Urban Waters Initiative, 2007

Sediment Quality in Elliott Bay

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For more information contact:

Publications Coordinator
Environmental Assessment Program
P.O. Box 47600
Olympia, WA 98504-7600
Phone: 360-407-6764

Washington State Department of Ecology - www.ecy.wa.gov/
- Headquarters, Olympia 360-407-6000
- Northwest Regional Office, Bellevue 425-649-7000
- Southwest Regional Office, Olympia 360-407-6300
- Central Regional Office, Yakima 509-575-2490
- Eastern Regional Office, Spokane 509-329-3400

Cover photo: The city of Seattle from Elliott Bay.

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Sediment Quality in Elliott Bay

by
Valerie Partridge, Sandra Weakland, Edward Long,
Kathy Welch, Margaret Dutch, and Marissa Jones

Western Operations Section
Environmental Assessment Program
Washington State Department of Ecology
Olympia, Washington 98504-7710

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Glossary, Acronyms, Abbreviations, and Units of Measure

Assemblage: A collection of organisms sharing a particular characteristic. This term also refers to a sample of a community.

Benthic: Relating to the bottom of a waterbody.

Benthos: Organisms living at the bottom of, or in the sediments of, a waterbody.

Bioindex: Single number characterizing a biological community.

Bray-Curtis similarity: Numerical measure of the similarity of two samples based on abundances of all species. The values range from 0 (completely dissimilar, no species in common) to 1 (completely similar, exactly the same species and abundances). Bray-Curtis dissimilarity is the opposite.

Colonial species: An invertebrate species of interconnected individuals which function as a single organism.

Community: A group of organisms occurring in a particular environment, presumably interacting with each other and with the environment and separable from other groups by means of an ecological survey.[1]

Cumulative distribution function: A statistical distribution of sample values based on cumulative probability. The samples may be unequally weighted (i.e., have unequal probability).

Demersal: Refers to animals (generally, fish) which feed at the bottom of a waterbody.

EC50: The effective concentration that causes a 50% response.

ERM quotient: Ratio of chemical concentration to that chemical's Effects Range-Median sediment-quality guideline.

Euclidean distance: Mathematical calculation of distance between points in multiple dimensions.

Exotic species: Non-indigenous or non-native species.

Index: Single number derived from measurements of multiple characteristics.

Indices: Plural of index.

Infauna: Animals that live burrowing or buried in the bottom.

Macrofauna: Invertebrates retained on a 1-mm mesh sieve.

Mean ERM quotient: Mean of ERM quotients for a group of chemicals.

Multidimensional scaling: A mathematical method which optimizes a 2-dimensional or 3-dimensional map representation of multidimensional data based on a matrix of dissimilarity measures. Bray-Curtis dissimilarity is the measure usually used for species abundance data. Euclidean distance is the measure usually used for environmental data.

[1] Mills, E.L. 1969. The community concept in marine zoology, with comments on continua and instability in some marine communities: a review. Journal of the Fisheries Research Board of Canada 26(6), 1415-1428.

Nondetect: Analyte not detected at or above detection limit (reporting limit or reported sample quantitation limit).

Nonpoint source: Pollution that enters any waters from any dispersed land-based or water-based activities, including, but not limited to, atmospheric deposition, surface water runoff from agricultural lands, urban areas, or forest lands, subsurface or underground sources, or discharges from boats or marine vessels not otherwise regulated under the National Pollutant Discharge Elimination System Program. Generally, any unconfined and diffuse source of contamination.

Pielou's Evenness (J'): A measure of how equitably distributed the taxa are among taxonomic groups.

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

Regression on order statistics: A statistical procedure used to estimate summary statistics (e.g., mean, median, variance) when nondetects are present in the data.

SQS quotient: Ratio of chemical concentration to that chemical's Washington State Sediment Quality Standard.

Swartz' Dominance Index: Minimum number of taxa accounting for 75% of the total abundance.

Taxa: Plural of taxon.

Taxa richness: Number of different taxa.

Taxon: Lowest level of identification for each organism, usually species.

Toxicity test: Laboratory test of the toxicity of environmental samples with ambient mixtures of chemicals.

Acronyms and Abbreviations

ANOSIM	Analysis of Similarity
ANOVA	Analysis of Variance
ASE	Accelerated solvent extraction
BNA	Base/Neutral/Acid semivolatile organic compounds
CDF	Cumulative distribution function
CI	Confidence interval
CO2	Carbon dioxide
CSL	Washington State sediment Cleanup Screening Level
CVAA	Cold vapor atomic absorption
DGPS	Differential Global Positioning System
Ecology	Washington State Department of Ecology
EIM	Ecology's Environmental Information Management System
EPA	U.S. Environmental Protection Agency
ERL	NOAA Effects Range-Low sediment-quality guideline
ERM	NOAA Effects Range-Median sediment-quality guideline
GC-DDC/ECD	Gas chromatography dual dissimilarity column/electron capture detection

GC/ECD	Gas chromatography/electron capture detection
GC/MS	Gas chromatography/mass spectrometry
GPC	Gel permeation chromatography
GRTS	Generalized random tessellation stratified survey design
Hg+	Mercury ion
HPAH	High molecular weight PAH
ICPMS	Inductively coupled plasma/mass spectrometry
KC DNRP	King County Department of Natural Resources and Parks
LPAH	Low molecular weight PAH
MDS	Non-metric multidimensional scaling
MEL	Manchester Environmental Laboratory
MESA	NOAA's Marine EcoSystems Analysis project
NOAA	National Oceanic and Atmospheric Administration
NS&T	NOAA's National Status and Trends program
PAH	Polycyclic aromatic hydrocarbon; Polynuclear aromatic hydrocarbon (synonymous)
PCB	Polychlorinated biphenyl
pH	Measure of acidity or alkalinity
PPW	Paired Prentice-Wilcoxon test
PSAMP	Puget Sound Assessment and Monitoring Program (Puget Sound Partnership); formerly the Puget Sound Ambient Monitoring Program
PSAMP/NOAA	Cooperative NOAA-Ecology sampling program in Puget Sound 1997-1999
PSEP	EPA's Puget Sound Estuary Program
PSP	Puget Sound Partnership
QA/QC	Quality assurance/quality control
QAPP	Quality assurance project plan
RI	Remedial Investigation
RL	Reporting limit
ROS	Regression on order statistics
SCAMIT	Southern California Association of Marine Invertebrate Taxonomists
SCCWRP	Southern California Coastal Water Research Project
SDI	Swartz' Dominance Index
SDISTD	Swartz' Dominance Index standardized by (divided by) taxa richness
SEDQUAL	Ecology's Sediment Quality Information System; superseded by EIM
SIM	Selective ion monitoring isotopic dilution analysis
SQG	Sediment quality guidelines
SQGQ	Sediment quality guidelines quotient
SQS	Washington State Sediment Quality Standard
SQTI	Sediment Quality Triad Index
TBA	Tetrabutylammonium hydrogen sulfate
TOC	Total organic carbon
USGS	U.S. Geological Survey
UWI	Ecology's Urban Waters Initiative
WSRT	Wilcoxon signed ranks test

Units of Measure

°C	degrees Celsius
cm	centimeter
km	kilometer
L	liter
m	meter
mL	milliliter
mm	millimeter
ng	nanogram
µg or ug	microgram

Abstract

Under the Urban Waters Initiative, the Washington State Department of Ecology (Ecology) is working with local governments near Puget Sound's urban bays to reduce toxic chemical pollution. As part of the Initiative, Ecology is assessing sediment quality throughout those bays, beginning with Elliott Bay and the adjoining waterways of the lower Duwamish River in 2007.

These bay-scale assessments of sediment-quality status and trends serve as a new effectiveness-monitoring tool, enabling environmental managers to determine whether collective localized cleanups and source control improve conditions over a wider area.

The urban embayment sediment surveys are nested within the ongoing Puget Sound Assessment and Monitoring Program (PSAMP) sediment monitoring sampling design. This probability-based sampling is designed to assess sediment condition on several spatial scales, from bay-wide to regional to Puget Sound-wide. Furthermore, the PSAMP sediment monitoring program has baseline conditions from 1997-2003 surveys against which current Urban Waters Initiative results can be compared.

Comparisons of the 2007 results with similar data collected in 1998 show bay-scale decreases in sediment contamination for numerous toxics, especially polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs). However, contamination by a few other chemicals did increase. Spatial extent (percent of area) of toxicity decreased from 1998 to 2007. The majority of measures of benthic invertebrate community health improved, whereas others did not change or indicated degradation.

The PSAMP Sediment Quality Triad Index combines information on measures of exposure (sediment contamination), response (toxicity), and biological effects (benthic invertebrates) to categorize sediment quality on a 4-level scale from high to degraded. In comparison to 1998 conditions in Elliott Bay and adjoining waterways, the 2007 conditions showed positive shifts in sediment quality, especially in harbor and urban areas. Bay-wide, more than 30% of the area had intermediate/degraded to degraded sediment quality in 1998. In 2007, that proportion was less than 20%.

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Executive Summary

Under the Urban Waters Initiative (UWI), the Washington State Department of Ecology (Ecology) is working with local governments near Puget Sound's urban bays to reduce toxic chemical pollution. As part of the UWI, Ecology is assessing sediment quality throughout those bays, beginning with Elliott Bay and the adjoining waterways of the lower Duwamish River in 2007. Monitoring results are being compared to results from previous studies to provide information on whether environmental regulation, source control, and localized cleanup efforts have had positive impacts bay-wide.

The objectives of the June 2007 UWI study in Elliott Bay and adjoining waterways were to:

1. Assess the current conditions in the area, particularly the overall extent of sediment contamination.
2. Determine whether there have been changes in sediment quality or spatial patterns over time.
3. Compare the extent of sediment-quality degradation in Elliott Bay and adjoining waterways with regional and Puget Sound-wide levels of degradation.

In 2007, surface sediments from 30 samples selected by a stratified random design were analyzed to measure three indicators of sediment quality: sediment chemistry, sediment toxicity, and the composition of benthic (bottom-dwelling) invertebrate communities. These three indicators were then combined into Ecology's Sediment Quality Triad Index (SQTI), an important high-level indicator of sediment quality in Puget Sound.

A weight-of-evidence approach was used to compare the results of the 2007 UWI study to results from Ecology's 1998 survey performed at the same sites, to determine what changes, if any, had taken place in the interim. The same area and stations had been sampled in a joint Ecology-NOAA survey in 1998. Bay-wide sediment quality was also compared with baseline conditions previously estimated by Ecology for central Puget Sound and all of Puget Sound using the SQTI.

The type of survey described in this report fits well with the objectives and mandates specified by the Puget Sound Partnership (PSP) in its *Puget Sound Action Agenda*. It provides a way for environmental managers to gauge progress in ecological health indicators at the bay scale.

Current Conditions in Elliott Bay and Adjoining Waterways

The probability-based sampling design enabled estimation of the spatial extent of sediment quality degradation for each sediment parameter measured, and for the measures combined in the SQTI, for the study area of Elliott Bay and adjoining waterways of the lower Duwamish River. Spatial extent was estimated as the proportion of the 26.3 km^2 study area represented by the sampling stations. Station area-weightings were unequal and defined by the statistical study design.

Sediment Contamination

In 2007, sediment samples were analyzed for more than 130 potentially toxic contaminants. These included metals, polycyclic aromatic hydrocarbons (PAHs), and chlorinated hydrocarbons, such as polychlorinated biphenyls (PCBs).

Spatial Extent

- Approximately 33% of the total study area was chemically contaminated as indicated by one or more chemicals not meeting (exceeding) Washington State Sediment Quality Standards (SQSs). Most stations exceeding SQSs did so for three or fewer chemicals or chemical groups in any given sample.
- Among all 30 stations, the SQSs were exceeded for 17 of 41 chemicals or chemical groups for which there are State standards. The chemical which exceeded the respective SQS most frequently was bis(2-ethylhexyl) phthalate, a common plasticizer. Mercury and total PCBs were second and third in frequency of exceeding their respective SQSs. Among classes of compounds, the SQSs were exceeded most frequently by the PAHs.

Location

- PCB concentrations were highest at the stations in the Duwamish and East Waterways. In general, metals and PAH contaminant concentrations were highest at or near the Port of Seattle piers, in the plume of the Denny Way Combined Sewer Overflow, or in the southeast portion of Elliott Bay. Levels of metals and PAHs were lowest in the outer (most seaward) portions of the bay. These spatial patterns were consistent with what was reported in sediment quality studies conducted there by NOAA in the early 1980s and by the joint Ecology-NOAA survey in 1998.

Sediment Toxicity

- Based on the results of the sublethal toxicity test performed, only a small fraction (1.6%) of the area (one station) had toxic sediments in 2007.

Invertebrate Communities

- More than half of the stations and study area (16 stations, representing 53.2% of the area) had benthic invertebrate communities judged by Ecology's benthic scientists to be adversely affected.
- Benthic invertebrate communities at the stations in the waterways of the lower Duwamish River often had large numbers of pollution-tolerant species and low species diversity. Low total invertebrate abundance or low species count, or both, characterized some other stations. Although the numbers of pollution-sensitive and pollution-tolerant species were similar overall, the pollution-tolerant species were far more abundant than the pollution-sensitive species.

Sediment Quality Triad Index

The Sediment Quality Triad Index (SQTI) combines information on measures of exposure (sediment contamination), response (toxicity), and biological effects (benthic invertebrates) to categorize sediment quality on a 4-level scale from high to degraded.

- Seven of the 30 stations, representing 8.3 km^2 (31.4% of the study area), had high sediment quality, as gauged by the SQTI.
- Twelve stations, representing 12.9 km^2 (49.1% of area), had intermediate-to-high sediment quality (degradation in one of the three triad elements).
- Another 11 stations, representing 5.1 km^2 (19.5% of area), had intermediate-to-degraded sediment quality (degradation in two triad elements).
- None of the stations or area sampled in 2007 had degraded sediment quality as measured with all three triad elements.

Comparison of 1998 Conditions to 2007 Conditions

Overall, there was a mixture of temporal trends between 1998 and 2007, but most measures indicated slight improvements in sediment quality on a bay-wide scale. The following changes were found.

Sediment Contamination

- *Metals:* The concentrations of lead, mercury, silver, and tin decreased significantly. Zinc concentrations increased. There were no statistically significant changes in the levels of arsenic, cadmium, chromium, copper, or nickel.
- *PAHs:* The concentrations of most low-molecular-weight PAHs (LPAHs) decreased or stayed the same. The concentrations of most high-molecular-weight PAHs (HPAHs) decreased. Contamination by two LPAHs, acenaphthylene and retene, increased. There were no changes in the levels of chrysene or perylene, two HPAHs.
- *PCBs:* Most individual PCB congeners decreased in concentration, as did total (summed) PCB Aroclors.
- *Phthalates:* Bis(2-ethylhexyl) phthalate concentrations increased.
- *Comparison to sediment-quality standards:* The number of chemicals exceeding their respective SQS decreased. For some of those chemicals, both the number of stations and amount of associated area exceeding the SQS also decreased.

Sediment Toxicity

- Sediment toxicity decreased significantly, from seven stations representing 9% of the study area in 1998 to a single station representing 1.6% of the area in 2007.

Invertebrate Communities

- Some measures of benthic invertebrate community health improved from 1998 to 2007. However, the total number of stations and amount of area with adversely affected benthos remained almost unchanged.

Sediment Quality Triad Index

- Sediment quality, as measured by the SQTI, improved for 24% of the study area, remained the same for 46%, and declined for 30%. All of the improvements were in the waterways and inner portion of Elliott Bay. Sediment quality in the outer portion of the bay, already high, remained high or declined slightly (to intermediate/high) due to adversely affected invertebrates at one station.
- Most of the shifts in sediment quality were from the degraded and intermediate/degraded SQTI categories (combined) to the intermediate/degraded and intermediate/high categories (combined).
- The proportion of the total area with degraded and intermediate/degraded sediment quality decreased from more than 30% in 1998 to slightly less than 20% in 2007, all in the intermediate/degraded category. None was classified as degraded in 2007.

Sediment Quality at Different Spatial Scales

The 2007 UWI Elliott Bay/lower Duwamish sampling frame is nested within the Puget Sound Assessment and Monitoring Program (PSAMP) Sediment Component's Central Region, which aligns well with the Puget Sound Partnership's South Central and North Central Action Areas. The bay, region, and Action Area sampling frames nest, in turn, within the Puget Sound sampling frame.

This nested series of sampling frames enables assessment of sediment quality at several spatial scales and for urbanized versus non-urbanized areas.

- The proportion of area with high sediment quality was much smaller in the Elliott Bay/ lower Duwamish study area than in all of the Central Region or in all of Puget Sound.
- The proportion of area with intermediate sediment quality was much higher in the study area than in all of the Central Region or in all of Puget Sound. These results reflect both the more heavily contaminated proportion of the bay and the large proportion of the Central Region comprising the relatively less contaminated central passages and basins of Puget Sound.
- Among just the urbanized/industrialized areas, the differences between bay-level, regional, and sound-wide results were not as large as for all areas combined. Elliott Bay and its adjoining waterways are part of the Central Region, but the region also encompasses other urbanized or industrialized areas, such as Commencement Bay and Sinclair Inlet.

Meeting the Needs of the Puget Sound Partnership

The UWI sediment monitoring program is a new tool for use by the Puget Sound Partnership (PSP), environmental managers, and other interested parties. Results from this work provide information on key components of the PSP Action Agenda and the Biennial Science Plan, including:

- *Status-and-trends monitoring*: The PSAMP Sediment Component has conducted status-and-trends monitoring of multiple aspects of ecosystem health throughout Puget Sound for more than 20 years. Thus, baselines of conditions already have been established for comparison to current conditions, to provide indications of change. As the PSAMP marine sediment monitoring continues, those baselines are being updated.

- *Effectiveness monitoring*: Application of the PSAMP Sediment Component sampling design at the bay scale can be used to quantify changes over time. These assessments provide information that environmental managers can use in determining whether *collective* localized cleanups and source control improve conditions over a wider area.

- *Indicators*: Indicators of sediment chemistry, toxicity, and benthic community structure have been used to characterize sediment quality throughout Puget Sound since 1989. Since 1997, these indicators have been combined into the multivariable SQTI and used to quantify the spatial extent of sediment quality degradation in Puget Sound. Work is currently underway to (1) enhance the sensitivity of the SQTI and (2) develop a quantitative benthic index.

- *Coordinated regional monitoring*: The UWI bay-scale sediment monitoring sampling frames are nested within the larger PSAMP geographical regions, which are nested within the sampling frame for all of Puget Sound. The PSAMP regions align well with the marine portions of the PSP's Action Areas. By this nested design, sediment quality can be gauged at different geographic scales (bay-, region-, and/or sound-wide). In addition, the PSAMP sediment monitoring design can be used to characterize ecological conditions in Puget Sound for urbanized versus non-urbanized areas, which can inform management decisions.

- *Science:* The PSAMP/UWI sediment monitoring component has incorporated accepted, state-of-the-science methods for study design and statistical analyses. Other technical developments are added as the program matures. Such methods are important for gleaning the best information possible from highly complex data.

- *Communication:* Since its inception in 1989, the PSAMP Sediment Component has provided information on sediment-quality status and trends to the PSP and its predecessors, and other interested parties. This information has been published in the *Puget Sound Update* and *State of the Sound*, numerous Ecology reports, peer-reviewed literature, and Ecology's Marine Sediment Monitoring website.

Recommendations

As a result of this 2007 study, recommendations are made for improving sediment monitoring at all scales, from bay-wide to Puget Sound-wide. Included in this report are recommendations to:

- Maintain and expand the existing PSAMP and UWI programs.
- Refine the sediment indices.
- Integrate sediment monitoring with other ecosystem monitoring.

Introduction

Problem Statement

Elliott Bay and the adjoining waterways of the lower Duwamish River have long been known to be adversely affected by toxic chemicals (Malins et al., 1982; Chapman et al., 1982; Long, 1982; Lower Duwamish Waterway Group, 2007). High concentrations of contaminants have been found in sediments, the water column, the sea surface microlayer, benthic invertebrates, demersal fish, marine birds, and marine mammals (Long, 1988; Lower Duwamish Waterway Group, 2007). The presence of toxic chemicals in all of these compartments of the environment suggest that these chemicals have accumulated over decades in the sediments, but are also still currently being discharged into the bay or resuspended by disturbance (Long, 1988; Lower Duwamish Waterway Group, 2007).

Millions of dollars have been spent to clean up the most contaminated sites. Cleanup and source-control programs have often focused on the immediate area around the source of the contamination and generally have not tested sediments farther removed from sources, leaving questions about the condition of the entire bay. To date, no programs have investigated whether cleanup and source-reduction efforts have improved conditions in the area as a whole.

Urban Waters Initiative Background

Ecology's Toxic Cleanup, Hazardous Waste, and Water Quality Programs are working with local governments near Washington's urban bays to reduce toxic chemical pollution from point and nonpoint sources. The waterbodies initially targeted by the Washington legislature are Elliott Bay and its adjoining waterways, Commencement Bay and its adjoining waterways, and the Spokane River.

This project identifies likely pollutant sources, establishes source controls, conducts inspections, and assists businesses and the public to reduce toxics and prevent contamination or re-contamination (Ecology, 2007).

As part of the Urban Waters Initiative, Ecology's Environmental Assessment Program is conducting effectiveness monitoring by assessing sediment quality in these urban bays, beginning with Elliott Bay and its adjoining waterways in 2007. Monitoring results are being compared to results from previous studies to provide information on whether environmental regulation, source control, and localized cleanup efforts have had positive impacts bay-wide.

Purpose and Objectives

The purpose of the sediment monitoring component of the Urban Waters Initiative is to gauge sediment-quality status and trends in Puget Sound's urban bays. It provides environmental managers with information on long-term effectiveness of collective toxics management efforts.

The objectives are to:

- Provide current and periodic *bay-scale* sediment-quality assessments for each bay.
- Determine whether *bay-scale* sediment quality is improving, deteriorating, or remaining unchanged over time, based on comparisons between existing baseline, current, and five-year *bay-scale* assessments.
- Provide a method for comparing and relating *site-specific* sediment-quality data with *bay-scale* data, and with larger-scale *regional* and *Puget Sound-wide* sediment-quality data sets.

Site Description

Elliott Bay is part of Puget Sound. The western boundary of the study area is a straight line from Alki Point to Fourmile Rock (Figure 1). The major metropolitan area of Seattle defines the study-area boundaries to the north, east, and south. Included in the study area are the waterways of the lower Duwamish River (East Waterway, West Waterway, and Duwamish Waterway).

The Duwamish River is the main freshwater source, entering Elliott Bay on the southeastern shore. The study area hosts a variety of urban and industrial activities, multiple stormwater and sewage outfalls, Superfund sites, and one of the busiest ports in the United States.

Resources at Risk

The Elliott Bay/lower Duwamish region is quite different from the time when the Duwamish Tribe flourished in the area. The Duwamish River, once meandering, has been straightened and channelized to support navigation and industry (Ecology, 2007). The nearshore water and sediment quality of Elliott Bay and its waterways have been degraded over decades by many pollution sources (Weston, 1999) and by a large and continuously growing urban population.

Although the area has been degraded, many species, both plant and animal, still depend on this estuary. The Elliott Bay/lower Duwamish region is a migratory pathway for salmon and home habitat for many other fish, marine birds, crabs, shellfish, and marine mammals (Weston, 1999). Elliott Bay still supports active recreational and tribal fishing industries (Weston, 1999). Degradation of Elliott Bay and the lower Duwamish River affect many people (Duwamish River Cleanup Coalition, 2008).

