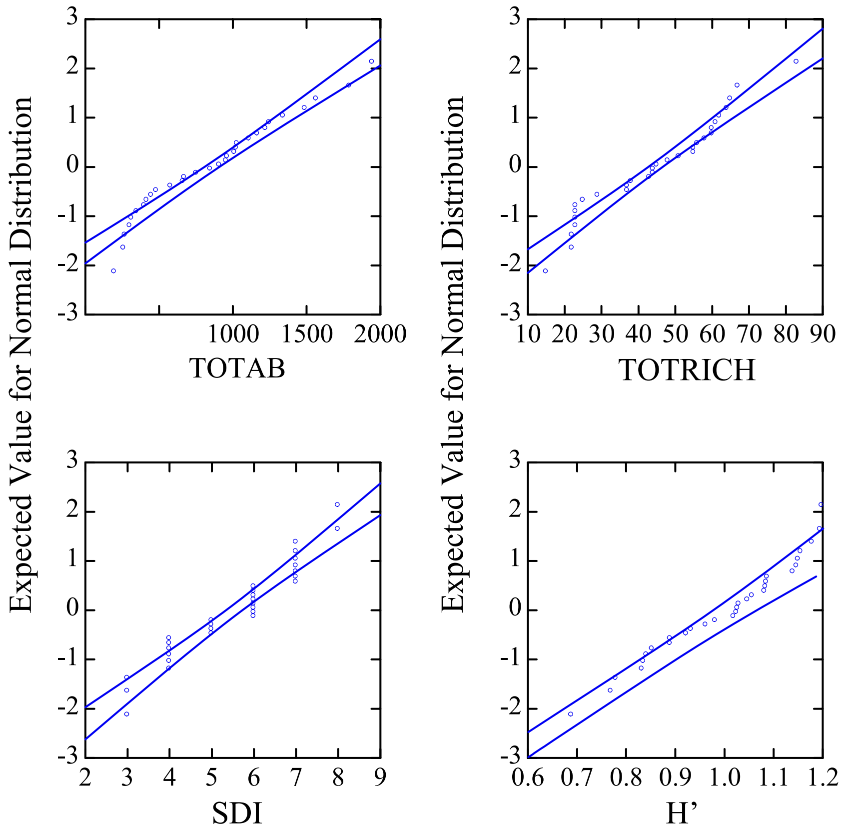

Figure D-3c. Normal probability plots for example benthic infaunal community metrics for 30 sampling locations in the Lower Duwamish Waterway.

TOTAB = total abundance of infaunal organisms.
TOTRICH = total number of taxa
SDI = Swartz dominance index
H' = Shannon Weiner diversity index

Table D-4. Spearman rank correlations between selected SPI parameters and 13 benthic community metrics.

For n = 30, Significant correlations (p<.05) between pairs of parameters have an absolute rho value of 0.362 (shown in bold).

	Penetration depth	Boundary roughness	RPD depth	Number of voids	No. mudclasts	No. of small tubes	No. of burrows	No. of oxic voids	No. of voids + tubes + burrows	OSI	BHQI
Total abundance	**0.371**	**-0.571**	0.299	0.353	-0.087	0.038	0.358	0.323	0.264	**0.364**	**0.502**
Annelida abund.	0.147	**-0.374**	0.175	0.262	-0.109	-0.161	**0.368**	0.24	0.168	0.239	0.221
Crustacea abund.	0.265	**-0.475**	0.04	0.169	-0.081	0.173	0.28	0.176	0.23	0.085	0.336
Mollusca abund.	**0.562**	**-0.458**	**0.398**	**0.377**	0.084	0.185	0.198	0.348	0.292	**0.451**	**0.632**
Miscellaneous taxa + Echinodermata abundance	**0.474**	-0.354	0.303	0.318	0.171	0.215	0.068	0.288	0.153	**0.375**	**0.54**
Total richness	**0.45**	**-0.44**	0.23	0.261	0.053	0.048	0.159	0.233	0.141	0.336	**0.447**
Annelida richness	**0.432**	**-0.368**	0.273	0.235	0.109	0.012	0.061	0.209	0.07	0.355	**0.398**
Crustacea richness	**0.483**	-0.348	0.226	0.291	0.006	0.047	0.307	0.285	0.206	0.331	**0.45**
Mollusca richness	0.351	**-0.593**	0.111	0.284	0.022	0.085	0.2	0.241	0.196	0.217	**0.419**
Miscellaneous taxa + Echinodermata richness	**0.456**	-0.341	0.307	0.346	0.156	0.191	0.063	0.316	0.136	**0.38**	**0.544**
SDI	**0.444**	-0.17	0.159	0.078	0.288	0.277	0.261	0.059	0.238	0.199	0.309
H	**0.498**	-0.199	0.22	0.147	0.269	0.355	0.108	0.13	0.232	0.29	**0.396**
J	0.14	0.245	0.016	-0.132	0.22	**0.409**	0.043	-0.107	0.214	-0.005	-0.004