Sediment Quality-Related Research

Summary of Ecology Databases

Numerous studies have generated data on the presence and concentrations of toxicants and their associated adverse biological effects in Puget Sound, including Elliott Bay and the adjoining waterways of the lower Duwamish River. Primarily, these studies included measures of sediment contamination, toxicity, and benthic community effects in sediments and histopathological abnormalities in demersal fishes. Data from many of the studies conducted in the Elliott Bay/lower Duwamish area are stored in Ecology's Environmental Information Management System (EIM) and Sediment Quality Information System (SEDQUAL). These data were extracted from EIM and SEDQUAL and compiled into a GIS-linked Urban Waters Initiative database (Appendix A[2]).

All of the data from the historical research, collectively, served to identify (1) those areas of Elliott Bay and adjoining waterways where problems of chemical contamination were greatest and (2) which chemicals were detected most often. Metals, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), dioxins and furans, and phthalates are some of the chemicals that were most often detected in Elliott Bay/lower Duwamish sediments. Maps depicting measured concentrations for several metals and organic compounds relevant to this Urban Waters 2007 survey are given in Appendix A.

To provide information on the degree and spatial patterns in chemical contamination, a subset of the historical data spanning the years 1990-2006 (96 studies) was compared to Washington State regulatory sediment criteria (Ecology, 1995). One or more of the 47 Sediment Quality Standards (SQS) were exceeded at each of 1,254 stations in the historical data for this region (Appendix A). Mercury, phthalates, PCBs, and PAHs exceeded SQS criteria most frequently. At 619 of those stations, one or more of 45 of the 47 Cleanup Screening Limits (CSL) were exceeded; only the CSLs for di-n-butylphthalate and di-n-octylphthalate were not exceeded.

Summary of Historical NOAA Studies

NOAA, through its Marine EcoSystems Analysis (MESA) Puget Sound Project, generated considerable information on sediment contamination and its effects on the biota in the Elliott Bay region in the early 1980s. Many of the methods and analyses developed in the Puget Sound studies were subsequently applied by NOAA and various state partners nationwide in marine bays and estuaries (Long et al., 1996; Long and Sloane, 2005). Many of the methods used in the MESA studies were sufficiently similar to those still used by Ecology in the current PSAMP monitoring to warrant qualitative comparisons.

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[2] Appendix A also contains other summarized results compiled from various local, state, and national natural resource agency publications (Washington Department of Fish and Wildlife, Puget Sound Partnership, King County, National Marine Fisheries Service, National Oceanic and Atmospheric Administration), as well as from peer-reviewed journals.

The MESA study in Elliott Bay/lower Duwamish area found that sediments were most degraded in the lower Duwamish River and along the Seattle waterfront (Appendix A). Substantial numbers and percentages of samples were contaminated. Each of the urban bays of Puget Sound has its own unique chemical signature based on the history of inputs, and Elliott Bay is no different. There were mixtures of toxic chemicals in the sediments that could have caused toxicity in various animals and adverse effects to the resident benthos. Substantial percentages of resident demersal fishes were adversely affected with various kinds of histopathological lesions and other disorders.

Chemicals that most frequently exceeded national sediment-quality guidelines or state criteria included polycyclic aromatic hydrocarbons (PAHs) from petroleum spills and pyrolysis, polychlorinated biphenyls (PCBs), mercury, lead, arsenic, silver, and cadmium (Appendix A). It is highly likely that other potentially toxic chemicals have occurred in Elliott Bay sediments, but laboratory analyses for them were not previously performed.

Chemical concentrations in water, sea surface microlayer, fish tissues, and sediment have historically been highest in the lower reaches of the Duwamish River, off the north shore of Harbor Island, and along the Seattle waterfront (Appendix A). Conditions tended to improve into the deep canyon of central Elliott Bay and seaward toward and beyond the mouth of the bay.

Subsequent tests of sediments indicated that many of the contaminated places also were toxic in a variety of laboratory acute and sublethal toxicity tests (Appendix A). Measures of toxicity ranged from acute mortality to impairment of reproduction, impairment of respiration, genotoxicity, and other kinds of cytological damage.

In a later phase of these studies, the resident benthic communities were sampled and examined to determine if the high degree of chemical contamination and toxicity were expressed in the local biota. In samples that were contaminated and toxic, only relatively resistant benthic species, mainly polychaete worms, were found. Toxicity and benthic effects were most apparent in the lower Duwamish River waterways and off the Seattle waterfront docks and Denny Way Combined Sewer Overflow. The stations where sediments were most toxic supported only relatively tolerant molluscs and polychaetes and were devoid of relatively sensitive amphipods and crustaceans.

Lower Duwamish Waterway Superfund Site[3]

The Lower Duwamish Waterway was added to the National Priorities List (otherwise known as Superfund) in 2001. Under the Superfund program, a comprehensive evaluation of conditions within the Lower Duwamish Waterway has been conducted, as reported in the remedial investigation (RI; Lower Duwamish Waterway Group, 2007). The Lower Duwamish Waterway RI included an extensive, high-quality dataset of 1,484 surface sediment samples and 895 subsurface sediment samples collected since 1990 throughout the entire 5-mile study area. Samples were collected from areas close to potential sources of contamination as well as from areas representing site-wide conditions.

[3] Information provided by L. McCrone, Exponent, Inc.

Samples were generally analyzed for a standard suite of chemicals, including PCBs, metals, and semivolatile organic compounds (including PAHs and phthalates). Tributyltin, dioxins and furans, and organochlorine pesticides were also analyzed in sediment samples throughout the waterway.

This extensive dataset was evaluated in detail for spatial and temporal chemical patterns in surface sediment using various mapping techniques and statistical evaluations. Subsurface sediment data were also evaluated for vertical patterns within sediment cores relative to surface sediment data.

In addition to evaluations of sediment chemistry, the Lower Duwamish Waterway RI summarized a substantial amount of information on sediment toxicity, sediment transport, surface water chemistry, porewater chemistry, seep water chemistry, tissue chemistry (fish, crabs, clams, and benthic invertebrates), and potential chemical sources. Those interested in learning more about conditions within the Lower Duwamish Waterway proper are encouraged to consult the Lower Duwamish Waterway RI (Lower Duwamish Waterway Group, 2007).

Brief Overview of Cleanups in Elliott Bay/Lower Duwamish

It has been 100 years since various agents and agencies began engineering enormous physical changes of the rivers, lakes, and land in the Seattle area, one result of which was the straightening, shortening, channelizing, and industrializing, of the lower Duwamish River. After decades of polluting the resources, efforts have been underway to clean up the bay and river and prevent recontamination. The lists of projects include numerous changes to outfalls, capping of contaminated sediments, and Superfund cleanups.

Multiple governmental agencies and nongovernmental organizations have become involved. Each has its websites, reports, and updates. Information on the status and accomplishments of the projects of the Lower Duwamish Waterway Superfund cleanup and other cleanups and source-control actions is available at the following websites:

www.ecy.wa.gov/programs/tcp/sites/lower_duwamish/lower_duwamish_hp.html

http://yosemite.epa.gov/r10/cleanup.nsf/sites/LDuwamish

www.ldwg.org/

www.ldwg.org/sedimentcleanup.htm

www.kingcounty.gov/environment/wastewater/SedimentManagement/Projects/DennyWay.aspx

www.ecy.wa.gov/programs/tcp/sites/denny_way/dw_hp.htm

www.ecy.wa.gov/programs/tcp/smu/sediment.html

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Methods

Sample Design

Sediment monitoring for the Urban Waters Initiative (UWI) uses the design and methods of the Puget Sound Assessment and Monitoring Program (PSAMP) marine sediment monitoring component. PSAMP uses a probability-based sampling design to assess sediment quality in Puget Sound at multiple geographic scales. Sediments are sampled annually for chemistry, toxicity, and sediment-dwelling invertebrate communities (called benthic invertebrates or benthos) to characterize the extent of degraded sediment quality within eight geographic "regions" and five anthropogenic/geomorphological "strata" developed for PSAMP (Figures 2, 3). For the UWI, smaller-scale urban embayment surveys (e.g., Elliott Bay/lower Duwamish) are nested within PSAMP sediment monitoring regions.

The PSAMP design is based on the stratified random sampling design that was used for the 1997-1999 joint NOAA-Ecology sediment survey called PSAMP/NOAA, conducted as part of NOAA's National Status and Trends Program and the PSAMP. The PSAMP/NOAA design was modified slightly for the current PSAMP sediment monitoring program, with assistance from the U.S. Environmental Protection Agency (EPA) Monitoring Design and Analysis Team statisticians in Corvallis, OR (Dutch et al., 2004).[4]

In the PSAMP/NOAA survey design, the study area was divided into irregularly-shaped strata based on boundaries of waterbodies and on relatively homogeneous depth, salinity, sediment grain size, and general land use (Long et al., 2003). More and smaller strata were defined in urban bays and industrial harbors, where sediment contamination was known or expected to be high, and where heterogeneous conditions or gradients were expected. Fewer and larger strata were defined in areas far removed from point sources of contaminants, and where sediment contaminant levels were known or expected to be low. In most strata, three randomly-chosen stations were sampled; in a few strata, four samples were taken. In 1998, 36 stations were selected at random from the 10 strata defined in Elliott Bay and the adjoining waterways (Long et al., 2000).

The current PSAMP sample frame encompasses the original PSAMP/NOAA survey area plus embayments in the San Juan Islands, Admiralty Inlet, and the eastern Strait of Juan de Fuca (Dutch et al., 2004). The 97 PSAMP/NOAA strata and other areas in the PSAMP sample frame were divided into multidensity categories forming eight geographical regions (Figure 2) and five anthropogenic-use/geomorphological "strata"[5] (Figure 3).

The 2007 Urban Waters Initiative (UWI) sediment survey area covered an estimated 26.32 km^2 and encompassed three "stratum" types. The PSAMP/NOAA strata forming the Elliott Bay UWI survey included areas recognized as: industrialized harbors (11.14 km^2), urban bays (4.02 km^2),

[4] Sampling site selection for the current PSAMP spatial sediment monitoring program was generated by EPA using a generalized random tessellation stratified (GRTS) survey design for areal sampling (Stevens and Olsen, 2004).
[5] In contrast to the PSAMP/NOAA strata, the current PSAMP anthropogenic-use/geomorphological categories of basin, harbor, passage, rural bay, and urban bay are not true strata in the statistical sampling-design sense, but are called "strata" for shorthand in this report.

and deep basins (11.16 km^2) (Long et al., 2003).[6] Thirty of the original 36 1998 PSAMP/NOAA sample stations in Elliott Bay and its waterways were re-sampled in June 2007 for the UWI survey. The sites consisted of two basin stations, 15 harbor stations, and 13 urban stations (Figure 4). The sample weights, or amounts of area represented, were obtained by dividing the areas of the PSAMP/NOAA strata by the numbers of stations in them. Table 1 lists the stations sampled, with "stratum" type and amount of area represented.

The majority of field and analytical methods used in the 2007 survey were the same as those used in PSAMP/NOAA; therefore, most of the data collected in the two surveys should be comparable. Specifically, the sampling and laboratory methods; including processing and identification of infauna were the same. Most of the sampling personnel, laboratories, and taxonomists were the same. As described in more detail in the comparisons of the 1998 and 2007 data (*Results and Discussion*), there were differences in the integration of the chemistry, toxicity, and benthos elements of the Sediment Quality Triad Index. Therefore, the PSAMP/NOAA data (30 stations only) were reassessed using the same methods and station weights as for the 2007 data.

Field Sampling

Sample collection methods followed the Puget Sound Estuary Program (PSEP) Protocols (http://psparchives.com/our_work/science/protocols.htm) to ensure compatibility with data from the PSAMP/NOAA study. Sediments were collected during June 2007 from the 42-foot research vessel *Kittiwake* (Bio-Marine Enterprises, Seattle, WA). Each station was sampled only once. Station positioning followed PSEP (1998). Differential Global Positioning System (DGPS) with an accuracy of better than five meters was used to position the vessel at the station coordinates, all of which had been previously selected by a computer program. All samples were collected in depths of six feet or more (mean lower low water), the operating limit of the sampling vessel.

Collection of sediments for chemistry, toxicity, and benthic infauna followed the protocols of PSEP (1987) and PSEP (1996a). Prior to sampling each station, all equipment used for toxicity testing and chemical analyses was washed with seawater and Alconox® detergent and rinsed with acetone, then seawater. Sediment samples were collected with a double 0.1-m^2 stainless steel van Veen grab sampler. Surficial sediments (the upper 2-3 cm) were collected for toxicity testing and chemical analyses to ensure that the sample represented sediment-sorbed toxicants that were recently introduced into the area. Chemistry and toxicity samples were collected simultaneously with sediment collected for the benthic community analyses to ensure synoptic data.

Upon retrieval of the sampler, the contents were visually inspected to determine if the sample was acceptable (jaws closed and no washout, clear overlying water, sufficient depth of penetration). If the sample was unacceptable, it was dumped overboard at a location away from the station. If the sample was acceptable, information on station coordinates and the sediment color, odor, and type was recorded in field logs.

[6] There were no stations previously recognized in Elliott Bay as passages or rural bays (Long et al., 2003).

A single 0.1-m^2 grab sample from one side of the sampler was collected from each station for the benthic infaunal analyses. The sediment was gently washed through a 1.0-mm sieve, using a low-pressure stream of on-site seawater. Large animals (e.g., the brittle star *Amphiodia* sp.) were gently picked out of the samples with forceps and placed into sample bags as sieving proceeded. Material retained on the sieve was bagged and preserved with a 10% solution of borax-buffered formalin in seawater.

From the other side of the sampler, sediment was removed for chemical analyses and toxicity tests using a stainless steel spoon. The top two to three cm of sediment was removed with the spoon and accumulated in a stainless steel pot. The sampler was deployed and retrieved three to six times at each station, until a sufficient amount (about 5 L) of sediment was collected. Between deployments of the grab, a stainless steel lid was placed on the pot to avoid shipboard contamination and to reduce the effects of oxidation and photo-activation of sediment-sorbed toxicants.

After 5 L of sediment were collected, the sample was stirred with a stainless steel spoon or a drill with a stainless steel paint stirrer to homogenize the sediment. The homogenized sediment was then subdivided and transferred to individual jars for the various toxicity tests and chemical analyses. A double-volume sediment sample was collected at three stations for duplicate chemical analyses. All samples were labeled and double-checked for station and sample codes, sampling date, and type of analysis to be performed.

Samples for chemical analyses, sediment characterization, and toxicity tests were stored on deck in sealed containers placed in insulated coolers filled with ice. These samples were off-loaded from the research vessel every 1-3 days and transported to the walk-in refrigerator at Ecology's Operations Center building in Lacey. They were held at 4 °C until shipped on ice by overnight courier to the analytical laboratories. Chain-of-custody forms accompanied all sample shipments.

Benthic infauna samples were off-loaded from the research vessel every one to three days and transported to Ecology's headquarters building in Lacey. They were held at room temperature (minimum 24 hours, maximum 10 days) until the samples were transferred from formalin to ethanol for preservation and sorting.

Physical and Chemical Analyses

Grain size analyses were conducted by Analytical Resources, Incorporated in Tukwila, Washington. Laboratory analyses for potentially toxic substances were performed for 132 chemicals and total organic carbon content (TOC) by Ecology's Manchester Environmental Laboratory (MEL), Manchester, Washington (Table 2).

Analytical procedures provided data quality that met or exceeded objective performance criteria specified in the PSEP Protocols, including analyses of blanks and standard reference materials. Information was reported on recovery of spiked blanks, analytical precision with standard reference materials, and duplicate analyses of every 20th sample. Practical quantitation limits (reporting limits) were reported for chemicals that were at or below the detection limits and qualified as being undetected. Laboratory analytical methods and reporting limits for quantification of chemical concentrations followed those of the PSEP (Table 3).

Grain Size

Grain size analyses were performed according to the PSEP Protocols (PSEP, 1986) with salt correction. The PSEP grain size method is a sieve-pipette method. The samples were passed through a series of progressively smaller sieves, with each fraction being retained and weighed. After this separation, the very fine material remaining was placed into a column of water and allowed to settle. Aliquots were removed at measured intervals, and the amount of material in each settling fraction was measured. The PSEP method was modified to include percent gravel, sand, silt, and clay, with sand subdivided into five categories: very coarse, coarse, medium, fine, and very fine, according to the Wentworth scale.

Total Organic Carbon (TOC)

Total organic carbon analysis was performed according to PSEP Protocols (PSEP, 1986). The method involved drying sediment material, pretreatment and subsequent oxidation of the dried sediment, and determination of CO_2 concentrations by infra-red spectroscopy.

Metals

Priority pollutant and trace metals preparation was performed according to EPA Method SW 846 3050B. Metals analysis was conducted with EPA Method 200.8 which employs inductively coupled plasma/mass spectrometry (ICPMS) to quantify metals concentrations.

Mercury

Total mercury concentrations were determined by EPA Method 245.5. The method consists of a strong acid sediment digestion, followed by reduction of ionic mercury to Hg^+, and analysis of mercury by cold vapor atomic absorption (CVAA), as recommended by the PSEP Protocols (PSEP, 1996b).

Base/Neutral/Acid (BNA) Organic Chemicals

These semivolatile organics were analyzed by EPA Method SW 846 8270, a method recommended by PSEP (PSEP, 1996c). This method uses a capillary column gas chromatography/ mass spectrometry (GC/MS) system. Sediments were prepared by Soxtherm extraction (EPA Method SW 846 3541). The extracts were analyzed without gel permeation chromatography (GPC) cleanup to minimize contamination.

Polycyclic Aromatic Hydrocarbons (PAH)

Sediment samples analyzed for PAHs were air-dried and extracted with methylene chloride using accelerated solvent extraction (ASE), following EPA Method SW 846 3545. A silica-gel cleanup (EPA Method SW 846 3630C) was performed on the extracts, followed by quantitation using the MEL modification of EPA Method SW 846 8270. This method uses a capillary column GC/MS system with selective ion monitoring (SIM) isotopic dilution analysis of the sample extracts to quantify the concentrations of the PAHs.

Chlorinated Pesticides and Polychlorinated Biphenyls (PCB)

For analysis of chlorinated pesticides and polychlorinated biphenyls, modifications of EPA Method SW 846 methods 3545 (extraction), 3620, 3665 (cleanup), and 8081/8082 (analysis) were used. Samples were air-dried and extracted into methylene chloride using accelerated solvent extraction, following EPA Method SW 846 3545. After extraction, the extracts were solvent-exchanged into hexane. Samples were then re-extracted twice with tetrabutyl-ammonium hydrogen sulfate (TBA) to remove sulfur.

The extract was eluted through a Micro-Florisil® column, first with 100% hexane, which was collected as the 0% fraction, and with a 50% preserved diethyl ether/ 50% hexane solution, which was collected as the 50% fraction. All extracts were then solvent-exchanged into iso-octane, adjusted to one mL in volume, and split into two portions. One portion from each fraction was treated with concentrated sulfuric acid (EPA Method SW 846 3665) prior to analysis by EPA Method SW 846 8081/8082. This quantitation method uses gas chromatography/electron capture detection (GC/ECD).

Polybrominated Diphenyl Ethers (PBDE)

Sediment samples analyzed for PBDEs were air-dried and extracted with methylene chloride using ASE, following EPA Method SW 846 3545. Samples then received a 6% Micro-Florisil® cleanup treatment (EPA Method SW 846 3620), followed by TBA to remove sulfur (EPA Method SW 846 3660). The extracts were then concentrated to a final volume of 1 ml and acid-treated (EPA Method SW 846 3665) prior to analysis, following EPA Method SW 846 8270 for semi-volatile analysis in SIM mode.

Toxicity Testing

Sea Urchin (*Strongylocentrotus purpuratus*) Fertilization in Porewater

Tests of fertilization success with sea urchin gametes in sediment pore waters were conducted by the U.S. Geological Survey (USGS), using methods largely developed by its laboratory in Corpus Christi (TX), i.e., Carr and Chapman (1995), Carr et al. (1996a,b), Carr (1998). These methods were developed initially for *Arbacia punctulata*, a resident species along southeastern U.S. estuaries, but adapted for use in the Pacific Northwest with the Pacific coast purple urchin, *Strongylocentrotus purpuratus*.

Sediment pore waters were extracted with a pneumatic apparatus and were stored frozen until just prior to testing. *S. purpuratus* gametes were exposed to 100%, 50%, and 25% pore waters at 12 °C for 20 minutes to determine toxicity. Local Texas seawater collected near the lab was used as the diluent.

Detailed methods for this toxicity test, as well as quality assurance procedures, are included in the USGS laboratory report (Appendix G). The data from this test met or exceeded the Ecology quality assurance criteria in all batches of samples.

The endpoint measured in this test was the percentage of fertilized embryos following exposure of both the sperm and eggs to the porewater samples. Sample test results were compared to Texas control results using ANOVA and Dunnett's test. Test means were compared to reference means by the percent minimum significant difference necessary to accurately detect a difference from the reference with 95% confidence. Details are given in the 2007 USGS laboratory report (Appendix G).

Benthic Community Analyses

Sample Processing and Sorting

All methods, procedures, and documentation (including chain-of-custody forms, tracking logs, and data sheets) were similar to those described in the PSEP (1987) protocols. They were the same as those used in the PSAMP/NOAA survey conducted in 1997 through 1999, except for the omission of the 0.5-mm sieves used to capture the benthos in the earlier survey.

At the end of field collections, sieved benthic infaunal samples were taken to the benthic laboratory at Ecology's headquarters in Lacey. After a minimum fixation period of 24 hours (and maximum of 10 days), the samples were washed on 0.5-mm sieves to remove the formalin and then transferred to 70% ethanol.

Samples were stained with Rose Bengal and then examined under dissection microscopes. All macroinfaunal invertebrates and fragments were removed and sorted into five major taxonomic groups: Annelida, Arthropoda, Mollusca, Echinodermata, and miscellaneous taxa. Meiofaunal organisms such as nematodes and foraminiferans were not sorted from samples. Representative samples of colonial organisms such as hydrozoans, sponges, and bryozoans were collected, and their presence and relative abundance were noted.

Sorting QA/QC procedures consisted of resorting 25% of each sample by a second sorter to determine whether a sample sorting efficiency of 95% removal was met. If the 95% removal criterion was not met, the entire sample was resorted.

Taxonomic Identification

Upon completion of sorting and sorting QA/QC, most of the taxonomic work was contracted to recognized regional taxonomic specialists. Organisms were enumerated and identified to the lowest taxonomic level possible, usually to species. In general, anterior ends of organisms were counted, except for bivalves (hinges), gastropods (opercula), and ophiuroids (oral disks). At least two scientific references (preferably including the original description) were used for the identification of each species.

A maximum of three representative organisms of any species not found in previous Ecology sampling efforts was removed from the samples and placed in a voucher collection. Taxonomic identification quality control for all taxonomists included re-identification of 5% of all samples identified by the primary taxonomist and verification of voucher specimens by a second qualified taxonomist.

Benthic infaunal data were reviewed and standardized for any taxonomic nomenclatural inconsistencies by Ecology personnel using an internally developed standardization process. The process includes comparing the list of species identified in the study with a taxonomically current master species list that is based on the SCAMIT list of soft-bottom macroinvertebrate species (SCAMIT, 2001).

Data Analyses

Sediment Chemistry Comparison to Regulatory Sediment-Quality Standards

Sediment contaminant concentrations were compared to the Washington State Sediment Quality Standards (SQS) applicable to those contaminants. Nondetects were treated as specified in Ecology (1995). Samples in which none of the state criteria were exceeded were classified as not contaminated. Samples in which one or more SQS values were exceeded were classified as contaminated. Likewise, samples in which one or more Cleanup Screening Level (CSL) values were exceeded were classified as highly contaminated.

SQS quotients, ratios of chemical concentrations to their respective Washington State Sediment Quality Standards (SQS; Ecology, 1995), were calculated where applicable. Likewise, ERM quotients, ratios of chemical concentrations to their respective NOAA Effects Range-Median sediment-quality guidelines (ERM; Long et al., 1995), were calculated where applicable. Means of the SQS and ERM quotients were calculated across all applicable chemicals. The mean SQS and ERM quotients are indices of chemical contamination that take into account both the presence and concentrations of mixtures of potential toxicants.

Data for six organic compounds were excluded from the analyses due to the relatively low reliability of the analytical results for these substances. These six compounds were benzyl alcohol, benzoic acid, phenol, 2-methylphenol, 4-methylphenol, and 2,4-dimethylphenol. They are virtually ubiquitous throughout Puget Sound (Long et al., 2003) and occurred in concentrations greater than their respective SQS values. However, the analytical precision and detection limits attained by the lab for analyses of these compounds are highly variable, and there were indications of laboratory contamination in some samples, thereby precluding confidence in the reported concentrations.

Benthic Community Analysis

Nine benthic infaunal measures were calculated, including total abundance, 5 major taxa abundance categories, taxa richness, Pielou's evenness (J'), and Swartz' Dominance Index (SDI) (Table 4). These indices were used to summarize the raw data and characterize the infaunal invertebrate assemblages[7] from each station.

Non-metric multidimensional scaling (MDS) analyses were conducted in PRIMER v.6 (PRIMER-E Ltd., 2006) to provide graphical depictions of how similar or disparate the benthic assemblages were (Clarke and Warwick, 2001). Abundance data were 4th-root transformed prior to calculation of the matrix of Bray-Curtis similarities, following Clarke and Warwick (2001). The MDS ordination algorithm computes two-dimensional maps from the Bray-Curtis similarities.

Benthos element of the sediment-quality triad index

No multi-metric indices of benthic community health have been developed for Puget Sound such as those available for other regions of the U.S. and Europe (e.g., Bergen et al., 2000; Borja et al., 2000; Gibson et al., 2000; Ranasinghe et al., 2002, 2003, 2004, 2007; Rosenberg et al., 2004; Smith et al., 2001, 2003; Thompson and Lowe, 2004; Van Dolah et al., 1999; Weisberg et al., 1997). Such indices must be tailored to the infaunal communities of each biogeographic area; therefore, application of indices from other regions to Puget Sound infaunal communities is not warranted.

Infaunal assemblage data from this survey were interpreted qualitatively and descriptively using both best professional judgment based on considerable local experience and the approaches identified in the following documents:

- The Washington State Sediment Management Standards (Chapter 173-204 WAC; Ecology, 1995) provides methods for comparing the relative abundance of benthic invertebrates between study sites and reference areas.
- Striplin and Weston (1999) calculated ranges of a variety of benthic indices for Puget Sound reference areas.

Neither document provides numerical standards or guidance, however, on a species-level basis for judging the relative condition of the benthos.

Best professional judgment took into account the values of the nine benthic measures mentioned above, presence (or absence) and abundance of known stress-tolerant and pollution-sensitive species (e.g., Diaz and Rosenberg, 1995), and habitat characteristics (depth, salinity, grain size). The values of the nine benthic infaunal measures were also compared to 80% confidence intervals for their respective Puget Sound baseline (1997-2003) medians to depict ranges of relatively high, relatively low, and intermediate values. These values did not by themselves provide any judgment value as to whether the benthic community was "adversely affected."

[7] Because collections of invertebrates in grab samples may not reflect entire benthic invertebrate communities, they are termed assemblages.

Sediment Quality Triad Index (SQTI)

The data from chemical analyses, toxicity test, and benthic infaunal analyses conducted for the 2007 Urban Waters Initiative were compiled and merged to form a weight-of-evidence matrix with which to classify the degree of degradation in sediment quality (Long et al., 2004, 2005). The criteria for the three elements of the triad are:

- Chemistry: Concentrations of one or more sediment contaminants in excess of the respective Washington State Sediment Quality Standards (SQS).
- Toxicity: Toxicity test results significantly different from control results and less than 80% of the control results (i.e., "highly toxic").
- Benthos: Best professional judgment of the invertebrate assemblage and five or more of the nine benthic measures outside an 80% confidence interval for the median for each measure for the Puget Sound baseline.

Based on the weight of evidence from the triad of results, each station was classified as to relative quality using methods that we previously used (Long et al., 2004, 2005). These methods do not necessarily align with the state regulatory standards, but are based on our Sound-wide database and peer-reviewed data acquired in other regions and countries (Long and Sloane, 2005). Sediment Quality Triad categories include:

- **High quality:** No degradation (no chemical concentrations exceeding State standards, no significant results in toxicity tests, and the majority of the benthic indices indicating unaffected infauna).
- **Intermediate/high quality:** Sediments with degradation in only one element of the triad (i.e., one or more chemical concentrations greater than the SQS, or a highly significant result in the toxicity test, or adversely affected infauna).
- **Intermediate/degraded quality:** Sediments with degradation in two of the three triad elements.
- **Degraded quality:** Degradation in all three triad elements: one or more chemical concentrations greater than SQS, a significant outcome in the toxicity test, and affected benthos (number and diversity of benthic organisms depressed relative to uncontaminated sediments, or infauna were dominated by pollution-tolerant species, or both).

Data Summaries and Displays

Where there were field or lab replicates, or both, the first field or lab replicate result was used as the value for that parameter at that station to preserve the statistical variability of the data. Nondetects in sediment chemistry were censored at the reporting limits (quantitation limits) specific to those samples.

Graphical summaries of the 1998 and 2007 results are given in the electronic Appendices D (physical parameters) and H (benthos) of this report. The graphical summaries contain:

- censored boxplots of the 1998 and 2007 data (explained below).
- a boxplot of the differences (2007 results minus 1998 results, by station).
- cumulative distribution function (CDF) curves for the 1998 and 2007 data (explained below).
- a bar chart displaying the 1998 and 2007 results side-by-side for each station.
- a bar chart of the differences (2007 minus 1998).
- a map of stations.

Summary statistics (mean, standard deviation, median, minimum, maximum, coefficient of variation) were computed for all parameters. When nondetects were present in the sediment chemistry data, summary statistics were estimated using a robust regression on order statistics (ROS) procedure (Helsel, 2005). In robust ROS, detected results are regressed against normal scores calculated for those detected results, or for log-transformed detected results if the data are lognormally distributed. Nondetect values are predicted from the regression line at equally-spaced *probability* intervals. Then summary statistics are estimated from the combined detected and predicted values (Helsel, 2005).

Relationships and Correlations among Variables

The objectives of this 2007 survey did not include determinations of cause/effect relationships among the variables that were measured. Such determinations in field-collected samples are very difficult because of the complexities in the variables that can affect measures of biological effects and the physical/chemical variables. However, we were curious to discover which variables co-varied with each other throughout the region. Co-varying variables may lead to future experiments to determine and verify cause/effect relationships.

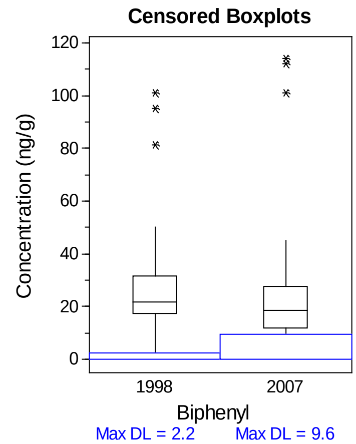
Multivariate nonparametric correlation between the benthic assemblages and environmental variables was conducted with the RELATE procedure in PRIMER v.6 (PRIMER-E Ltd., 2006). Analogous to the matrix of similarities of benthos among stations, a matrix of similarities of ten environmental variables among stations was calculated. The environmental variables chosen for analysis were: geographic location (latitude, longitude), site characteristics (depth, salinity), sediment characteristics (penetration depth of the van Veen grab, percent fines, TOC content, temperature), contamination (mean ERM quotient), and toxicity (control-corrected percent fertilization of sea urchin gametes). The data were normalized for each variable, and Euclidean distances were calculated as the metric of similarities. The two matrices of similarities were then correlated by Spearman’s rho, as described in Clarke and Warwick (2001).

Comparisons of 2007 Results to 1998 Results

To determine whether parameter values bay-wide had increased, decreased, or remained the same from 1998 to 2007, a weight-of-evidence approach was used. The CDF-comparison tests use the unequal weighting of samples but not the repeated measures (i.e., 1998 and 2007 results for each station) or censoring for chemical nondetects. Other procedures account for the repeated measures or nondetects but not the unequal sample weights. Therefore, several procedures were used to test partial questions. All tests were conducted at the 0.05 individual level of significance without error-rate adjustment.

Descriptions follow for graphical, descriptive, and inferential procedures used to display and compare the 1998 and 2007 results.

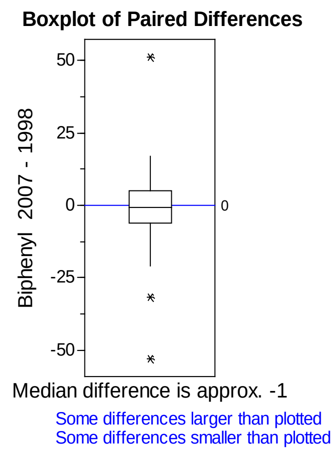
Censored Boxplots



Boxplots are graphical representations of datasets which indicate the median, range, quartiles, and outliers. Two or more datasets can be compared visually. Censored boxplots depict graphically the uncertainty inherent in nondetects.

In this report, side-by-side boxplots display the unweighted 1998 and 2007 parameter results (Appendices D and H). When nondetects were present in the sediment chemistry data, the boxplots were censored at their respective highest reporting limits ("DL" in figure).

Tests of Paired Differences



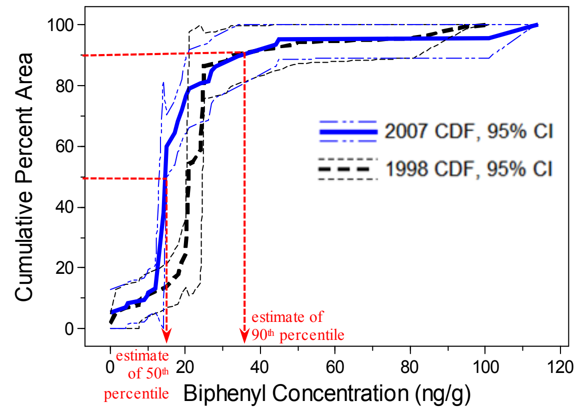
Differences between the 1998 and 2007 results were calculated for each station for each parameter (displayed in bar charts and boxplots in Appendices D and H). Negative values reflected decreases; positive values reflected increases. Due to the inherent uncertainty in nondetects, median differences were estimates when nondetects were present.

To determine whether parameter values had increased or decreased from 1998 to 2007, tests of hypothesis (no change vs. change) were conducted on unweighted and weighted differences. Median differences which were statistically significantly different from zero provided evidence of change.

For sediment chemistry results with nondetects present, these paired differences, *unweighted*, were compared to zero by the Prentice-Wilcoxon test, a nonparametric censoring procedure (Helsel, 2005). The test was conducted in Minitab v.15 (Minitab Inc., 2007) with a macro written and provided by Helsel (2005; www.practicalstats.com/nada). The paired Wilcoxon signed ranks test was used when there were no nondetects.

Weighted paired differences were compared to zero with the Wilcoxon signed ranks test for each of two treatments of nondetects (set to zero and set to the reporting limit). Test results which were consistent were used in the weight-of-evidence. Results which were inconsistent (different answers for different treatments of nondetects) were considered inconclusive and were not used.

CDF Comparisons



Cumulative distribution functions (CDF) display graphically distributions of parameter values. In a CDF, sample results are ordered by increasing size and weighted by the amount of area each station represents, and the weights (% area) are summed cumulatively. Confidence intervals can be calculated. Two distributions for a given parameter (e.g., biphenyl concentrations in 1998 vs. 2007) can be compared by statistical hypothesis tests of the CDFs (see Diaz-Ramos et al., 1996). In this way, change in bay-wide parameter spatial extent (e.g., proportion of area with biphenyl contamination) can be determined.

CDFs were generated to depict the spatial distribution for each parameter. Fiftieth and 90th percentiles of the distributions were estimated from the CDF curves by linear interpolation. In the absence of procedures to handle nondetects in CDFs, nondetects were treated two ways: set to zero (shown in Appendix D) and set to the reporting limit.

CDFs for 1998 and 2007 were compared with the Wald F test (Kincaid, 2000, 2006), using a function developed by EPA (Diaz-Ramos et al., 1996; U.S. EPA, 2007) and written for the S-PLUS statistical software language (Insightful Corporation, 2005). The Wald F test was applied to CDFs separately for the two treatments of nondetects. Test results which were consistent were used in the weight-of-evidence. Results which were inconsistent were considered inconclusive and were not used.

Comparisons of Proportions

To compare the incidence and spatial extent of sediment contamination in 1998 and 2007, the following statistical tests were used:

- Fisher's exact test, to compare the numbers of stations exceeding SQS levels.
- Two-proportion comparison test (normal approximation), to compare the proportions of area exceeding SQS levels.

Similarly, Fisher's exact test was used to compare the numbers of stations in 1998 and 2007 meeting the criteria for:

- Highly toxic sediment (significant toxicity test results).
- One individual element (e.g., chemistry) of the Sediment Quality Triad Index.
- A specific number of triad elements (e.g., zero elements).

The two-proportion test was used analogously to compare the percent of area in 1998 and 2007 meeting such criteria.

The chi-square test of homogeneity was used to compare the 1998 and 2007 multinomial distributions of:

- Grain size (proportions of gravel, sand, silt, and clay)
- Sediment Quality Triad Index (number of stations meeting criteria for 0, 1, 2, or 3 triad elements).

Multivariate comparisons: ANOSIM

Analogous to ANOVA (analysis of variance), the analysis of similarities (ANOSIM) is used to test whether the rank similarities between replicates in a study differ from the rank similarities among replicates (Clarke and Warwick, 2001). A permutation test is used to determine the p-value (lowest significance level at which the null hypothesis of no difference can be rejected, based on the particular set of data). In this study, PRIMER v.6 (PRIMER-E Ltd., 2006) was used to conduct ANOSIM analyses to compare the results from 1998 and 2007 for:

- Benthic assemblages, based on Bray-Curtis similarities.
- SQS quotients, based on Euclidean distance.
- Environmental variables, based on Euclidean distance.

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Results and Discussion

Site Characteristics (2007)

Sampling station numbers, names, and locations and the sizes of the areas that they represented are listed in Table 1. Final station coordinates and water depths for all 30 stations sampled, and rejected stations not sampled, are listed in the navigation report (Appendix B). The physical and visual characteristics of each sample, including water salinity, water temperature, visual sediment description, sediment color, odor, and sampler penetration depth, are included in the field notes (Appendix C). Station depths are depicted in Figure 5. As expected, stations were most shallow in the dredged Duwamish Waterway and around the perimeter of the bay, and deepest in the glacially-carved canyon down the middle of the bay.

Physical and Chemical Analyses (2007)

Grain Size

The sizes of the particles in sediment samples can be an important determinant in the concentrations of contaminants in estuaries (Wenning et al., 2005). Because of the greater surface area available for chemicals to bond to per volume, chemical concentrations often are expected to be highest in fine-grained sediments, such as those that are composed primarily of fine-grained silts and clays. In contrast, physical actions of currents and waves can wash away fine-grained particles and attached toxicants from coarse sands and gravel.

The grain size values measured for these samples are listed in Appendix D Table D-1. Frequency distributions of the four particle size classes (percent gravel, sand, silt, and clay) are depicted for all stations in Figure 6. Figure 7 and Appendix D Figure D-1 display percent fines (silt+clay content) by station.

The northern and southern shorelines of Elliott Bay had predominantly sandy sediment, whereas particle sizes were more mixed in the waterways and generally finer in the deeper stations of the inner and outer bay (Figure 6).

Table 5 lists the numbers of stations and percent of area represented for which the sediment compositions were classified as predominantly sandy (>80% sand), silty sand (60-80% sand, 20-40% fines), silt+clay (>80% fines), and mixed. Almost one-half of the stations (14) and almost one-half of the study area (42%) had mixed sediment, ranging from 20% sand/80% fines to 60% sand/40% fines (Table 5). Six stations, representing 10% of the area, had predominantly sandy sediment, whereas sediments at five stations, representing 36.5% of the area, were predominantly silt+clay. The remaining five stations (11.5% of area) were classified as having silty sand.

Such complexity and heterogeneity in the surficial sediments of Puget Sound has been observed and reported previously (Long et al., 2003; Partridge et al., 2005). It is to be expected in a region influenced historically by glacial carving and more recently by riverine transport of sediments.

Total Organic Carbon (TOC)

TOC contents are summarized in Table 6, grouped by “stratum” type[8]. Individual values are listed in Appendix D Table D-2, with graphical displays in Appendix D Figure D-2.

TOC concentrations ranged from 0.15 to 5.76%, with a mean of 1.7% ± standard deviation 1.2%. The next highest TOC concentration measured was 4%; all others were 3.3% or less. In the samples in which lab duplicate analyses were performed, the two sets of concentrations often were in good agreement (Appendix D Table D-2).

Three of the 30 stations (177, 178, 190) had TOC values lower than 0.2%, which should be considered when comparing TOC-normalized data from these stations to Washington State sediment-quality criteria (Michelsen, 1992).

With the exception of high TOC (5.76%) at Station 199, just outside the entrance to the West Waterway, TOC content tended to be low at the northern and southern margins of Elliott Bay (Figure 8). TOC content was generally higher in the vicinity of Piers 54 and 55 near the Denny Way Combined Sewer Overflow than elsewhere (Figure 8).

Total organic carbon is a measure of the amount of organic matter in a sediment sample, whether derived from plant materials, dead and decaying animals, or sewage (Wenning et al., 2005). There is empirical and experimental evidence that demonstrate that the degree of binding and bioavailability of organic toxicants can be strongly affected by TOC content (Wenning et al., 2005). In a region such as Elliott Bay, samples with highest TOC content are usually those in deeper, depositional areas with highest percent fines.

Chemical Contamination

Concentrations of individual trace metals and organic compounds measured in each sample in 2007 are listed in Appendix D Table D-3, with graphical summaries in Appendix D Figures D-3 through D-132. Summary statistics and numbers of nondetects for each contaminant measured are given in Table 7. Table 7 also lists the 50th and 90th percentiles of the distributions for each chemical analyte, indicating the upper limits of concentrations for 50% and 90% of the total study area.

In the samples for which duplicate analyses were performed, the two sets of concentrations often were in good agreement (Appendix D Table D-3).

Many of the concentrations of individual chemicals were qualified values; that is, they were undetected at the detection limits attained by the lab (nondetects) or were detected but estimated values, because the concentrations were very low. The numbers of nondetects for a given analyte ranged from occurring in no stations to occurring in all 30 stations (Table 7).

[8] These “stratum” types were defined in a previous Ecology publication (Long et al., 2003).

With few exceptions, metals and PAHs were always detected. Metals and PAHs are virtually ubiquitous in Puget Sound (Dexter et al., 1981; Long et al., 2003). PCB congeners were usually detected. There has been a long history of PCB spills, discharges, and leaks in the bay and river. A few PBDEs and PCB Aroclors were detected; most were not. Except for some DDT isomers, chlorinated pesticides were almost always undetected. This area has not been important agriculturally, due to the extensive development and industrialization. The remaining organic analytes, BNAs, were a mixture of detects and nondetects.

There was generally greater variability in concentrations among stations for PAHs, PBDEs, and BNAs than for metals and PCBs.

There was considerable heterogeneity in some areas. For example, two pairs of stations at the southern and eastern shores of Elliott Bay (Stations 183-184 and 197-199, respectively) had remarkably different contaminant levels despite intra-pair distances of about 100 meters. At Stations 184 and 197, arsenic, copper, zinc, dibenzofuran, and other chemicals were found in high concentrations relative to the rest of the study area, some exceeding SQS criteria. At Stations 183 and 199, respectively, concentrations were less than half, sometimes an order of magnitude lower. At Stations 183-184, the ratio of TOC at one station relative to the other was similar to the corresponding ratio of contaminant concentrations. At Stations 197-199, however, the ratio was reversed: TOC was an order of magnitude higher at the station with the lower contaminant concentrations.

Spatial Extent and Severity of Chemical Contamination

Sediment chemical contamination is defined and expressed as the numbers of stations and proportion of study area for which one or both of the Washington State regulatory sediment-quality standards[9] (SQS, CSL) were exceeded. Tables 8 and 9 list the stations at which sediment-quality standards for applicable chemicals were exceeded in 2007.

Of the 41 SQS/CSL chemicals or chemical groups for which sediment-quality criteria can reliably be applied, no criteria were exceeded for 24 chemicals (Table 8). For 12 chemicals or chemical groups, only the SQS was exceeded. Both the SQS and CSL were exceeded for five chemicals.

The chemical whose sediment-quality standards were exceeded most frequently was bis(2-ethylhexyl) phthalate (Table 8). The SQS was exceeded at eight stations (2.88 km^2, 10.9% of area) and the CSL at five stations (1.83 km^2, 7% of area).

The next most frequent was mercury, whose SQS was exceeded at five stations (4.03 km^2, 15.3% of area) and CSL at four stations (3.06 km^2, 11.6% of area).

[9] The Washington State regulatory sediment criteria were derived with the apparent-effects threshold approach, a method of comparing sediment chemical concentrations with both sediment toxicity and adverse effects to the resident benthos. Two sets of values were derived for each chemical. The Sediment Quality Standards (SQS) are sediment chemical concentration levels below which adverse biological effects are not expected to occur or above which at least minor adverse impacts on benthic macrofauna are expected always to occur. The Cleanup Screening Limits (CSL) are concentration levels above which at least moderate adverse biological effects are expected to occur (Ecology, 1995).

The SQS for total PCB Aroclors was exceeded four times (0.98 km^2, 3.7% of area).

All other criteria were exceeded three or fewer times. In general, the criteria for PAHs were most frequently exceeded (8 of 21 chemicals or groups of chemicals), followed by BNAs (5 of 14 compounds), then metals (3 of 8 metals).

One or more SQS criteria were exceeded at 17 of the 30 stations, representing 9.0 km^2 or 34.2% of the study area (Table 8). One CSL criterion was exceeded at 10 stations and two CSL criteria were exceeded at an 11^{th} station, together representing 5.36 km^2 or 20.3% of the study area.

Station 184 had 6 PAHs or PAH sums that exceeded the SQS criteria, one of which (fluoranthene) also exceeded the CSL (Table 9). The other 16 stations with concentrations exceeding sediment-quality criteria did so with three or fewer chemicals or chemical groups each. No Washington State sediment-quality standards were exceeded at 13 stations, representing a total of 17.3 km^2 or 65.8% of the study area.

Normalization of the concentrations of organic compounds to TOC in estuarine sediments is a method frequently used by EPA to account for both the concentration of the toxicant and its relative degree of bioavailability (U.S. EPA, 2003). The Washington State sediment-quality standards for PAHs, PCBs, phthalates, and miscellaneous organic compounds are expressed as TOC-normalized criteria (Ecology, 2005). Although the TOC levels at three stations (177, 178, and 190) were very low (< 0.2%), the contaminant concentrations were also low, so TOC-normalization did not produce abnormally high or insightful results.

The mean ERM quotient, the mean ratio of chemical concentrations to NOAA ERM sediment-quality guidelines over 27 chemicals or chemical groups, is an index of chemical contamination that takes into account both the presence and concentrations of mixtures of potential toxicants. In this study, the mean ERM quotient ranged from 0.02 at Station 177 (off Magnolia Bluff) to 1.57 at Station 184 (off Pier 55) (Table 9). Only Station 184, representing 0.11 km^2 (0.4% of total area), had a mean ERM quotient greater than 1. The next highest mean ERM quotients were 0.51 (Station 188, west of Pier 57) and 0.48 (Station 195, west of Pier 48); all others were below 0.4. Mean ERM quotients were overall highest in the harbor “stratum” type and lowest in the basin “stratum” type (Table 10).

Spatial Patterns in Chemical Contamination

Of the 17 stations where SQS sediment-quality criteria were exceeded, 11 were in the harbor “stratum” type and represented 2.86 km^2 or 10.9% of the study area. Six of the 17 stations were in the urban “stratum” type and represented 5.89 km^2 or 22.4% of the study area. No sediment-quality criteria were exceeded in samples from the outer portion of Elliott Bay (west of both Duwamish Head and Smith Cove) or the deep central portion of the inner bay (Figure 9).

Of the 11 stations where CSL criteria were exceeded, seven were in the harbor “stratum” type and represented 1.37 km^2 or 5.2% of the study area, and four were in the urban “stratum” type and represented 3.99 km^2 or 15.1% of the study area (Figure 9).

Mercury criteria were exceeded in the southeastern portion of the bay and at Duwamish Head (Figure 10). With the exception of mercury at Duwamish Head, metals concentrations were generally lowest in the outer bay and at one station just west of the mouth of the West Waterway. Metals concentrations were generally highest at or near the Port of Seattle piers and just outside the mouth of the West Waterway.

PAHs were generally highest near the Port of Seattle piers, though one station just south of Duwamish Head also was high in LPAHs (Figures 11, 12). PAH contamination was lowest in the outer bay and at one station just west of the mouth of the West Waterway. LPAH concentrations were low in the West Waterway, as well.

Six of the eight stations where the SQS were exceeded for bis(2-ethylhexyl) phthalate were in the Duwamish, East, and West Waterways (Figure 13). The other two stations where bis(2-ethylhexyl) phthalate criteria were exceeded were just west and northwest of Pier 70 along the Seattle waterfront. Conversely, all but one station in the waterways exceeded the standards for bis(2-ethylhexyl) phthalate. At three of those six stations, in the Duwamish and West Waterways, bis(2-ethylhexyl) phthalate was the only chemical exceeding sediment-quality criteria.

In the East Waterway, the stations near the piers exceeded Washington State standards for total PCB Aroclors (Figure 14) and 1,4-dichlorobenzene.

Dibenzofuran was highest at the margins of the southern portion of the inner bay (Figure 15).

All of these spatial patterns are consistent with those found in other studies (Appendix A) and the NOAA MESA surveys (Appendix A).

Summary

The northern and southern shorelines of Elliott Bay had predominantly sandy sediment. Particle sizes were more mixed in the waterways and largely finer in the deeper stations of the inner and outer bay. TOC content tended to be low at the northern and southern margins of Elliott Bay and generally higher in the vicinity of Piers 54 and 55 than elsewhere in the study area.

Most metals, PAH, and PCB congener concentrations were measurable, whereas the majority of other organic compounds on the analyte list were not detected.

No Washington State sediment-quality standards were exceeded at 13 stations, representing 65.8% of the study area. This means that the majority of the study area was not classified as contaminated and, therefore, did not represent a high toxicological threat to the local benthos according to the interpretation of the sediment management standards. No SQS criteria were exceeded for 24 of 41 chemicals or chemical groups. Six chemicals exceeded SQS criteria at one station; all other stations had 3 or fewer SQS violations each. One or more SQS criteria were exceeded at 17 stations, representing 34.2% of the study area. CSL criteria were exceeded at 11 stations, representing 20.35% of the study area. These are the stations in which ecological risks are highest. Two chemicals exceeded CSL criteria at one station; the other 10 stations had one CSL violation each.

Sediment-quality standards were exceeded most frequently by bis(2-ethylhexyl) phthalate (8 stations, 10.9% of area), followed by mercury (5 stations, 15.3% of area) and total PCB Aroclors (4 stations, 3.7% of area). Standards for all other chemicals were exceeded three or fewer times. In general, among the classes of chemicals, the criteria for PAHs were most frequently exceeded (8 of 21 chemicals or sums), followed by BNAs (5 of 14 compounds), then metals (3 of 8 metals).

PCB concentrations were highest in the Duwamish and East Waterways. In general, metals and PAH contaminant concentrations were highest at or near the Port of Seattle piers or in the southeast portion of Elliott Bay, and lowest in the outer bay.

Toxicity Tests (2007)

For the purposes of the Urban Waters Initiative, samples were classified as "toxic" in tests of 100% pore water when mean sea-urchin fertilization success was significantly lower than in the Texas control sediment. When fertilization success was both significantly lower than in the control and less than 80% of the control response, samples were classified as "highly toxic." The samples that were toxic according to those criteria were collected from stations 177, 190, and 201: Magnolia Bluff, Duwamish Head, and East Waterway Pier 32, respectively (Table 11, Figure 16), representing 5.8% of the study area. Of those, only sample 177 (Magnolia Bluff), representing 1.6% of the study area (0.4 km^2), was highly toxic. Station 177 off Magnolia Bluff is near the former dredged material disposal site at Fourmile Rock.

There was no obvious or discernible spatial pattern or gradient in toxicity with this test in this study area. The percent incidence and spatial pattern in toxicity might have been different if there had been data for multiple types of toxicity tests.[10]

Benthic Community Analyses (2007)

Assemblage Characteristics

Graphical summaries of the quantitative benthos measures and major taxa abundances are given in Appendix H Figures H-1 through H-10.

Total Abundance and Taxa Richness

Among the 30 samples collected in 2007, 385 taxa of benthic invertebrates were identified, 351 to species level (Appendix I Table I-1). Of these, seven are provisional species that are probably new to science. Averages of 671 individuals (range 33-1912) and 67 taxa (range 24-110) per sample were collected in the study area (Table 12). Figures 17 and 18 display total abundance and taxa richness by station.

[10] In the 2007 survey, three types of toxicity tests had been performed (sea urchin fertilization, amphipod mortality, and sand dollar embryo development). However, the data from the amphipod and sand dollar tests did not meet Ecology's quality assurance criteria and therefore were not acceptable. Because those data could not be used to reliably classify sediments as toxic or not, they were not used for this report.

Evenness and Dominance

Pielou's Evenness Index, a measure of the equitability of species distribution, ranged from 0.4 to 0.97 (Table 12, Figure 19). Over the 30 stations, the mean evenness was 0.68.

Swartz' Dominance Index (SDI) is the minimum number of taxa accounting for 75% of the infaunal abundance in a sample. When standardized by taxa richness, the SDI (SDISTD) represents the proportion of taxa which account for 75% or more of the total abundance. In the 30 samples in this study, SDI ranged from 2 to 25 taxa, averaging about 11.5 (Table 12, Figure 20). SDISTD ranged from 4.1 to 66.7%, with mean 18.3% and median 15.9%.

Major Taxa Abundance

Annelids accounted for 54% of the taxa and 55% of the total abundance from the 30 samples (Tables 13, 14). Molluscs were represented by 62 taxa and made up about 32% of the total abundance. Seventy-eight arthropod taxa constituted almost 12% of the total abundance. Echinoderms in 14 taxa made up 0.5% of the total abundance, and 23 miscellaneous taxa made up just over 1% of the animals across all samples. The abundances of the major taxa groups are displayed by station in Figure 21.

Dominant Fauna

The most abundant species in each sample ranged from 3 to 1129 individuals and accounted for 9.1 to 67.7% of the total abundance (Appendix I Table I-2). Eleven species in ten genera were represented. In 11 of the 30 samples, the most abundant species was the bivalve *Axinopsida serricata*. The polychaete *Aphelochaeta glandaria* was the most abundant species in six samples, and in five samples the most abundant species was *Prionospio steenstrupi*. The other eight species were the most abundant taxon in one or two samples each.

Five taxa averaged 40 or more individuals per sample and occurred at 60% or more of the stations. *Axinopsida serricata* was found at all 30 stations and accounted for 15.3% of all infauna sampled across all stations. The species which occurred next most frequently were the bivalve *Parvilucina tenuisculpta* at 26 stations, 8% of all infauna sampled, and the polychaete *Aphelochaeta glandaria* at 18 stations, 13.9% of all infauna sampled. The only other organism accounting for more than 5% of all infauna sampled was the polychaete *Prionospio (Prionospio) steenstrupi*, found at 23 stations and composing 6.6% of total abundance. The ostracod *Euphilomedes carcharodonta*, found at 23 stations, made up 4.5% of total abundance. All other organisms accounted for less than 3% each.

Infaunal Assemblages

Four distinct groupings of infauna were identified in the study area. These assemblages differed from each other based primarily on dominant taxa, depth, and sediment characteristics. The groups were based initially on the MDS map of the similarities of the assemblages (Figure 22). Investigation revealed that assemblages within each group had certain species in common. Outlying assemblages and assemblages which were similar to more than one group were assigned to the most similar groups based on dominant species as well as less common species in the assemblages. The groups are named based on the overall dominant species in each assemblage. A closer look revealed that, for the most part, the stations within each of the four groups had similar depths and sediment types.

The infaunal assemblages at seven stations (114, 200, 201, 202, 203, 204, 205) in the Duwamish, East, and West Waterways tended to be relatively similar to each other and distinct from the other communities (Figures 22, 23). Also included in this group was Station 115, located along the northern margin of Elliott Bay at Pier 90. These stations were relatively shallow (6-22 m), had mixed and silty sand sediments, and were numerically dominated by the stress-tolerant polychaete, *Aphelochaeta glandaria*.

In Elliott Bay, similarities in benthic assemblages tended to follow depth contours (Figures 22, 23). Infaunal assemblages in the deeper stations (172, 173, 185, 187, 194, 195, 196) in both the outer and inner bays tended to be more similar to each other than to assemblages elsewhere. These stations ranged in depth from 72-152 m, had mixed and silt-clay sediments, and were characterized by the presence of the bivalve species *Axinopsida serricata* and the polychaetes *Levinsenia gracilis, Aricidea lopezi,* and *Cossura* spp.

The assemblages along the 35-40-m depth contours parallel to the shore of Elliott Bay from west of Pier 56 to northwest of Pier 70 (Stations 181, 182, 186, 188) were quite similar (Figures 22, 23). These stations were characterized by mixed and silty-sand sediments and were numerically dominated by *Axinopsida serricata* and the ostracod species *Euphilomedes producta*. Station 192, located at the end of a ridge running north from the mouth of West Waterway, displayed a similar sediment type and benthic assemblage, though it was about twice as deep (72 m) as the other four stations in this group.

Ten shallow (6-22 m) stations along the shoreline of Elliott Bay (176, 177, 178, 180, 183, 184, 189, 190, 197, 199) had sandy and silty-sand sediments and infaunal assemblages that were dominated by the bivalve *Parvilucina tenuisculpta* and the polychaete *Prionospio steenstrupi* (Figures 22, 23).

Affected Benthos

Sixteen stations, representing 14 km^2 (53.3% of area), were judged to have adversely affected benthic infaunal communities (Table 15, Figure 24). These judgments were based on (1) the quantitative measures of abundance and diversity, (2) presence of stress-tolerant species or absence of pollution-sensitive species, and (3) best professional judgment of experienced benthic ecologists. (See Methods section, above.) Of those, eight stations (representing 2.09 km^2) were in the harbor “stratum” type, seven stations (representing 6.35 km^2) were in the urban “stratum” type, and one station (representing 5.58 km^2) was in the basin “stratum” type.

Large numbers of stress-tolerant species, such as the polychaete *Aphelochaeta glandaria*, and low taxa richness, evenness, and dominance were characteristic of benthic assemblages in the waterways. Low total abundance or taxa richness, or both, characterized other adversely affected communities. The most adversely affected was Station 185, where only 33 animals were found, representing a total of 24 taxa.

Summary

Benthic assemblages tended to group by geographic area, sediment type, and depth. Four assemblage groups were identified:

- The *Aphelochaeta glandaria* group which occurred in shallow mixed sediments in the waterways.
- The *Axinopsida serricata/Levinsenia gracilis* group, found at the deep silt-clay stations in Elliott Bay.
- The *Axinopsida serricata/Euphilomedes producta* group, found at silty sand stations along the 35-40 meter depth contour in Elliott Bay.
- The *Parvilucina tenuisculpta*/*Prionospio steenstrupi* group, found at shallow sandy stations along the shoreline of Elliott Bay.

Total abundance in the samples varied by two orders of magnitude between the lowest and highest. The highest taxa richness was about four times the lowest. Annelids constituted about 54% of the taxa and 55% of the total abundance.

A few species were essentially ubiquitous and tended to dominate the infauna at many stations. The bivalve *Axinopsida serricata* was found in all 30 samples and was the most abundant species in 11 of the 30 samples. Two stress-tolerant polychaete species, *Aphelochaeta glandaria* and *Prionospio steenstrupi*, were the most abundant species in 6 samples and 5 samples, respectively.

Sixteen of the 30 stations, representing just over half of the area, were determined to have adversely affected benthic communities, based on a weight of evidence from multiple benthic indices of quality. In most of these 16 samples, the numbers of species were relatively low and the majority of species were known to be stress-tolerant.

Relationships and Correlations among Variables

Spearman rank correlation between the similarity matrices of the benthic assemblages and the ten environmental variables was 0.606, a moderate correlation (Figure 25). The correlation between just the “top ten” taxa (the ten most abundant taxa at each station, which may consist of more than ten species per station due to ties; Appendix I Table I-2) and the environmental variables was essentially the same: 0.611. The moderate magnitude of the correlation indicates that other factors besides the ten physical characteristics factor into the constitution of the invertebrate assemblages. The fact that the same correlation results were obtained with only the dominant taxa is an indication that the less abundant and rare species do not determine the similarity or dissimilarity of the assemblages.

Sediment Quality Triad Synthesis (2007): A Compilation of Chemistry, Toxicity, and Infauna Data

There is a great amount of empirical evidence that the incidence and magnitude of both toxicity and benthic impairment increases as the numbers of chemicals that exceed effects-based guidelines or criteria increase (Wenning et al., 2005). The data in Wenning et al. (2005) were compiled from studies performed in estuaries throughout the U.S. (including southeastern estuaries, California, Puget Sound, and Hawaii) and Australia.

The basic concept of the triad approach to sediment-quality assessments is to build a weight of evidence that scientists can use to classify relative sediment quality (Long and Chapman, 1985). The chemistry data are intended to establish whether or not the sediments are chemically contaminated. The toxicity data are intended to determine empirically whether or not these toxicants are sufficiently concentrated and bioavailable to pose a threat to local biota under controlled laboratory conditions. The benthic data are intended to provide a reality check that the infauna communities, in fact, are adversely affected or not.

Samples that are not contaminated, not toxic, and have a robust and healthy benthos are frequently classified as high quality, whereas samples that are contaminated, toxic and have a depauperate benthos are classified as degraded (Chapman, 1996). Experience has shown that the three kinds of data do not always agree; in fact, they often disagree. There are logical reasons for them to disagree (Chapman, 1996). These sediments for which the data disagree often are classified as intermediate in quality (Long et al., 2003).

The triad concept was adopted as the basic analytical approach for PSAMP in the late 1990s. It has become a commonly used approach for most U.S. coastal states, some Midwestern states (e.g., Minnesota, Indiana), several Canadian provinces (e.g., British Columbia, Manitoba, Quebec), two Australian states (Western Australia, New South Wales), France, Belgium, Germany, The Netherlands, Antarctica, South Africa, New Zealand, Brazil, and Hong Kong (Wenning et al., 2005). It forms the basis for Washington’s sediment-quality criteria. It is also the basis for the California sediment-quality “objectives” which are currently being developed under legislative mandate (California State Water Resources Control Board., *in prep.*).

There were 17 stations, representing 8.75 km^2 (33.3% of total area), where one or more chemical concentrations exceeded the Washington State effects-based sediment-quality standards (Table 16). These stations constituted a significant degree of chemical contamination. At a different set of 16 stations, representing 14 km^2 (53.3% of area), the benthic infauna were judged to have been adversely affected. Ten of the stations had both chemical contamination and affected benthos; those ten stations represented 4.7 km^2 (17.9% of the study area).

There was only one station that was classified as highly toxic[11] in the sea urchin fertilization tests, Station 177 (Magnolia Bluff), representing 0.42 km^2 or 1.6% of area (Table 17). That station also had affected benthos, but did not exceed chemical sediment standards.

[11]As defined earlier in this report, “highly toxic” denotes (1) mean control-adjusted fertilization less than 80% of controls, (2) outcome significantly different from that in the Texas controls, and (3) outcome greater than the detectable significance criterion (Carr, 2008, in Appendix G).

Seven stations, representing 8.3 km^2 (31.4% of area), exhibited no chemical, toxic, or benthos impairment and therefore met the criteria for high sediment quality (Table 16, Figure 26). Twelve stations, representing 12.9 km^2 (49.1% of area), met the criteria for one element of the SQTI, indicating intermediate-to-high sediment quality. Another 11 stations, representing 5.1 km^2 (19.5% of area), met the criteria for two elements of the SQTI, or intermediate-to-degraded sediment quality.

None (0%) of the area met the criteria for all three elements of the triad for degraded sediment quality. This outcome is similar to that for the entire 1997-99 PSAMP/NOAA survey area (1.0%) or the central Sound (2.8%), but lower than in the harbors (14.7%) and urban bays (6.8%) (Long et al., 2003).

Comparison with 1998 Data

In this section, we compare the results from the 2007 Elliott Bay/lower Duwamish Urban Waters Initiative survey to those from the 1998 PSAMP/NOAA survey within the same geographical boundaries. We performed these data analyses to determine whether changes had occurred at the scale of the entire bay based on the full triad of data. It is important to note that these comparisons are based on a *reassessment of the 1998 data* from the same 30 stations sampled in 2007. In 1998, 36 stations were sampled in the Elliott Bay/lower Duwamish area as part of PSAMP/NOAA. Because in this 2007 study we made paired comparisons of data from only 30 resampled stations, the amount of area represented by some stations differed from the original 1998 weights. Therefore, some of the 1998 results in this discussion differ slightly from those published previously by Ecology (Long et al., 2000, 2003).

Graphical depictions of weighted and unweighted, paired and unpaired, results for 1998 and 2007 are displayed for each parameter in Appendices D (grain size, TOC, chemistry) and H (benthos). For each parameter, the appendices include: (a) censored boxplots of the 1998 and 2007 data and a boxplot of the differences (2007 results minus 1998 results, by station); (b) cumulative distribution function (CDF) curves for the 1998 and 2007 data; (c) a bar chart displaying the 1998 and 2007 results side-by-side for each station; (d) a bar chart of the differences (2007 minus 1998). A map of stations is included for perspective. Below, we describe and discuss the results of the comparisons.

Sediment Characteristics and Chemistry

Grain Size

Paired comparison tests, both weighted by area represented and unweighted, indicated that the silt+clay content (percent fines) decreased from 1998 to 2007. However, the CDF comparison (weighted, unpaired) was not statistically significant at α=0.05 (Table 17). This means that the changes were noticeable, but not statistically significant or huge.

The grain size distributions, as proportions of gravel/sand/silt/clay, differed in 1998 and 2007 (χ^2= 17.647, *df*=3, P-Value=0.001). In 2007, there were significantly higher proportions of gravel and lower proportions of silt than in 1998. Both of these results suggest that either less silt and clay were deposited in the bay, principally from the Duwamish River, or some of the finer-grained materials were dispersed or removed by natural or human-caused events, or both.

Sloan and Gries (2008) found similar results and reached similar conclusions in their comparison of sediment grain size in the surface 2-3 cm vs. the top 10 cm for 18 Elliott Bay stations. Their samples were collected at the same stations at the same time as this Urban Waters Initiative survey. They reported lower percent silt in the shallower, more recently deposited sediment than in the deeper, older sediment.

Total Organic Carbon (TOC)

The unweighted, paired comparison test and the unpaired, weighted CDF comparison test both indicated that TOC increased from 1998 to 2007, though that change was not significant at $\alpha = 0.05$ in the test of differences weighted by area (Table 17). TOC increased several-fold at stations 182 and 199. This is an unusual outcome, given that the percent fines decreased. The concentrations of TOC and percent fines frequently are correlated with each other in estuarine sediments (e.g., Long et al., 2003).

Sloan and Gries (2008) did not find differences in TOC with depth of sediment sampled, but their subset of these UWI samples did not include stations 182 or 199.

Metals

Both the weighted and unweighted paired tests indicated decreases in lead, silver, and tin, and increases in zinc and selenium. With the exception of tin, none of the unpaired, weighted CDF comparisons for metals indicated statistically significant changes in contamination bay-wide (Table 17). Tin contamination decreased. The paired Wilcoxon signed rank test (WSRT) weighted by area indicated a decrease in mercury contamination, though none of the other tests did, at the 0.05 level of significance.

In their comparisons of sediment metals in the surface 0-2 cm vs. 0-10 cm, Sloan and Gries (2008) found only equal or lower concentrations in the shallower (presumably more recent) samples than in the deeper samples. No results were reported for mercury. However, tests of the paired concentration differences from 1998 to 2007 (surface 2-3 cm only) for the same subset of stations show different, often contradictory results. Further study would be required to determine why.

The King County Department of Natural Resources and Parks (KC DNRP) found sediment mercury concentrations to have decreased between 1988 and 2004 at one Seattle waterfront station (PSAT, 2007). Unpublished data from that same station indicate a further decrease measured in 2007 (Mickelson, 2009).

PAHs

All of the individual HPAHs except chrysene and perylene decreased in concentration bay-wide from 1998 to 2007, according to both the weighted and unweighted WSRT, though none of those changes showed up in the weighted, unpaired CDF test (Table 17). In addition, both the number of stations and percent of area exceeding the SQS for benzo(g,h,i)perylene decreased (Table 17).

The unweighted, paired Prentice-Wilcoxon test (PPW) indicated concentration decreases for eight of the 14 individual LPAHs (Table 17). A few changes were found also by the weighted, paired WSRT and weighted, unpaired CDF comparisons. Concentrations increased for retene (all three tests), acenaphthylene (weighted and unweighted WSRT), and 2,6-dimethylnaphthalene (weighted WSRT).

By contrast, Sloan and Gries (2008) found almost no differences in PAH concentrations between 0-2 cm and 0-10 cm samples at 18 stations in Elliott Bay. However, their study excluded the waterways, where most of the PAH decreases from 1998 to 2007 occurred. (See difference bar charts in Appendix D.)

Unpublished data from one KC DNRP Seattle waterfront station sampled biennially indicate a pattern of concentrations of multiple PAHs (both LPAH and HPAH) remaining level or increasing slightly from 1998 to 2002, then dropping in 2004 (Mickelson, 2009).

The Washington State Department of Fish and Wildlife reported that liver disease resulting from PAH exposure has dropped dramatically since the late 1990s in English sole caught by the Seattle waterfront (PSAT, 2007). Although HPAHs decreased from 1998 to 2007 at most of the Seattle waterfront stations in this Urban Waters Initiative study, the results for LPAHs were mixed. Concentrations of several LPAHs increased substantially at Station 184, by Pier 55. (See difference bar charts in Appendix D.) Most of the HPAHs measured in this Urban Waters Initiative study are carcinogenic.

PCBs

The unweighted PPW and weighted WSRT tests both indicated significant decreases in almost all of the 19 PCB congeners analyzed in both years and in two of the PCB Aroclors (1254, 1260). Aroclors 1254 and 1260 have historically been the most abundant and common in the Elliott Bay area (e.g., Malins et al., 1982). There were too few detected values to test the other congeners and Aroclors. The CDF comparisons indicated significant decreases in congeners 28, 44, 77, 105, and 128 (Table 17).

PCB levels in surface sediment decreased almost everywhere. The decreases tended to be larger in the waterways than elsewhere, but were relatively uniform throughout the rest of the study area. (See difference bar charts in Appendix D.) These results suggest not only that cleanups in the waterways have been successful but also that cleaner sediments are gradually burying PCB-laden sediments.

These results support the outcome predicted by the Ecology box model for transport and fate of PCBs (Pelletier and Mohamedali, 2009). That model predicts that *"Sediment PCB concentrations in the urban bays could be decreasing due to the combined effect of burial with newly deposited material that is less concentrated than the original source material, and transport of sediment from the urban bays into the adjacent main basin. Concentrations could decrease more depending on whether external loads are reduced."* (Pelletier and Mohamedali, 2009). However, burial is insufficient to sequester PCBs in nearshore contaminated sites, due to physical and biological disturbance. Hence, cleanup is still required. Furthermore, because PCB concentrations throughout Puget Sound result primarily from watershed runoff, PCB levels could actually increase outside of urban areas (Pelletier and Mohamedali, 2009).

Even without sampling in the waterways or measuring PCB congeners, Sloan and Gries (2008) found results for total Aroclors and Aroclors 1254 and 1260 which were consistent with the results reported here. They drew similar conclusions about decreasing contamination.

Unpublished data from one KC DNRP Seattle waterfront station sampled biennially indicate a decreasing trend in PCB Aroclor 1260 at that station, but an increasing trend in PCB Aroclor 1254 there (Mickelson, 2009).

Pesticides

Agricultural pesticides have rarely been a problem in Elliott Bay because almost all of the Green/Duwamish River watershed has been industrialized and therefore does not drain a large farming area. Most of the chlorinated pesticides were undetected in both 1998 and 2007, or there were too few detected values, so that comparisons could not be made (Table 17). Only the DDT isomers 4,4'-DDD, 4,4'-DDE, and 4,4'-DDT could be tested. Of those, there were decreases in 4,4'-DDD (both paired tests), 4,4'-DDE (all three tests) and 4,4'-DDT (PPW test). Reporting limits were significantly lower in 2007 than in 1998 for virtually all of the pesticides.

Base/Neutral/Acid (BNA) Organic Compounds

There were too few detected values to compare 1998 and 2007 concentrations of most BNA compounds. CDF comparison indicated that concentrations of bis(2-ethylhexyl) phthalate increased overall.

Sediment Quality Criteria — Chemistry

Comparisons between 1998 and 2007 results in this discussion are based on the same chemical lists for both years. As mentioned in the Methods section above, the 1998 results of sample concentrations in relation to the SQS criteria for several BNA compounds (Long et al., 2000) are not included here, due to the unreliability of chemical-analytical results for those compounds.

The number of chemicals or groups of chemicals exceeding the SQS decreased from 23 to 17 (not statistically significant) between 1998 and 2007. The number of stations at which each chemical exceeded the SQS declined for almost all of the chemicals (most of the changes not statistically significant). A few changes were notable (Table 17):

- The number of stations at which total PCB Aroclors exceeded the SQS decreased from 14 in 1998 to four in 2007. The proportion of represented area affected declined from 20.9% to 3.7%. Both changes were statistically significant.

- The number of stations at which benzo(g,h,i)perylene exceeded the SQS dropped from ten in 1998 to two in 2007, a statistically significant change, though the associated change in represented area, from 14.1% to 5.6%, was not statistically significant.
- Bis(2-ethylhexyl) phthalate exceeded the SQS at three stations, representing 1.47 km^2 (5.6% of area), in 1998, and eight stations, representing 2.88 km^2 (10.9% of area), in 2007. Neither increase (incidence, spatial extent) was significant at $\alpha = 0.05$, however.

ANOSIM results indicated a significant difference between the years for matrices of mean SQS quotients (ratios of concentrations to SQS criteria) for individual contaminants (permutation test p-value = 0.022).

Sediment Toxicity

In the 1997-1999 PSAMP/NOAA baseline surveys, four kinds of toxicity tests were performed on each sample throughout Puget Sound to provide a weight of toxicological evidence (Long et al., 2003). Typically, Ecology has continued to test the relative toxicity of Puget Sound sediments with multiple tests using a variety of species and test procedures to gauge acute and sublethal effects.

In the 2007 survey, three types of toxicity tests were performed, with a sea urchin, an amphipod, and a sand dollar. The protocols were the same as used previously, but the labs for the amphipod mortality and sand dollar embryo development were not those used in the PSAMP/NOAA survey. The data from the amphipod and sand dollar tests in 2007 did not meet Ecology's quality assurance criteria and therefore were not acceptable. Because those data could not be used to reliably classify sediments as toxic or not, they were not used for this report.

We elected to report the data from the one test for which we had the most data and experience throughout Puget Sound, namely the sea urchin fertilization test. This test also had the advantage of having been performed nationwide for NOAA by the same lab with very low within-sample variability for many years (Long and Sloane, 2005). Because the comparisons of sediment toxicity in this 2007 study are based on only the sea urchin fertilization test, the bay-wide toxicity results for 1998 discussed here differ somewhat from those in Long et al. (2000, 2003).

In 1998, seven stations were highly toxic; whereas in 2007, only a single station was highly toxic. That decrease was borderline statistically significant (Fisher exact test p-value = 0.052). The decrease in the area affected, from 2.38 to 0.42 km^2 (from 9 to 1.6% of area), however, was not statistically significant at $\alpha = 0.05$.

The urchin fertilization sediment pore-water test, conducted annually for the PSAMP sediment component since 1997, underwent a methods modification in 2003. Exposure test time was reduced from 60 to 40 minutes, and test temperatures were reduced from 15 to 12 °C to minimize pH effects from the control pore water and dilution water on sperm survival (USGS, 2003). These improved test conditions increased the precision and reliability of the results, and the overall test sensitivity.

These test modifications have been applied annually since 2003 for both the PSAMP and UWI surveys. Side-by-side comparison tests (applying both protocols to the same samples) and comparison of the EC50 values for all PSAMP and UWI surveys indicated that the results generated in 1998 and 2007 are comparable.

Community Composition and Benthic Indices

The paired WSRT, both weighted and unweighted, indicated significant changes bay-wide in all of the benthic measures except taxa richness and echinoderm abundance. Total abundance and abundance of annelids, arthropods, and molluscs decreased from 1998 to 2007 (Table 18). Pielou's Evenness (J'), Swartz' Dominance Index (SDI), SDI standardized by taxa richness (SDISTD), and abundance of miscellaneous taxa all increased. The CDF comparisons (weighted, unpaired), however, indicated a significant increase in Pielou's Evenness index and a likely increase in echinoderm abundance (Wald F test p-value = 0.051), but no significant shifts in the other benthic measures.

Although in the MDS map (Figure 27) at first glance there appears to be considerable similarity between the 1998 and 2007 benthos, the analysis of similarity (ANOSIM) results indicate a significant difference between the years (permutation test p-value = 0.007). Closer inspection reveals large dissimilarities (displayed as distances) between the two years for certain stations. For some of those stations (e.g., 185, 205), the 2007 benthic assemblages were also considerably different from the benthos at the remainder of the stations. Despite the differences between years, there was fidelity in the groupings of benthic assemblages based on dominant taxa, depth, and grain size (Figure 27).

Environmental Variables

ANOSIM results indicated that the matrices of environmental variables were significantly different between 1998 and 2007 (permutation test p-value = 0.001). The environmental variables included in that analysis were sediment temperature, salinity of overlying water, grab penetration depth, percent silt-clay, TOC content, mean ERM quotient, and control-corrected percent fertilization of sea urchin gametes.

Sediment Quality Triad Index

Chemistry Element

The number of stations with a triad chemistry "hit" (one or more chemicals exceeding the SQS) decreased from 23 to 17, and the proportion of area affected decreased from 41.3 to 33.3% (from 10.86 to 8.75 km^2). Neither change was statistically significant at $\alpha = 0.05$. One harbor station, #183 (Elliott Bay, Pier 54), representing 0.11 km^2, improved from 11 chemicals exceeding the SQS to none.

Toxicity Element

In 1998, seven stations were highly toxic (triad toxicity “hit”), and in 2007, only a single station had a toxicity “hit” (Table 20). That decrease was on the borderline of statistical significance (Fisher exact test p-value = 0.052). The decrease in amount of area affected, from 2.38 to 0.42 km^2 (from 9 to 1.6% of area), however, was not statistically significant at $\alpha = 0.05$.

Benthos Element

Prior to comparison of benthic community health in 1998 vs. 2007 for this report, the 1998 benthos were reexamined using the same methods as for the 2007 benthos. That reassessment resulted in different classifications of several benthic assemblages from those published in Long et al. (2000, 2003). Three urban assemblages previously categorized as unaffected (185, 186, and 195) were reclassified as affected.

The number of stations with affected benthos, after the reassessment of the 1998 benthos, remained almost unchanged (15 in 1998 and 16 in 2007), with one basin station recharacterized as affected. The amount of area affected increased from 9.2 to 14 km^2 (from 34.8 to 53.3% of area), not statistically significant at $\alpha = 0.05$. Eight harbor and five urban stations, collectively representing 7.1 km^2, had affected benthos in both years.

All of the benthic infauna in the waterways remained affected, as did the benthos at Station 115 (Pier 90). The benthic infauna remained or became affected at the deepest stations in the inner and outer bay, with the exception of Station 173, whose benthos remained unaffected. The benthos remained unaffected adjacent to the downtown piers, along most of the northern shore of Elliott Bay, and along the southern shore between West Waterway and Duwamish Head.

Triad

Due to the above-mentioned alterations in the set and treatment of 1998 results for comparison to the 2007 UWI results, the 1998 sediment-quality triad results differ somewhat from those in Long et al. (2000, 2003). The comparisons presented here of the triad results from 2007 to the reassessed 1998 triad results were made on the same bases.

The number of stations with high sediment quality (no triad elements degraded) increased from four in 1998 to seven in 2007 (not statistically significant at $\alpha = 0.05$). The amount of area with high sediment quality, however, decreased from 13 to 8.3 km^2 (from 49.5 to 31.4% of area), though not statistically significant (Tables 19, 20).

The numbers of stations with intermediate/high sediment quality (one triad element degraded) increased from 10 in 1998 to 12 in 2007 (not statistically significant at $\alpha = 0.05$), with the proportion of area increasing statistically significantly from 18.9 to 49.1% (from 5 to 12.9 km^2). Intermediate/degraded sediment quality (two triad elements degraded) decreased from 13 stations in 1998, representing 28.6% of area (7.5 km^2), to 11 stations in 2007, representing 19.5% of area (5.1 km^2), neither change statistically significant. The proportions of stations with intermediate/high and intermediate/degraded sediment quality were similar to each other and across both years.

Whereas three stations in 1998, representing 0.8 km^2 (3% of area), had degraded sediment quality (degradation in all three triad elements), none did in 2007 (Tables 19, 20). That change was not statistically significant at $\alpha = 0.05$, however.

Two harbor stations (180, 199), together representing 3% of the study area, moved up from intermediate/degraded classification in 1998 to high in 2007. Three urban stations (189, 190, 195) and one basin station (172), collectively representing 29.8% of the study area, with high or intermediate/high sediment quality in 1998 were intermediate/high or intermediate/degraded, respectively, in 2007 (i.e., moved down one category). Eleven stations, representing 20.8% of the area, improved one classification (i.e., moved up one category) from 1998 to 2007 (Tables 19, 20), and 13 stations remained the same. Most of the improvements in sediment chemistry and toxicity occurred at the landward margins of Elliott Bay and in East Waterway. Degradations in sediment quality (chemistry and benthos) were found in the southwest portion of inner Elliott Bay, at and just east of Duwamish Head, and at the outer margin of the study area.

Overall, sediment quality, as measured by the Sediment Quality Triad Index (SQTI), improved one or even two categories at 13 of the 30 stations, representing 24% of the study area (Table 21, Figure 28). At four stations, representing almost 30% of the study area, sediment quality declined one category. That figure indicates the strong influence of the benthos “hit” at one of the two basin stations (Table 19). For the remaining 13 stations and 46% of area, the SQTI category remained unchanged (Table 21, Figure 28).

Correspondence between the elements of the triad was imperfect. Such a lack of correspondence is not unusual (Long et al., 2003). For example, the station with the lowest mean ERM quotient (lowest level of chemical contamination) in 2007, Station 177, was the sole site at which the sediment was classified highly toxic. The benthic assemblage at that same station was classified as adversely affected.

Summary

Most of the changes in sediment-quality conditions between 1998 and 2007 were in individual parameters (e.g., contaminant concentrations or benthic measures). Overall, based on the weight of evidence, there was a mixture of changes between 1998 and 2007, but most indicators that we measured indicated slight improvements in sediment quality on a bay-wide scale. The following changes were found.
So, the data show a mixed bag of changes with time, with some stations improving in quality, others decreasing, and others remaining about the same. It is possible that more changes would have been evident (statistically significant) with the greater discriminating power of a larger number of samples.

Sediment Contamination

- *Metals:* The concentrations of lead, mercury, silver, and tin decreased. Zinc concentrations increased. There were no statistically significant changes in the levels of arsenic, cadmium, chromium, copper, or nickel.

- *PAHs:* The concentrations of most low-molecular-weight PAHs (LPAHs) decreased or stayed the same. The concentrations of most high-molecular-weight PAHs (HPAHs) decreased. Two LPAHs, acenaphthylene and retene, increased. There was no change in the levels of chrysene or perylene, two HPAHs.
- *PCBs:* Most individual PCB congeners decreased in concentration, as did total (summed) PCB Aroclors.
- *Phthalates:* Bis(2-ethylhexyl) phthalate concentrations increased.
- *Comparison to sediment-quality standards:* The number of chemicals exceeding the SQS decreased. For some of those chemicals, both the number of stations and amount of associated area exceeding the SQS also decreased.

Sediment Toxicity

- Sediment toxicity decreased significantly, from seven stations representing 9% of the study area to a single station representing 1.6% of the area.

Invertebrate Communities

- Some measures of benthic invertebrate community health improved from 1998 to 2007. Abundances of some stress-tolerant species decreased. However, the total number of stations and amount of area with adversely affected benthos remained almost unchanged.

Sediment Quality Triad Index (SQTI)

- Sediment quality, as measured by the SQTI, improved for 24% of the study area, remained the same for 46%, and declined for 30%. All of the improvements were in the waterways and inner portion of Elliott Bay. Sediment quality in the outer portion of the bay, already high, remained high or declined slightly (to intermediate/high) due to adversely affected invertebrates at one station.
- Most of the shifts in sediment quality were from the degraded and intermediate/degraded SQTI categories (combined) to the intermediate/degraded and intermediate/high categories (combined).
- The proportion of the total area with degraded and intermediate/degraded sediment quality decreased from more than 30% to slightly less than 20%, all in the intermediate/degraded category. None was classified as degraded in 2007.

So, the data show a mixed bag of changes with time, with some stations improving in quality, others decreasing, and others remaining about the same. It is possible that more changes would have been evident (statistically significant) with the greater discriminating power of a larger number of samples.

Comparisons with Central Region, Puget Sound

The Urban Waters Initiative (UWI) bay-scale study design was deliberately nested within the regional and Puget Sound-wide sampling design for the PSAMP sediment monitoring component. Therefore, we can put these bay-scale results in context by comparing them with results for the PSAMP Central Sound region (based on the PSAMP/NOAA survey) and for all of Puget Sound (1997-2003).

As well, the basin, harbor, and urban portions of this UWI study area are nested within the corresponding current PSAMP sediment monitoring "strata". Combined, there were 28 harbor and urban stations in the UWI study area in both 1998 and 2007. Therefore, we compare those results to the *combined harbor and urban* results for the PSAMP Central Sound region and for the PSAMP Puget Sound baseline.

The baseline Central Sound region and Puget Sound SQTI results published in Long et al. (2003, 2008) have been updated for consistency with the methods in this UWI study and will be published in the near future. All of the 1997-2003 PSAMP data constituting the PSAMP sediment spatial monitoring baseline (including regional and "strata" results) were reassessed to:

- Use the same set of chemical contaminants as for the UWI study.
- Use only the sea urchin fertilization and amphipod mortality pore-water toxicity tests.[12]
- Combine expert Best Professional Judgment and the quantitative comparisons of nine benthic measures to the 80% confidence intervals for the medians for determination of affected/unaffected benthos.
- Update sample areas with more-precise GIS calculations instead of manually-calculated estimates from the PSAMP/NOAA survey.
- Weight the sample stations selected under the revised PSAMP spatial sediment monitoring design (Dutch et al., 2004) to reflect revised estimates of the area of the target population[13] based on success in the field, according to the methods specified in Stevens and Olson (2004).

Therefore, the results for the PSAMP sediment monitoring Central Sound region and entire Puget Sound described here differ somewhat from those published in Long et al. (2000, 2003, 2008).

The Central Sound region is being sampled in 2008-2009, and by 2012 the PSAMP rotation through Puget Sound will be complete, so these comparisons will be updated in the future.

Comparison to Central Region and Puget Sound (All Areas)

As indicated in Table 22, the *incidence*, or percent of *stations* with high sediment quality was quite similar for the PSAMP Central Sound region and the PSAMP Puget Sound baseline, at 53±1%, but substantially lower for the 30 UWI stations in 1998 (13%) and 2007 (23%). The *spatial extent*, or percent of *area* with high sediment quality, however, was considerably

[12] Although the inclusion of two toxicity tests is technically inconsistent with the one toxicity test in the 2007 Urban Waters Initiative, the amphipod test results in 1998 did not materially affect the Elliott Bay comparison.
[13] The PSAMP sediment monitoring Spatial target population consists of areas of soft sediment covered by 2 meters or more of water in Puget Sound proper, Admiralty Inlet, and embayments of the San Juan Islands and Straits of Georgia and Juan de Fuca (Dutch et al., 2004).

different for the Central Sound region (91%) vs. all of Puget Sound (62%) vs. Elliott Bay/lower Duwamish (49% and 31% in 1998 and 2007, respectively) (Figure 29). The high proportion of area in the Central Sound region with high sediment quality reflects the large proportion of the region comprising the large central passages and basins of Puget Sound.

Incidence of intermediate/high sediment quality was similar at the bay-wide and sound-wide scales and slightly lower at the region-wide scale, but the spatial extent was quite different. The significant increase in percent of area with intermediate/high sediment quality from 1998 to 2007 straddled the PSAMP baseline. All were considerably higher than the percent of Central Sound region area categorized as intermediate/high (Table 22).

Incidence of intermediate/degraded sediment quality at the level of the bay was higher than at the levels of the region or all of Puget Sound (Table 22). That pattern was even more pronounced for spatial extent (Figure 29).

At all levels, the percent of stations with degraded sediment quality (all three triad "hits") was higher than the corresponding percent of area. This indicates that sediment degradation, as one would expect, tended to occur in harbor and urban areas. The sampling frequency is higher in harbor and urban areas than in basins, passages, or rural areas – a deliberate design – so harbor and urban stations represent less area per station than do sampling stations in other areas. The Elliott Bay/lower Duwamish results for 2007 (no stations with degraded sediment quality) must be interpreted with caution due to the relatively small number of samples taken (30).

Comparison of Harbor and Urban Areas Across Spatial Scales

The harbor and urban "strata" compose 8±1% of the PSAMP sampling areas in the Central Sound region and all of Puget Sound. The importance of those "strata" is reflected in the rates at which they are sampled: 59% of stations in the Central Sound region and 39% of all stations composing the PSAMP Puget Sound baseline.

The Central Sound region contains 30% of the PSAMP sediment monitoring area and 59% of the baseline stations, reflecting the importance of the Central Sound region, where the majority of the population and industrialization are. Among the harbor and urban portions of all of Puget Sound, those in the Central Sound region account for 38% of the area and 50% of the samples composing the Puget Sound baseline. Again, this indicates the relative importance of both the Central Sound region and the harbor and urban areas in PSAMP sediment monitoring.

In this 2007 UWI study, the harbor and urban areas formed 57.6% of the entire study area and received 93% of the sampling effort.

The incidence of high sediment quality in harbor and urban stations was highest for all of Puget Sound (44% of stations), lower in the Central Sound region (29% of stations), and lower still in the study area (Table 22). In both Central Sound region and all of Puget Sound, 55±1% of the area had high sediment quality, compared to 17.7% in Elliott Bay/lower Duwamish in 2007 and even less in 1998. The percent of the study area with high sediment quality was similar to the percent of stations with high sediment quality.

The percent of stations with intermediate/high sediment quality in harbor and urban areas was similar across spatial scales. The percent of area varied slightly more: the spatial extent of intermediate/high sediment quality was the same (about 33%) in Elliott Bay/lower Duwamish in 1998 as in all of Puget Sound (1997-2003). The proportion was lower (about 21%) for the Central Sound region (1998-1999) and considerably higher (over 48%) in the 2007 UWI study area.

Incidence of intermediate/degraded sediment quality was almost the same as for the intermediate/high category, but the pattern for spatial extent was different. The percent of the harbor/urban area with intermediate/degraded sediment quality in the UWI study area dropped (though not statistically significantly) from about 50% in 2007 to 34% in 1998. The Central Sound region harbor/urban area was lower yet, at 21% (again, based on 1997-1999 data). Over 1997-2003, about 10% of all PSAMP Puget Sound harbor and urban area had intermediate/degraded sediment quality.

The patterns and magnitude of degraded sediment quality in the harbor and urban areas were quite similar to those for all areas.

Summary

Consistent patterns of SQTI incidence and spatial extent were found. With one exception, the relative orderings (by decreasing size) of the SQTI categories in both incidence and spatial extent in both the PSAMP Central Sound region (1998-1999) and PSAMP entire Puget Sound baseline (1997-2003) for both harbor/urban areas and all types of area was: high, intermediate/high, intermediate/degraded, degraded. The exception was in Central Sound region harbor and urban areas, in which incidence (percent of stations) with high sediment quality was slightly lower than the tied intermediate/high and intermediate/degraded categories.

The SQTI incidence and spatial extent patterns in the study area were ordered intermediate/degraded, intermediate/high, high, degraded in 1998 and intermediate/high, intermediate/degraded, high, degraded in 2007 for all areas and for just harbor and urban areas, with a few exceptions. In 1998, the percent of harbor and urban stations with high sediment quality was the smallest, slightly lower than the percent degraded. As a consequence of the large area-weighting of the two basin stations, the percent of all area with high sediment quality was the largest category in 1998 (no triad “hits” at either station) and the second-largest in 2007, due to a benthic “hit” at one of the two stations.

In summary, the proportions of Puget Sound and the Central Sound region were largest for high sediment quality and decreased with successively declining sediment quality. Although the proportion of the Elliott Bay/lower Duwamish study area with high sediment quality was not commensurate with those in the larger areas, sediment quality did improve bay-wide from 1998 to 2007. More area was in the intermediate/degraded category than in the intermediate/high category in 1998; but in 2007, more area was classified as intermediate/high than as intermediate/degraded, and no stations had degraded sediment.

Comparison with PSAMP Puget Sound Ambient Values

Puget Sound sediment-chemistry average ambient values were calculated as the mean of all PSAMP sediment data from basin, passage, or rural "strata" (290 stations from surveys in 1997-2003, all results including nondetects). Data from harbor and urban "strata" were not included. Nondetects were represented by the reporting limits. Figures 30-34 illustrate the comparison of the 2007 UWI results to the PSAMP Puget Sound mean ambient results as boxplots of ratios. Values above 1 indicate contaminant levels in Elliott Bay/lower Duwamish that are above the 1997-2003 PSAMP ambient means.

Cadmium and chromium levels in Elliott Bay/lower Duwamish in 2007 were below Puget Sound ambient levels, and silver concentrations were generally similar to ambient (Figure 30). With a few exceptions (outliers), usually Stations 184 and 197, concentrations of arsenic, copper, and zinc were within 2-3 times ambient (Figure 30). Arsenic at Station 197 was more than 30 times the mean ambient level. Mercury and lead concentrations were somewhat higher than the other metals, mostly within five times ambient levels, but with a few high outliers (Figure 30).

The bulk of the LPAH concentrations in the study area were above Puget Sound ambient levels, but within an order of magnitude (Figure 31). Along the Seattle waterfront, between the ferry terminal and the aquarium, and near Pier 90, LPAHs were consistently 10-30 times ambient and sometimes 60-80 times ambient.

With the exception of dibenzo(a,h)anthracene, HPAHs in Elliott Bay/lower Duwamish were also higher than ambient (Figures 32, 33). The majority were less than 25 times ambient. Along the Seattle waterfront and near Pier 90, HPAH concentrations were 20-60 times ambient, with concentrations at Station 184 being 75-550 times ambient levels for a few HPAH compounds.

Although the level of PCB Aroclor 1242 in 2007 was the same as ambient, the levels of PCB Aroclors 1254 and 1260 were mostly 3-10 times ambient (Figure 34). In the East Waterway, concentrations of those two Aroclors were up to 80 times ambient. Other PCB Aroclors were undetected throughout the study area.

The median concentration of bis(2-ethylhexyl) phthalate across the study area was similar to the mean ambient concentration, but in the waterways, the concentrations were up to 20 times ambient levels (Figure 34). The results for dibenzofuran were similar to those for LPAHs (Figure 34).

Comparison with Other Elliott Bay Studies

The spatial patterns of chemical contamination in the 2007 UWI survey were similar to those found in 96 surveys from 1990-2006, the results for which are in the EIM and SEDQUAL databases. (See Appendix A for maps and details.) The concentration levels in this UWI survey were similar to or lower than those reported in the other studies. Some of the decreases were likely the result of multiple cleanup and source-control activities or burial by less-contaminated sediment (or both) over the past two decades, as found in the comparisons to 1998 in this 2007 study. Other lower concentration levels likely resulted from differences in study design, probability-based in the UWI study vs. targeted in some other studies.

As part of the Marine EcoSystems Analysis (MESA) Puget Sound project, 19 samples were taken by NOAA at 16 stations throughout Elliott Bay and the waterways of the lower Duwamish River in 1979 (Malins et al., 1982). Ecology and NOAA sampled the same region again as part of PSAMP in 1998, and Ecology sampled it once again as a part of this 2007 UWI survey. The sampling and analytical methods were sufficiently similar in all three surveys to warrant comparing the data among the three periods.

There were several kinds of temporal patterns in the data. Although some changes with time may be attributable to changes in inputs, some portions of changes may have been caused by changes in methods between surveys. For example, the numbers of detected values increased over time for all chemicals, probably as a result of improved analytical methods (i.e., lowered detection limits).

Comparisons of unweighted means of detected values indicated a substantial reduction in sediment cadmium and silver concentrations from 1979 to 1998 and 2007 (Appendix A Figures A-13, A-16). The highest lead concentrations declined for the same interval, as did mean *measured* arsenic concentrations (Appendix A Figures A-14, A-12). The latter comparison is incomplete, however, because in 1979 arsenic was not detected in 13 of 19 samples. What is not known is what the detection limit was in 1979. It is possible that the same concentrations would be measurable with today's techniques.

Mercury concentrations did not change much from 1979 to 1998 and 2007 (Appendix A Figure A-15). The mean concentrations appear to have declined over time, but insufficient information is available to determine whether the trend is statistically significant. The maximum value observed for mercury was largest in the 1998 survey, but about 40% lower in the 2007 survey. Similarly, the concentrations of PAHs did not change much between surveys. Although the mean summed PAH concentrations remained about the same, it appears that the maximum concentrations increased (Appendix A Figure A-17).

Comparison of PCB concentrations is problematic. Somewhat different methods were used to estimate the total concentrations. In the MESA survey, PCB chlorination levels were summed, whereas 7 Aroclors or 19 congeners were summed in the PSAMP/NOAA and UWI surveys. The Aroclor sums can double-count some congeners, whereas the congener sums may count only a fraction of the 209 congeners.

The MESA surveys found that concentrations of PAHs, PCBs, and most trace metals often (but not always) were highest in various reaches of the lower Duwamish River (Appendix A). In 2007, the same pattern held for PCBs. PAH levels, however, were highest along the Seattle waterfront, between the ferry terminal and the aquarium, and near Pier 90. Metals in the UWI survey tended to be highest just outside the mouth of the West Waterway and by the Seattle waterfront. Consistent with the MESA findings, this UWI study found that chemical concentrations often were highly variable from one station to the next, possibly reflecting the heterogeneity of and proximity to local sources. In both the MESA studies and the UWI study, the concentrations of some chemicals decreased slightly to moderately in central Elliott Bay off Harbor Island and continued to decrease into the center of the bay and seaward.

Health of Benthic Communities

Although much of the discussion of changes in sediment quality is focused on chemical contamination, toxicity, and other manifestations of human activity, some changes may result from natural events such as low dissolved oxygen. Since benthic invertebrates are low in the food web on which more-visible organisms, such as salmon and orcas, rely, changes in the health of the benthos are an important aspect of sediment quality. Thus, we include some discussion of benthic community health. There are also links between health of benthos and human health, since human diets include both benthos (e.g., shellfish) and top predators (e.g., salmon).

Sediment monitoring is not a study of causation, so it can be difficult to distinguish between natural and anthropogenic stresses. This is particularly the case when the sediment chemistry and sediment toxicity elements of the triad are not in agreement with each other or with the benthos element (i.e., when the triad results are characterized as "intermediate," either "intermediate/high" or "intermediate/degraded"). Many of the areas with intermediate sediment quality are nearshore locations which are critical habitat for numerous marine organisms. Thus, these areas are suggested as in most need of continued surveillance.

The SQTI currently relies on assessment of benthic assemblages by professional benthic ecologists for determination of whether benthic communities are "adversely affected" or "unaffected". The binary designation of "affected" or "unaffected" does not have a category for intermediate results. Although environmental characteristics and presence or absence of stress-tolerant and invasive species are factored into the assessment, the "affected/unaffected" designation does not provide information on types of effects on the benthos. A quantitative, multivariate index of the health of benthic communities is needed.

Large numbers of stress-tolerant species, such as the polychaete *Aphelochaeta glandaria*, often were characteristic of benthic assemblages in the waterways of the lower Duwamish River.

Benthic assemblages tended to be similar by geographic area and along depth contours. The bivalve *Axinopsida serricata*, which was ubiquitous and often the single most abundant species, is thought to be slightly stress-tolerant. Two stress-tolerant polychaete species, *Prionospio steenstrupi and Aphelochaeta glandaria*, were found in the majority of samples and in a few cases were the most abundant species. Although the numbers of pollution-sensitive and stress-tolerant species were similar overall, the stress-tolerant species were far more abundant than the pollution-sensitive species.

In a recent study of tribal shellfish-harvesting areas in northern Puget Sound, inorganic and organic contaminants were found in crabs and clams and in the sediments which the shellfish inhabited (Swinomish Tribe, 2006). The shellfish species, size, and tissues analyzed were consistent with those normally eaten by humans. Calculations of human-health risk included not only ingestion of the tissues, but also accidental ingestion due to residual sediment in the clams and to exposure through the skin from the act of harvesting. PCBs, arsenic, and dioxins/furans were determined to be the greatest contributors to human-health risk. Mercury, other heavy metals, chlorinated pesticides, and PAHs contributed to lesser extents (Swinomish Tribe, 2006).

Inorganic mercury can be methylated to methylmercury, the most toxic form, by microorganisms in the environment (Swinomish Tribe, 2006). Methylmercury and other toxics bioaccumulate and generally act synergistically. Crabs tend to bioaccumulate more contaminants, especially arsenic, than clams, with concentrations higher in the hepatopancreas than in the muscle of the crab (Swinomish Tribe, 2006). According to the tribe's study (Swinomish Tribe, 2006), the crabs had higher exposure than the clams to more contaminated sediment.

Thus, contamination of sediments is associated with contamination of infauna and epibenthos inhabiting the sediments. This poses risks to other organisms, including humans, higher in the food web.

Monitoring to Meet the Needs of the Puget Sound Partnership

The Puget Sound Partnership's (PSP) Action Agenda for cleaning up, restoring, and protecting Puget Sound by 2020 explicitly calls for effectiveness monitoring for management actions, not only specific to those actions, but also integrated to the PSP Action Areas and to the entire Puget Sound (Puget Sound Partnership, 2008a). The Action Agenda and the PSP's Biennial Science Plan (Puget Sound Partnership Science Panel, 2008) include the following key components.

- *Status-and-trends monitoring* to address the questions: What is the status of Puget Sound, and what are the major threats to its recovery? Such monitoring provides information on:
    1. Current conditions of, and changes to, the ecosystem.
    2. Impacts to important ecosystem goods and services.
    3. Factors that affect ecosystem conditions (i.e., magnitudes of drivers and pressures throughout the region).

- *Effectiveness monitoring* to determine effectiveness of management actions, including strategies, programs, and projects, implemented to improve ecosystem condition. Monitoring results are to be integrated into regional decision-making and adaptive management.

- *Indicators* to provide information on the condition of Puget Sound. These indicators may be single-variable or multi-variable. Quantitative numerical targets and benchmarks are required for gauging status and progress. Some indicators are already in use; others need to be enhanced or developed (Phase 2 indicator development for the 2009-2011 biennium).

- *Coordinated regional monitoring* to determine:
    - Ecosystem status and trends.
    - Program and project effectiveness.
    - Cause-and-effect relationships.

- *Science programs* aligned with the needs of the PSP and the Action Agenda to continually improve the scientific basis for management actions.

- *Communication* of status and trends results to the PSP, local resource managers, stake-holders, and citizens needs to be effective and timely to inform and facilitate regional decision-making and adaptive management strategies.

The sediment monitoring component of the Urban Waters Initiative addresses these needs by assessing the effectiveness of collective cleanup and source-control efforts at the scale of an entire bay. Furthermore, nesting the UWI sampling design within the PSAMP sediment monitoring sampling design facilitates comparison of sediment quality conditions at multiple geographic scales.

The Puget Sound Partnership has divided Puget Sound into seven "action areas" based on common issues and interests, physical characteristics, and oceanographic properties (Puget Sound Partnership, 2008b). The marine portions of most of the PSP Action Areas correspond fairly well to the previously-established geographical regions of the Puget Sound Assessment and Monitoring Program (PSAMP). For example, the PSAMP Central Sound region lines up quite well with the South Central and North Central PSP Action Areas (Figure 35). The correspondence is sufficiently similar that the nested design of the PSAMP sediment monitoring enables managers to obtain information directly relevant to the goals of the Action Agenda.

Thus, the UWI sediment monitoring component is a new management tool which meets the needs of the Puget Sound Partnership's Action Agenda in the following ways:

- *Status-and-trends monitoring*: The PSAMP spatial sediment monitoring component has conducted status-and-trends monitoring throughout Puget Sound for more than 20 years. Thus, baselines of conditions have already been established for bays, regions, and sound, as well as for the geomorphological/anthropogenic-use "strata". Comparison of current conditions to baseline conditions provides indications of change.

  As the temporal aspect of PSAMP marine sediment monitoring continues, those baselines are being updated. For example, the entire central region was sampled during 1998-1999 as part of the PSAMP/NOAA survey. In 2008 and 2009, the PSAMP sediment monitoring program will complete sampling throughout the PSAMP Central Sound region and thus will provide updated information on the region/action area.

  Furthermore, the PSAMP/UWI sediment monitoring program measures many parameters. By including several lines of evidence, the program provides information on multiple aspects of ecosystem health.

- *Effectiveness monitoring*: Application of the PSAMP Sediment Component sampling design at the bay scale has created a new effectiveness monitoring tool for use by the PSP and other stakeholders. Using this tool, sediment quality degradation can be quantified on the bay-wide scale and assessed for changes over time. These assessments enable environmental managers to determine whether *collective* localized cleanups and source control improve conditions over a wider area.

- *Indicators*: Three separate indicators of sediment chemistry, toxicity, and benthic community structure have been developed and used by the PSAMP Sediment Component to characterize sediment quality throughout Puget Sound since 1989. Since 1997, those indicators have been combined into the multivariable Sediment Quality Triad Index and used to quantify the spatial extent of sediment quality degradation at different geographic scales. Work is currently underway to (1) enhance the sensitivity of the SQTI and (2) develop a quantitative benthic index.

- *Coordinated regional monitoring*: The Urban Waters Initiative bay-scale sediment monitoring sampling frames are nested within the larger PSAMP geographical regions, which are nested within the sample frame for all of Puget Sound. This nested design enables managers to assessment sediment quality among different geographic scales (bay-, region-, and/or sound-wide). For example, ecosystem managers for the Elliott Bay/lower Duwamish area can see the 2007 UWI results in the context of both Central Sound (South Central and North Central Action Areas) and all of Puget Sound.

  In addition, the component of the PSAMP sediment monitoring design which characterizes portions of Puget Sound according to geomorphology and anthropogenic use ("strata") provides a means to assess conditions in urbanized and non-urbanized areas, which can inform management decisions. Further, it is possible to compare conditions over time within the same "stratum" types (e.g., harbor at time 1 vs. harbor at time 2), another useful tool in adaptive management. In the 2007 UWI study, for example, we compared sediment quality in the harbor+urban portions of the Elliott Bay/lower Duwamish study area with the collective harbor+urban areas of the entire Puget Sound. Another use of the PSAMP "strata" in this study was the comparison of Elliott Bay/lower Duwamish conditions to the PSAMP "ambient" conditions.

- *Science:* The PSAMP/UWI sediment monitoring component has incorporated accepted, state-of-the-science methods for (1) probability-based design and analysis of spatial extent, (2) statistical analysis of chemical-contamination data containing nondetects, (3) statistical comparison of benthic assemblages, and (4) relation of benthic assemblages to environmental conditions. Other technical developments are added as the program matures. Such methods are importance for gleaning the best information possible from highly complex data.

- *Communication:* Since the inception of the PSAMP in 1989, the Sediment Component has generated and communicated information regarding the status and trends of sediment quality in Puget Sound to the PSP and its predecessors, and other stakeholders. This information has been published in successive editions of the *Puget Sound Update* and *State of the Sound*, in Ecology reports and "glossy" summaries, and in peer-reviewed literature. All PSAMP sediment publications are listed and available on Ecology's Marine Sediment Monitoring website (www.ecy.wa.gov/programs/eap/psamp/index.htm).

Summary and Conclusions

As part of the Urban Waters Initiative, Ecology's Environmental Assessment Program conducted a sediment survey throughout Elliott Bay and its adjoining waterways in 2007. The purpose was to provide information on the long-term effectiveness of collective toxics management efforts in that area.

The objectives were to:

1. Assess the current conditions in the bay, particularly the overall extent of sediment contamination.
2. Determine whether there had been changes in sediment quality over time.
3. Compare the extent of sediment-quality degradation in the Elliott Bay/lower Duwamish area with regional and Puget Sound-wide levels of degradation.

A weight-of-evidence approach was used to compare the results of the 1998 PSAMP/NOAA study and the 2007 Urban Waters study to determine what changes had taken place in the interim. The results of the survey and analyses showed the following.

Current Conditions in Elliott Bay and Adjoining Waterways

Sediment Contamination

- Approximately 33% of the total study area was chemically contaminated as indicated by one or more chemicals exceeding Washington State SQS sediment management standards. SQS criteria were exceeded for 17 of 41 chemicals or chemical groups for which there are State standards. Most stations exceeding SQS criteria did so for three or fewer chemicals or chemical groups in any given sample.
- The chemical which exceeded the respective SQS most frequently was bis(2-ethylhexyl) phthalate, a common plasticizer. Mercury and total PCBs were second and third in frequency of exceeding their respective SQSs. Among classes of compounds, the SQSs were exceeded most frequently for PAHs, followed by BNAs and then metals.
- PCB concentrations were highest at the lower Duwamish and East Waterway stations. In general, metals and PAH contaminant concentrations were highest at or near the Port of Seattle piers or in the southeast portion of Elliott Bay, and lowest in the outer bay.

Sediment Toxicity

- Only a small fraction of the area had toxic sediments, based on the single sublethal toxicity test. Benthos were also affected for that proportion. There was no obvious or discernible spatial pattern or gradient in toxicity with this test in this study area. The percent incidence and spatial pattern in toxicity might have been different if there had been data for a full set of tests.

Invertebrate Communities

- More than 50% of the study area had adversely affected benthic infauna, and 17.9% of the area had both chemical contamination and affected benthos. Benthic communities tended to be similar by geographic area and along depth contours. Large numbers of pollution-tolerant species and low evenness and dominance often were characteristics of benthic assemblages from stations in the waterways. Low total abundance or taxa richness, or both, characterized some other stations. Although the numbers of taxa thought to be pollution-sensitive and pollution-tolerant were similar overall, the pollution-tolerant species were far more abundant than the pollution-sensitive species.

Sediment Quality Triad Index

- Seven of the 30 stations sampled, representing 8.3 km^2 (31.4% of the study area) had high sediment quality, as gauged by the Sediment Quality Triad Index (SQTI) of sediment chemistry, toxicity, and benthic infauna. Twelve stations, representing 12.9 km^2 (49.1% of area), met the criteria for intermediate/high sediment quality (degradation in one of the three triad elements). Another 11 stations, representing 5.1 km^2 (19.5% of area), met the criteria for intermediate/degraded sediment quality (degradation in two triad elements). None of the stations or area had degraded sediment quality (degradation in all three triad elements).

Comparison to 1998 Conditions

Overall, there was a mixture of temporal trends between 1998 and 2007. Most measures indicated slight improvements in sediment quality on a bay-wide scale. A few parameters indicated degradation of sediment quality, and others indicated no statistically significant changes. The following changes in conditions in the study area were found.

Sediment Contamination

- *Metals:* The concentrations of lead, mercury, silver, and tin decreased significantly. Zinc concentrations increased. There were no statistically significant changes in the levels of arsenic, cadmium, chromium, copper, or nickel.
- *PAHs:* The concentrations of most LPAHs decreased or stayed the same. The concentrations of most HPAHs decreased. There were no changes in the levels of chrysene or perylene, two HPAHs. Contamination by two LPAHs, acenaphthylene and retene, increased.
- *PCBs:* Most individual PCB congeners decreased in concentration, as did total (summed) PCB Aroclors.
- *Phthalates:* Bis(2-ethylhexyl) phthalate concentrations increased.
- *Comparison to sediment-quality standards:* The number of chemicals exceeding their respective SQS decreased. For some of those chemicals, both the number of stations and amount of associated area exceeding the SQS also decreased.

Sediment Toxicity

- Sediment toxicity decreased significantly, from seven stations representing 9% of the study area in 1998 to a single station representing 1.6% of the area in 2007.

Invertebrate Communities

- Some measures of benthic invertebrate community health improved from 1998 to 2007. However, the total number of stations and amount of area with adversely affected benthos remained almost unchanged.

Sediment Quality Triad Index

- Sediment quality, as measured by the SQTI, improved for 24% of the study area, remained the same for 46%, and declined for 30%. All of the improvements were in the waterways and inner portion of Elliott Bay. Sediment quality in the outer portion of the bay, already high, remained high or declined slightly (to intermediate/high) due to adversely affected invertebrates at one station.
- Most of the shifts in sediment quality were from the degraded and intermediate/degraded SQTI categories (combined) to the intermediate/degraded and intermediate/high categories (combined).
- The proportion of the total area with degraded and intermediate/degraded sediment quality decreased from more than 30% to slightly less than 20%, all in the intermediate/degraded category. None was classified as degraded in 2007.

Sediment Quality at Different Spatial Scales

The 2007 UWI Elliott Bay/lower Duwamish sampling frame is nested within the PSAMP Sediment Component's Central Region, which aligns well with the Puget Sound Partnership's South Central and North Central Action Areas. The bay, region, and Action Area sampling frames nest, in turn, within the Puget Sound sampling frame. This nested series of sampling frames enables assessment of sediment quality at several spatial scales and for urbanized vs. non-urbanized areas.

- A much smaller proportion of the Elliott Bay/lower Duwamish study area had high sediment quality than in the Central Region or all of Puget Sound.
- The proportion of area with intermediate sediment quality was much higher in the study area than in the Central Region or in the entire Puget Sound. These results reflect both the more heavily contaminated proportion of the bay and the large proportion of the Central Region comprising the relatively less contaminated central passages and basins of Puget Sound.
- Among just the urbanized/industrialized areas, the differences between bay-level, regional, and sound-wide results were not as large as for all areas combined. Elliott Bay and its adjoining waterways are part of the Central Region, but the region also encompasses other urbanized or industrialized areas, such as Commencement Bay and Sinclair Inlet.

Comparisons to Other Studies

- The chemical concentration levels in this 2007 Urban Waters survey were generally similar to or lower than those reported in other studies. Some of the decreases are likely the result of multiple cleanup and source-control activities or burial by less contaminated sediment, or both, over the past two decades, as found in the comparisons to 1998 in this study. Other lower concentration levels likely resulted from differences in study design. The UWI and PSAMP/NOAA surveys were probability-based, whereas other studies were targeted toward contamination.
- Concentrations of most metals, PAHs, and PCBs were considerably higher than mean Puget Sound ambient levels, defined as the mean concentrations over combined 1997-2003 PSAMP rural, basin, and passage “strata” types.
- There have been improvements in sediment quality bay-wide since 1998 and since the historical 1982 NOAA surveys. However, many of the spatial patterns in contamination and toxicity reported first in 1982 still are apparent. For example, arsenic from the shipyards is apparent in the bay north of and near Harbor Island, PAHs are apparent along the Seattle waterfront, and PCBs are apparent in the Duwamish Waterway upstream of Harbor Island.

Meeting the Needs of the Puget Sound Partnership

The Urban Waters Initiative sediment monitoring program is a new tool for use by the Puget Sound Partnership (PSP), environmental managers, and other stakeholders. Results from this work provide information on key components of the PSP Action Agenda and the Biennial Science Plan, including:

- *Status-and-trends monitoring*: The PSAMP Sediment Component has conducted status-and-trends monitoring of multiple aspects of ecosystem health throughout Puget Sound for more than 20 years. Thus, baselines of conditions already have been established for comparison to current conditions, to provide indications of change. As the PSAMP marine sediment monitoring continues, those baselines are being updated.
- *Effectiveness monitoring*: Application of the PSAMP Sediment Component sampling design at the bay scale can be used to quantify changes over time. These assessments provide information that environmental managers can use in determining whether *collective* localized cleanups and source control improve conditions over a wider area.
- *Indicators*: Indicators of sediment chemistry, toxicity, and benthic community structure have been used to characterize sediment quality throughout Puget Sound since 1989. Since 1997, they have been combined into the multivariable Sediment Quality Triad Index and used to quantify the spatial extent of sediment quality degradation in Puget Sound. Work is currently underway to (1) enhance the sensitivity of the SQTI and (2) develop a quantitative benthic index.
- *Coordinated regional monitoring*: The Urban Waters Initiative bay-scale sediment monitoring sampling frames are nested within the larger PSAMP geographical regions, which are nested within the sample frame for all of Puget Sound. The PSAMP regions align

well with the marine portions of the PSP's Action Areas. By this nested design, sediment quality can be gauged at different geographic scales (bay-, region-, and/or sound-wide). In addition, the PSAMP sediment monitoring design can characterize ecological conditions in Puget Sound for urbanized vs. non-urbanized areas, which can inform management decisions.

- *Science:* The PSAMP/UWI sediment monitoring component has incorporated accepted, state-of-the-science methods for study design and statistical analyses. Other technical developments are added as the program matures. Such methods are important for gleaning the best information possible from highly complex data.
- *Communication:* Since its inception in 1989, the PSAMP Sediment Component has provided information on sediment-quality status and trends to the PSP and its predecessors, and other stakeholders. This information has been published in the *Puget Sound Update* and *State of the Sound*, numerous Ecology reports, peer-reviewed literature, and Ecology's Marine Sediment Monitoring website.

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Recommendations

The results of the 2007 Urban Water Initiative study point to the following recommendations for improvement of sediment monitoring at all scales, from bay-wide to Puget Sound-wide.

1. Maintain and expand the existing PSAMP and UWI programs.

- Expand the UWI bay-scale sediment monitoring to other urban bays or urbanized regions (Sinclair and Dyes Inlets, Bellingham Bay, Budd Inlet, Everett Harbor/Port Gardner).
- Resample the urban bays at five-year intervals. Ongoing effectiveness monitoring is essential to determining progress in the Puget Sound Partnership's mandate to clean up Puget Sound by 2020.
- Extend bay-scale sediment monitoring to selected non-urban bays (e.g., Port Gamble) and nearshore sampling frames identified as critical habitat for estuarine organisms.
- Increase sample size to improve discrimination ability. Funding levels must be commensurate with the magnitude and complexity of the questions to be answered.

2. Refine the sediment indices.

Refine the chemistry, toxicity, and benthic indicators and the Sediment Quality Triad Index (SQTI) to employ state-of-the-science criteria to increase their discrimination power and improve their effectiveness as monitoring tools. Improving existing indices and developing new indices is part of the 2009-2011 Biennial Science Plan put forward by the Puget Sound Partnership. Specific suggested improvements include the following.

Sediment Contamination

- Enhance the chemistry element of the SQTI to take into account (1) the presence of contaminant concentrations greater than the State standards, (2) the degree by which the SQS values are exceeded, and (3) the relative potential for biological effects of chemical mixtures in the sediments. Potentially toxic chemicals invariably occur as mixtures in estuarine sediments such as those in the Elliott Bay/Duwamish waterways region.

  One approach that could be explored is the recently developed and adopted Canadian Water Quality Index, which incorporates measures of scope, frequency, and amplitude of environmental variables (CCME, 2001). Another method that has been developed recently is the mean sediment quality guideline quotient (SQGQ) approach (Long et al., 1998; 2006). It is a major step in accounting for both the presence and magnitude of sediment-quality guidelines (SQG) exceeded. A similar approach could be taken for the chemistry element of the SQTI in Puget Sound.

  The relationships between mean sediment-quality guidelines and both the incidence and degree of toxicity was recently published with data from many estuarine case studies performed nationwide (Long et al., 1998, 2000; Wenning et al., 2005). The strengths and limitations of this approach were summarized in a review (Long et al., 2006). The state of

California has been developing numerical indices for their estuaries based on a weight of toxicity, chemistry, and benthic evidence (California State Water Resources Control Board, in prep.). California is pursuing a mean SQG approach for the chemistry.

- Develop a multi-chemical index for Puget Sound using the Washington State SQS values. Such an index could be calibrated with a sufficiently large database of matching chemistry and measures of biological effects. The index could be provided as a tool for inclusion in triad studies to classify and rank sampling stations.

- Expand the list of environmental parameters to include new, relevant physical, chemical, and biological variables not currently being measured. For example, current contaminants of concern which should be measured include pharmaceuticals and personal care products, endocrine disruptors, and perfluorinated compounds.

Sediment Toxicity

- Any given toxicity test can provide information on only a single aspect of toxicity. For example, information from one kind of test cannot be used to infer outcomes of other kinds of tests. Usually a variety of tests are performed on portions of each sample to provide a comprehensive evaluation of the different partitions (components) of sediments and different kinds of endpoints. Research on state-of-the-science in toxicity testing is needed to ensure selection of the best kinds of tests for answering questions about the effects of sediment quality on benthic health.

- The toxicity component of the SQTI is limited to whichever toxicity tests were performed for all samples. Budgetary constraints and analytical-laboratory procedural errors have resulted in the elimination of certain toxicity tests over time. Whereas four toxicity tests were conducted for the PSAMP/NOAA survey, only three, and later only two, tests were conducted for subsequent PSAMP spatial surveys. For the Urban Waters Initiative, the results of only a single toxicity test were available and reliable. Restoration of funds for toxicity testing is necessary to maintain continuity so that temporal comparisons (e.g., “Has sediment quality improved?”) can be made.

Benthic Invertebrates

- Develop a quantitative, multivariate index of the health of invertebrate communities. The SQTI currently relies on assessment of benthic assemblages by professional benthic ecologists for determination of whether invertebrate communities are “adversely affected” or “unaffected”. Furthermore, the binary designation of “affected” or “unaffected” does not allow for intermediate results. The intent and approach used to develop a benthic index would be similar to those of such indices developed for other U.S. regions, including the bays and estuaries of California and the east coast (e.g., Weisberg et al., 1997; Ranasinghe et al., 2007), but would necessarily be tailored to and unique to assemblage types in Puget Sound.

- A benthic index that can distinguish between natural and anthropogenic effects is needed. The current designations of “affected” or “unaffected” do not indicate whether the benthic community has been impaired by contamination or reflects natural conditions (e.g., low dissolved oxygen in a shallow terminal inlet).

3. Integrate sediment monitoring with other ecosystem monitoring.

- Integrate the results of other PSAMP monitoring elements with the PSAMP marine sediments monitoring to study further the links between ecosystem components. For example, parallel patterns have emerged in sediment PAH contamination and PAH-caused liver lesions in demersal fish. Work has begun to explore those patterns.

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Figures

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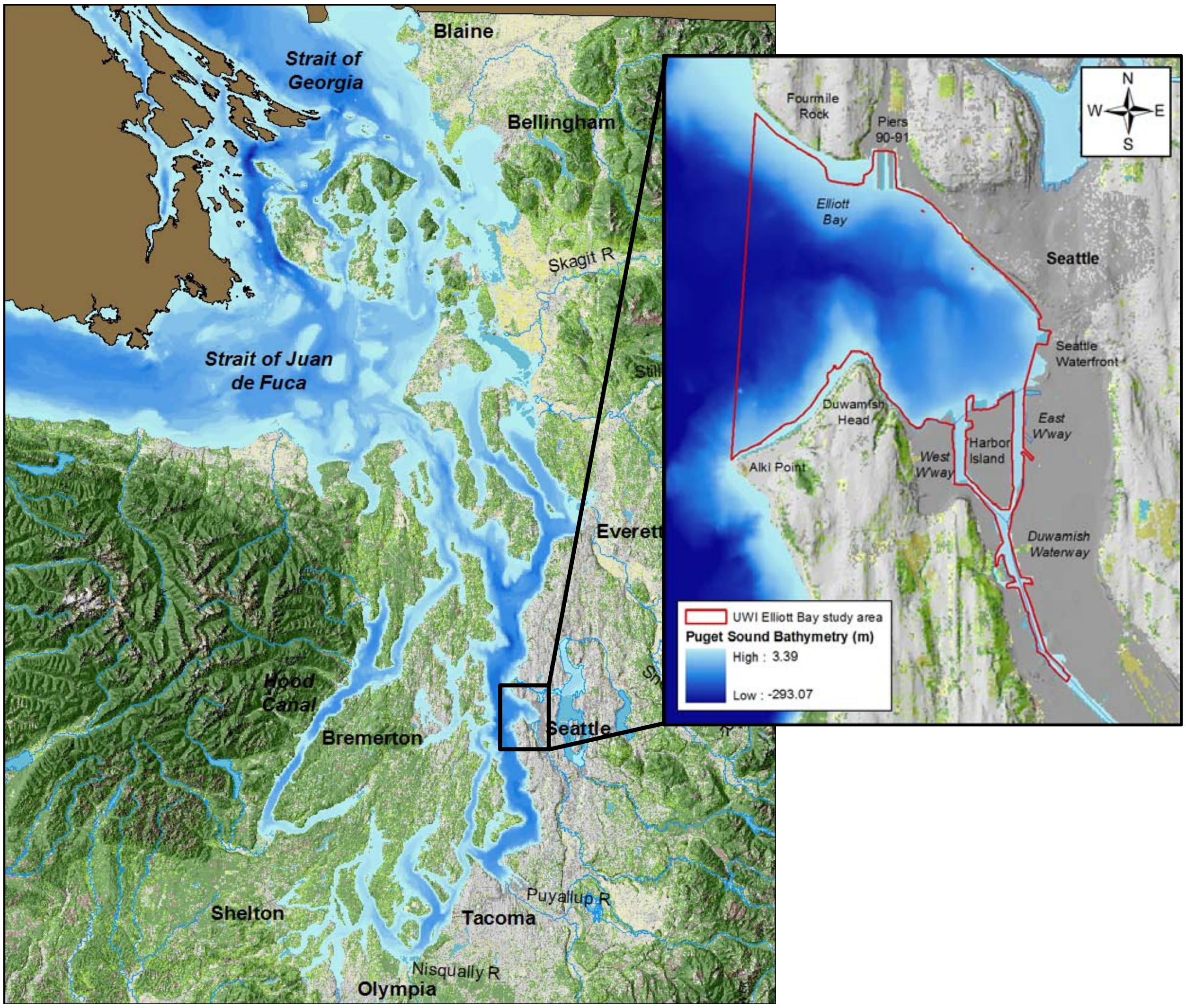

Figure 1. Urban Waters Initiative 2007 study area (Elliott Bay and the adjoining waterways of the lower Duwamish River, inset) in context of Puget Sound.

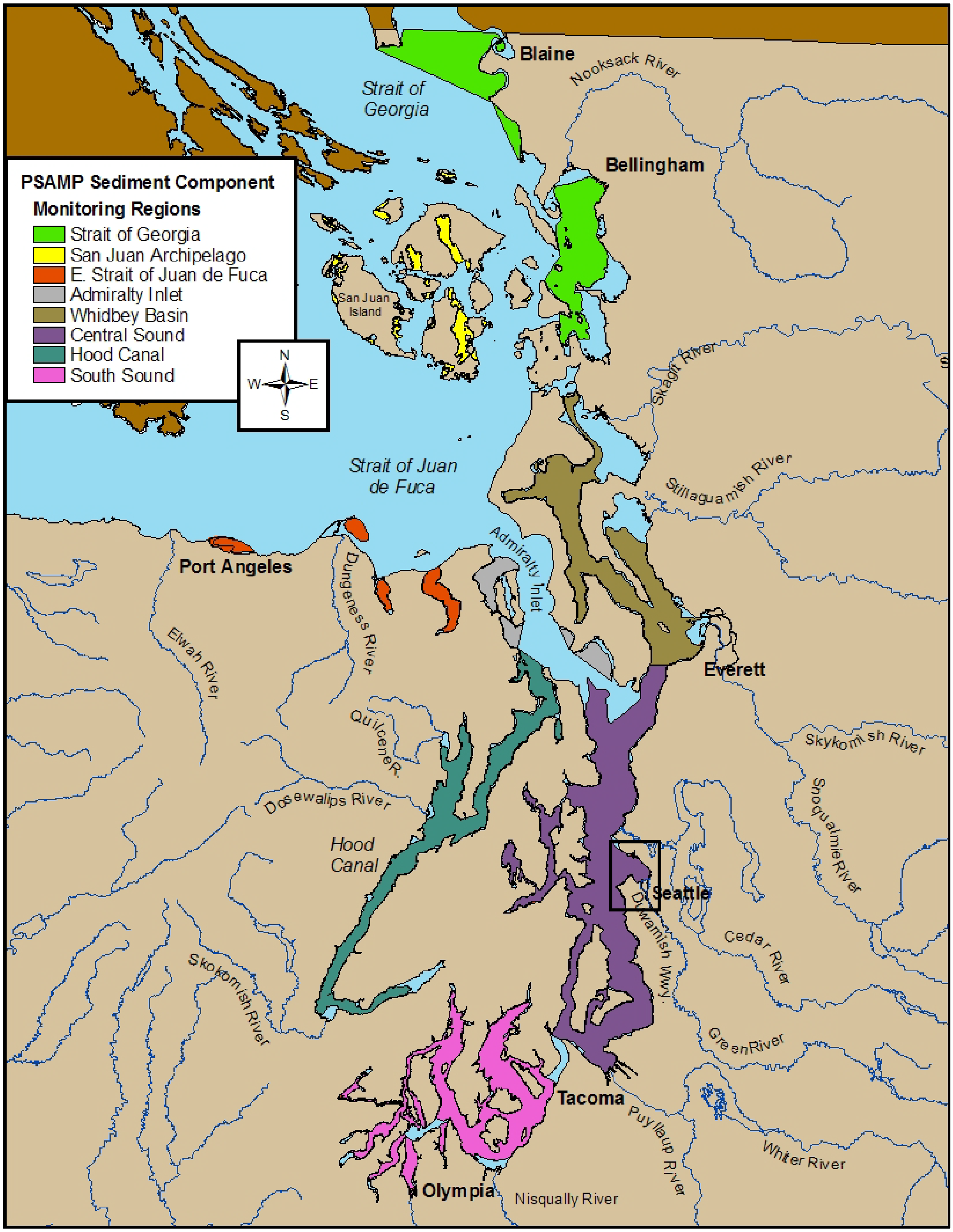

Figure 2. Eight sediment monitoring regions defined for the PSAMP sediment component. The study area (outlined) is in the Central Sound region.

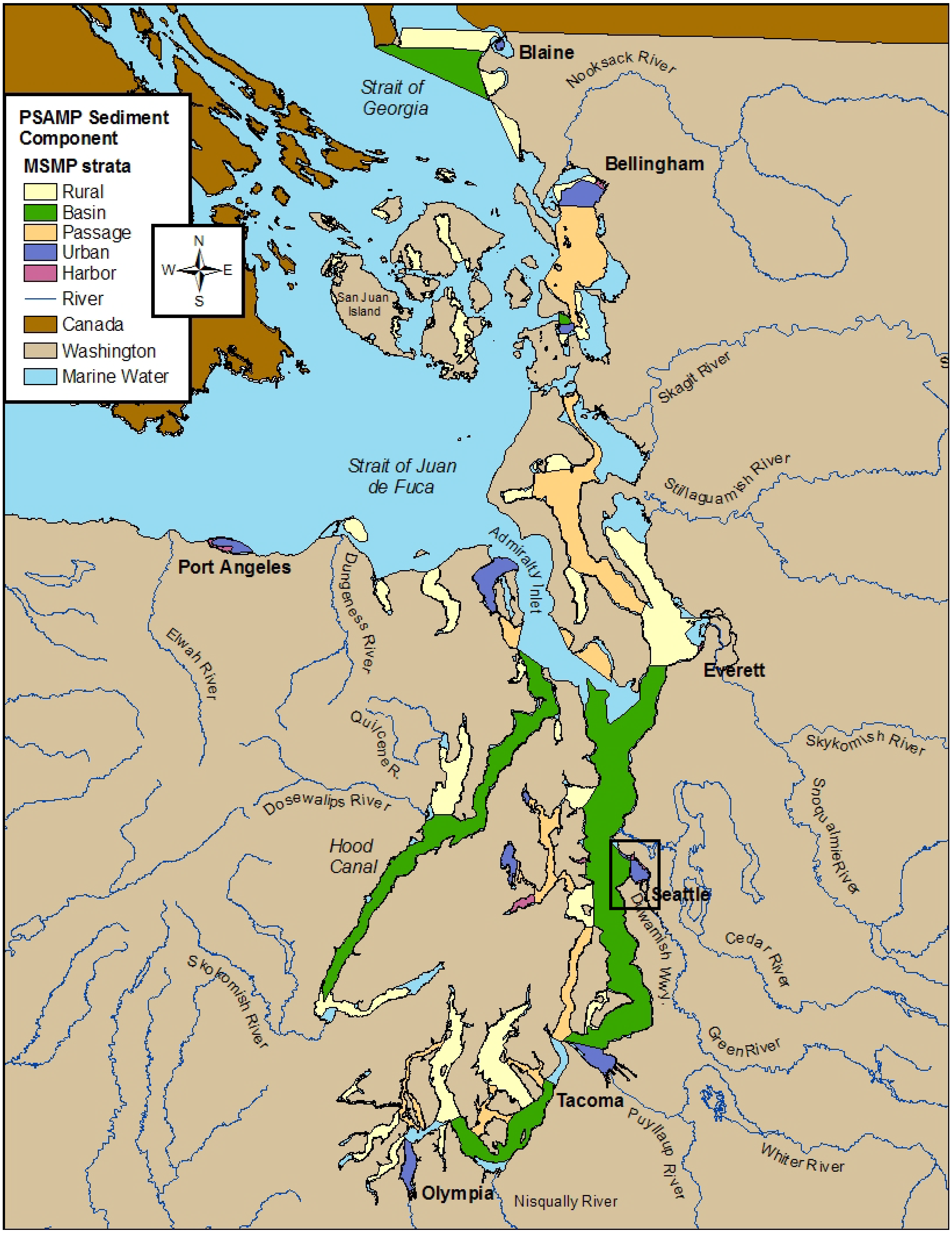

Figure 3. Five sediment monitoring "strata" defined for the PSAMP sediment component. The study area (outlined) includes basin, harbor, and urban "stratum" types (detailed view in Figure 4).

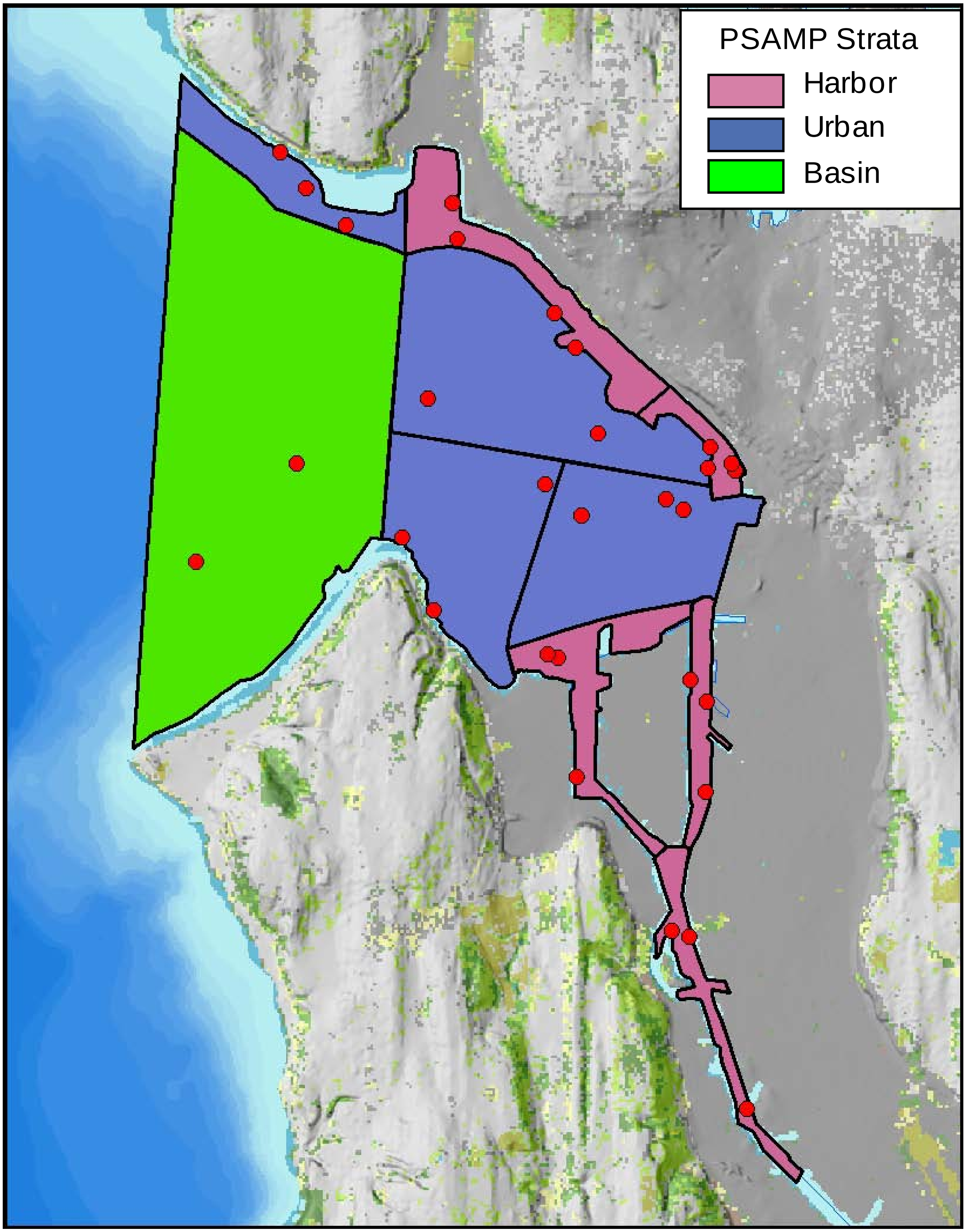

Figure 4. Station locations for the 2007 Urban Waters Initiative sediment study.

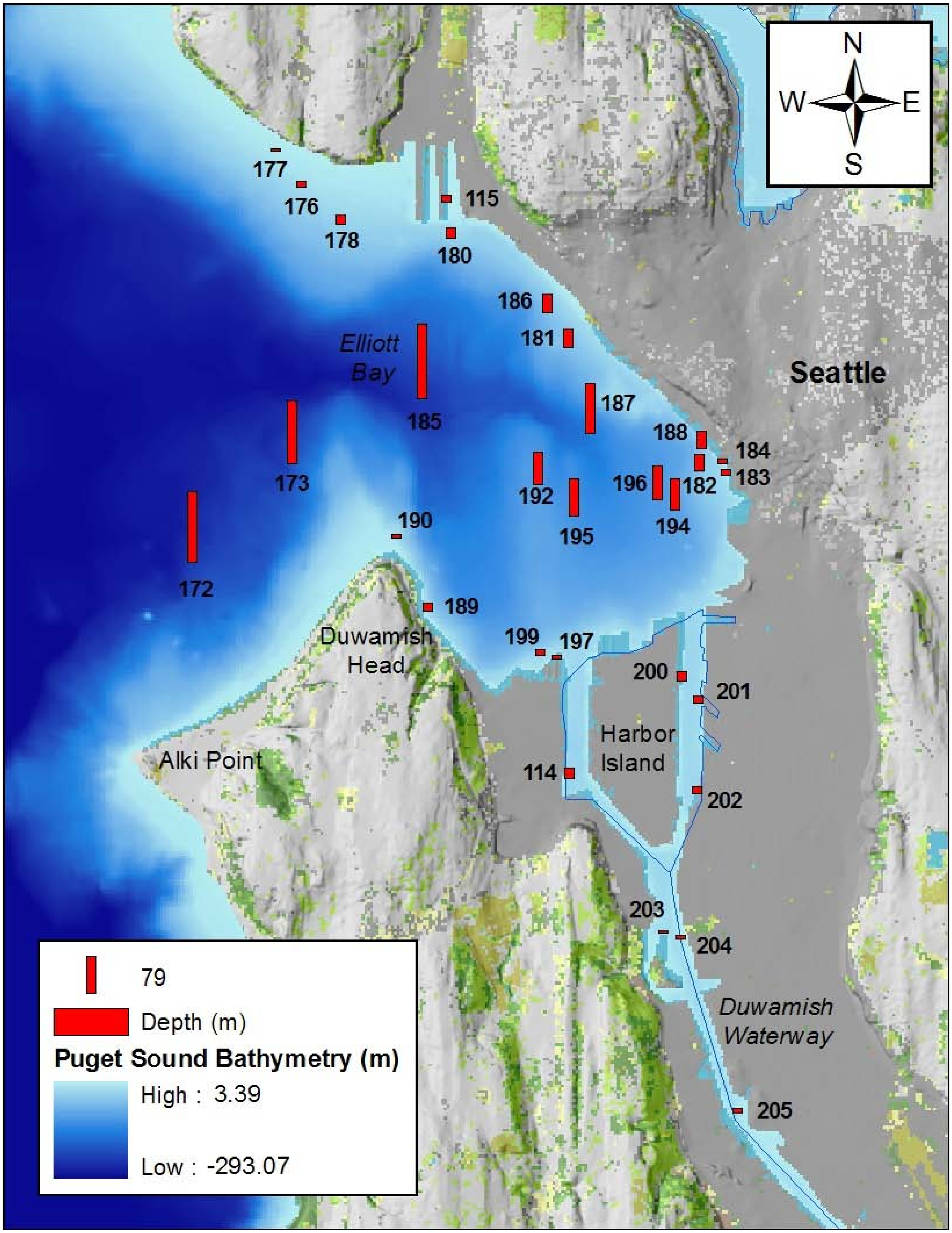

Figure 5. Water depths at 30 sediment stations sampled for the 2007 Urban Waters Initiative study.

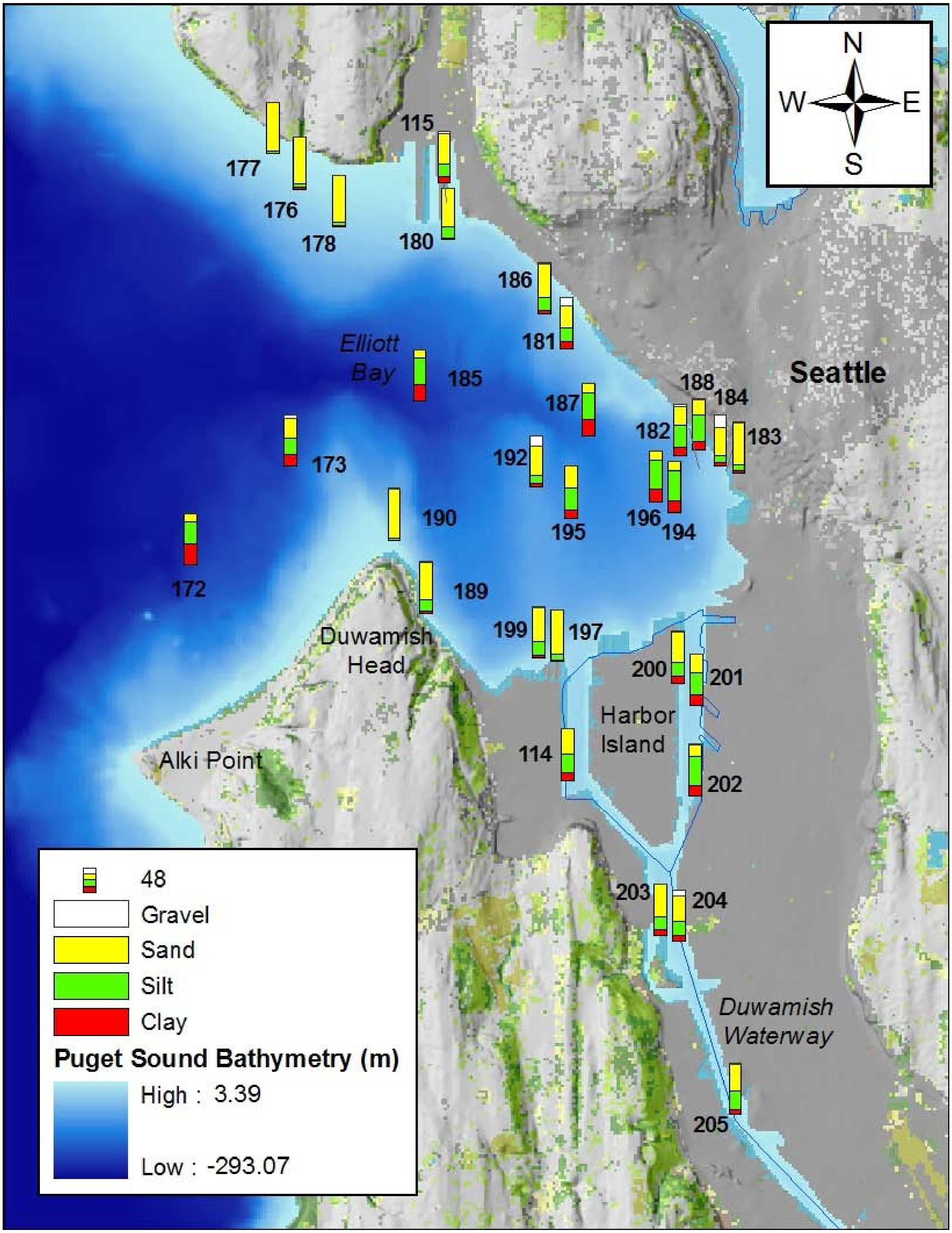

Figure 6. Spatial patterns in particle size classes (percent gravel, sand, silt, and clay) for the 2007 Urban Waters Initiative sediment study.

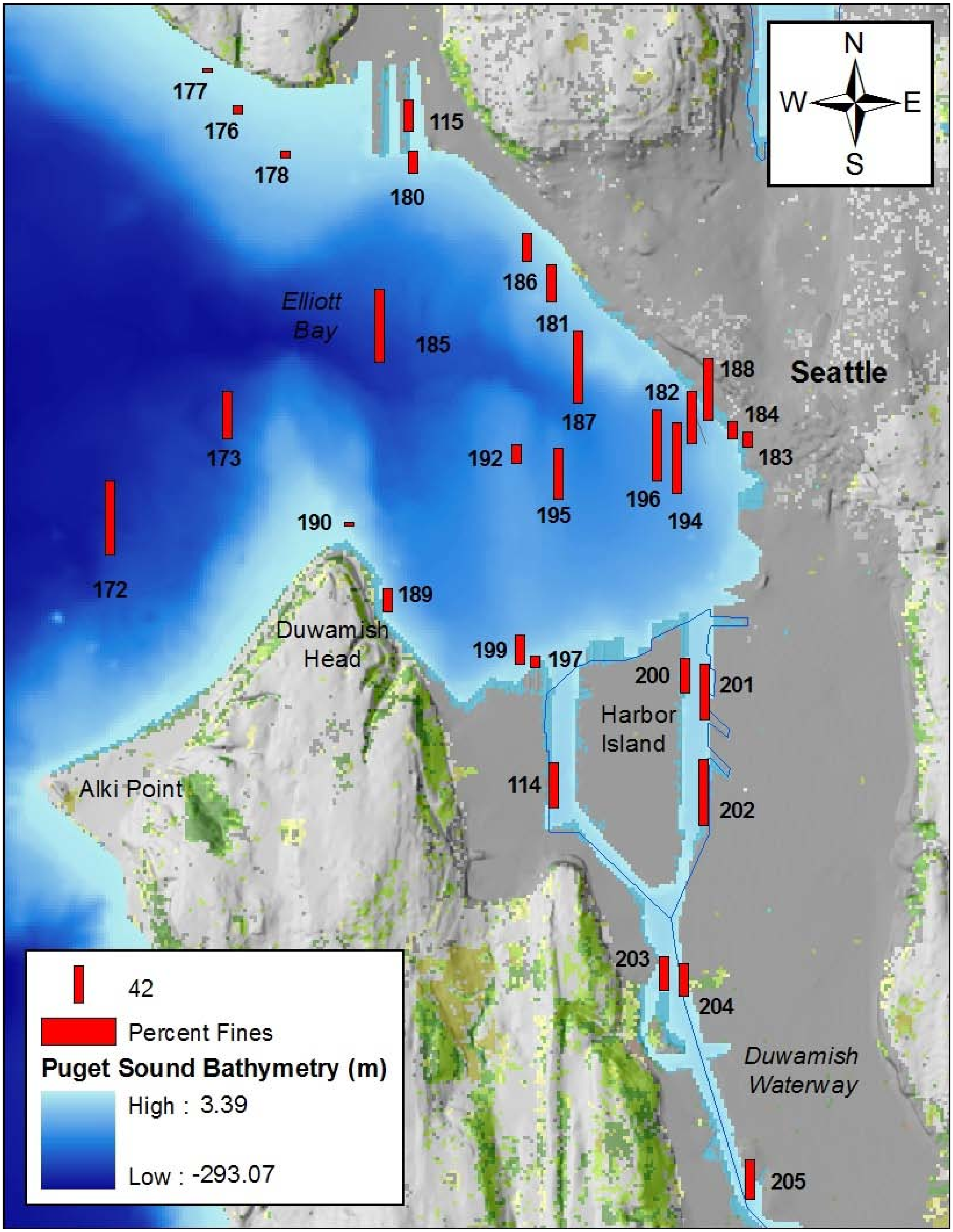

Figure 7. Spatial patterns in percent fines (silt + clay) for the 2007 Urban Waters Initiative sediment study.

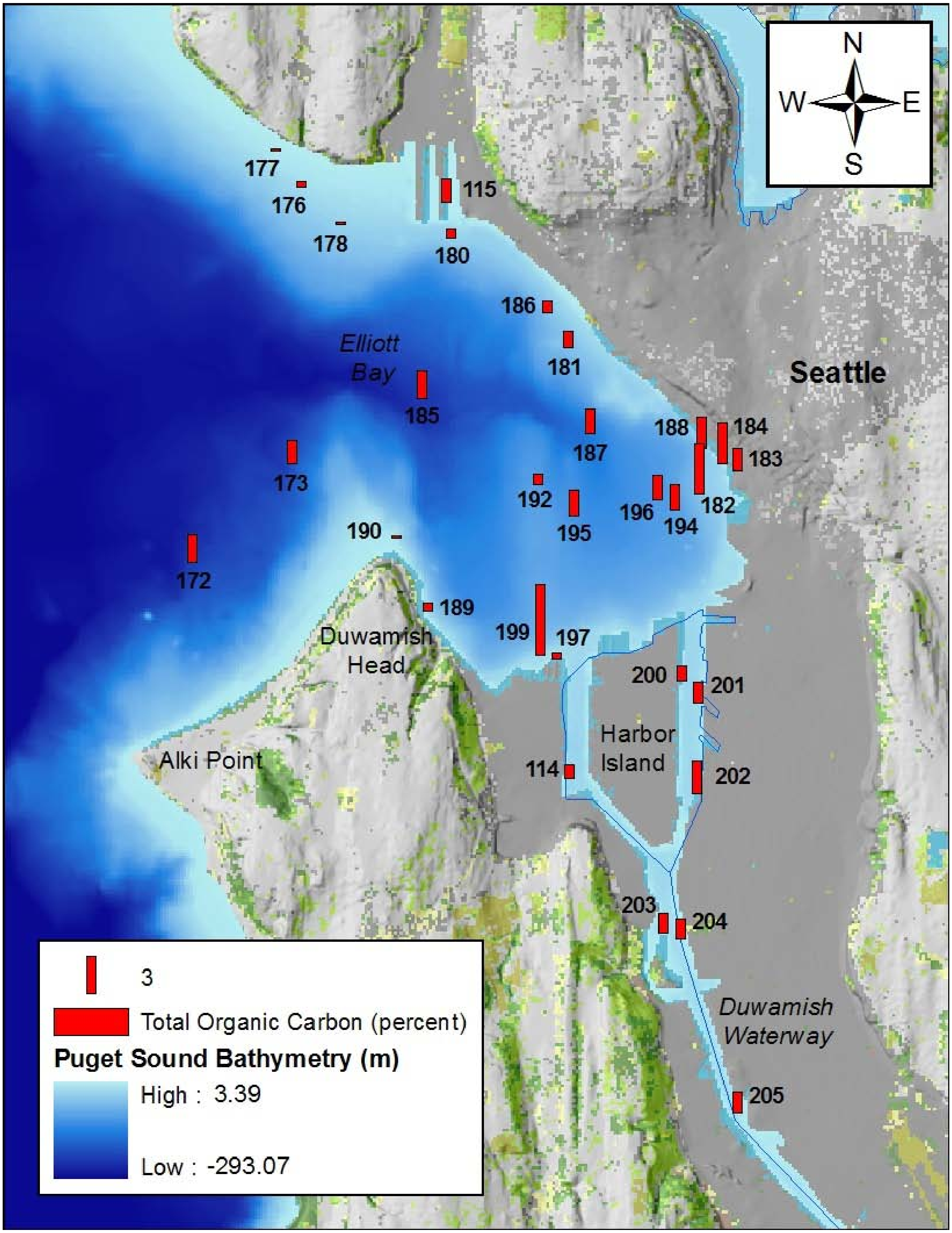

Figure 8. Spatial patterns in total organic carbon for the 2007 Urban Waters Initiative sediment study.

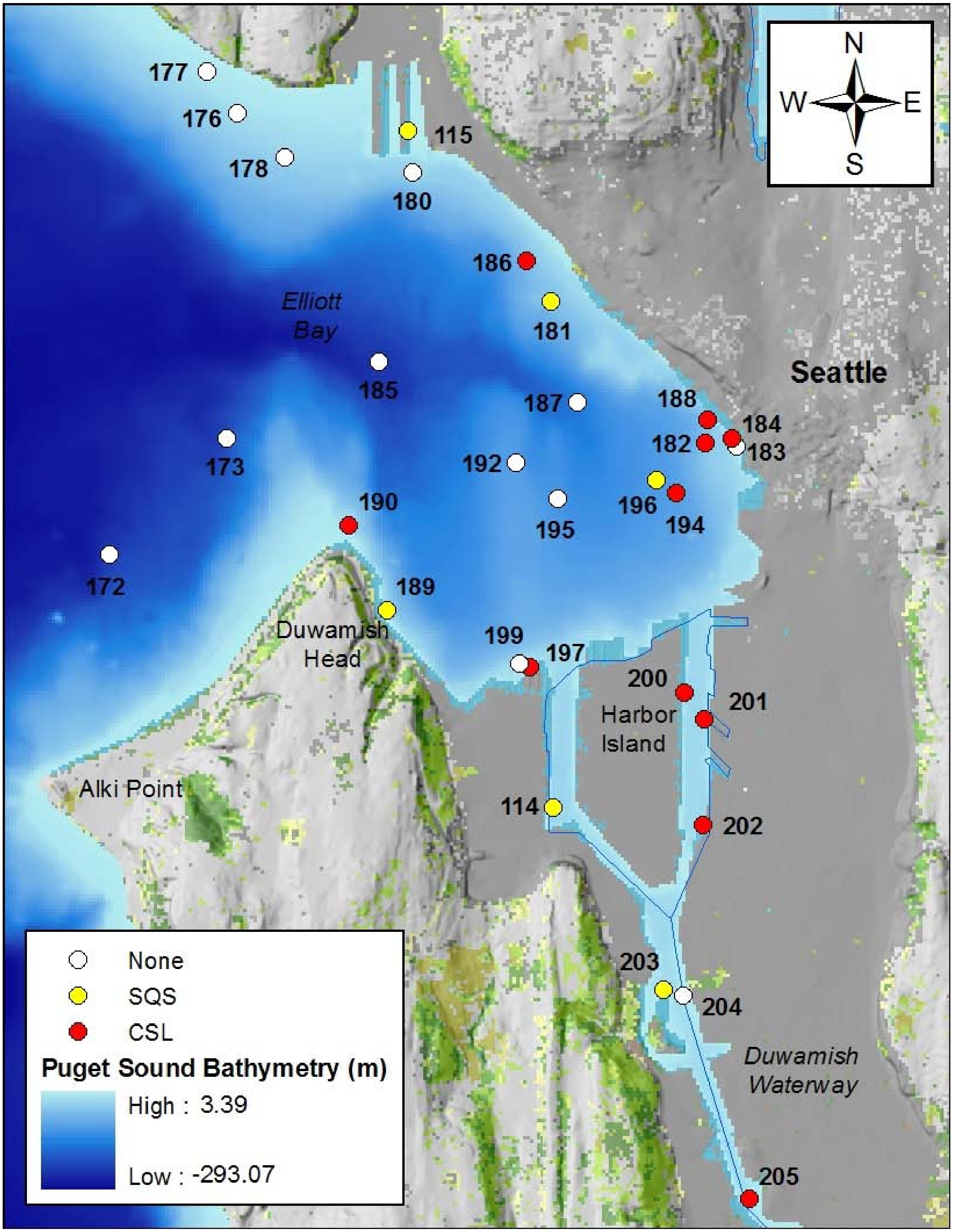

Figure 9. Sampling stations at which state sediment quality standards were exceeded for the 2007 Urban Waters Initiative sediment study.

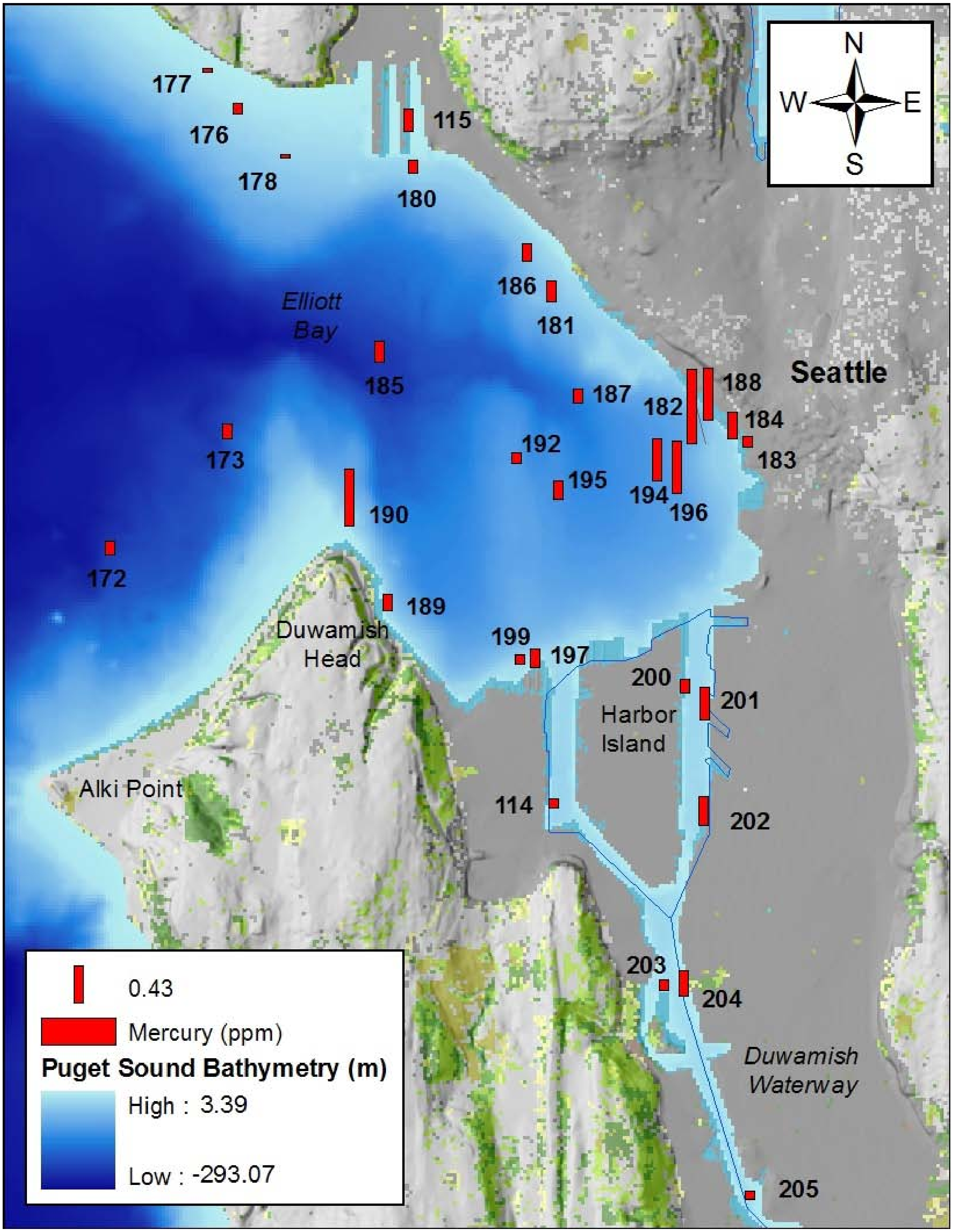

Figure 10. Spatial patterns in Mercury for the 2007 Urban Waters Initiative sediment study. The Sediment Quality Standard for Mercury is 0.41 ppm.

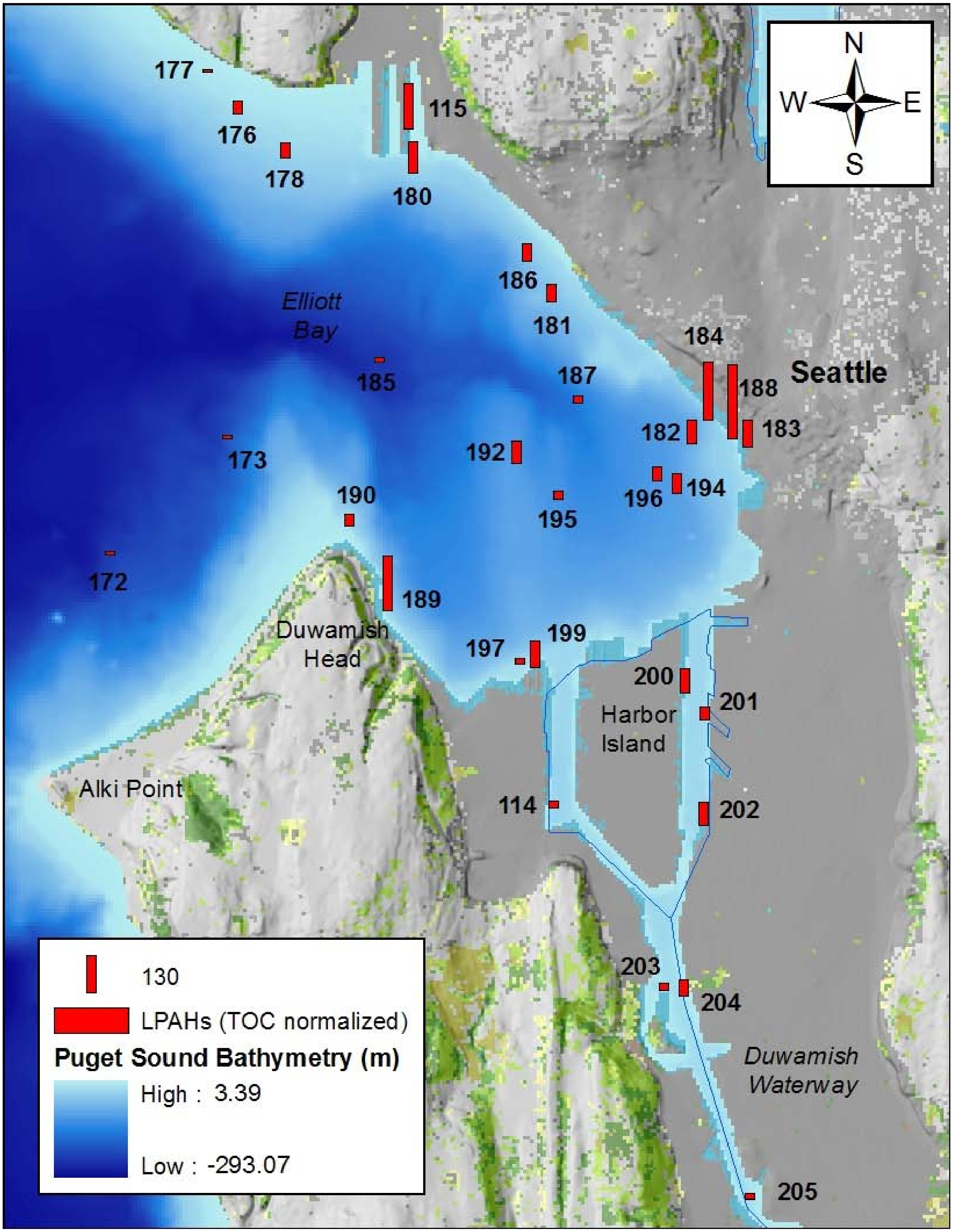

Figure 11. Spatial patterns in TOC-normalized Total LPAH (sum of 6 LPAH compounds) for the 2007 Urban Waters Initiative sediment study. The Sediment Quality Standard for Total LPAH is 370 ppm organic carbon.

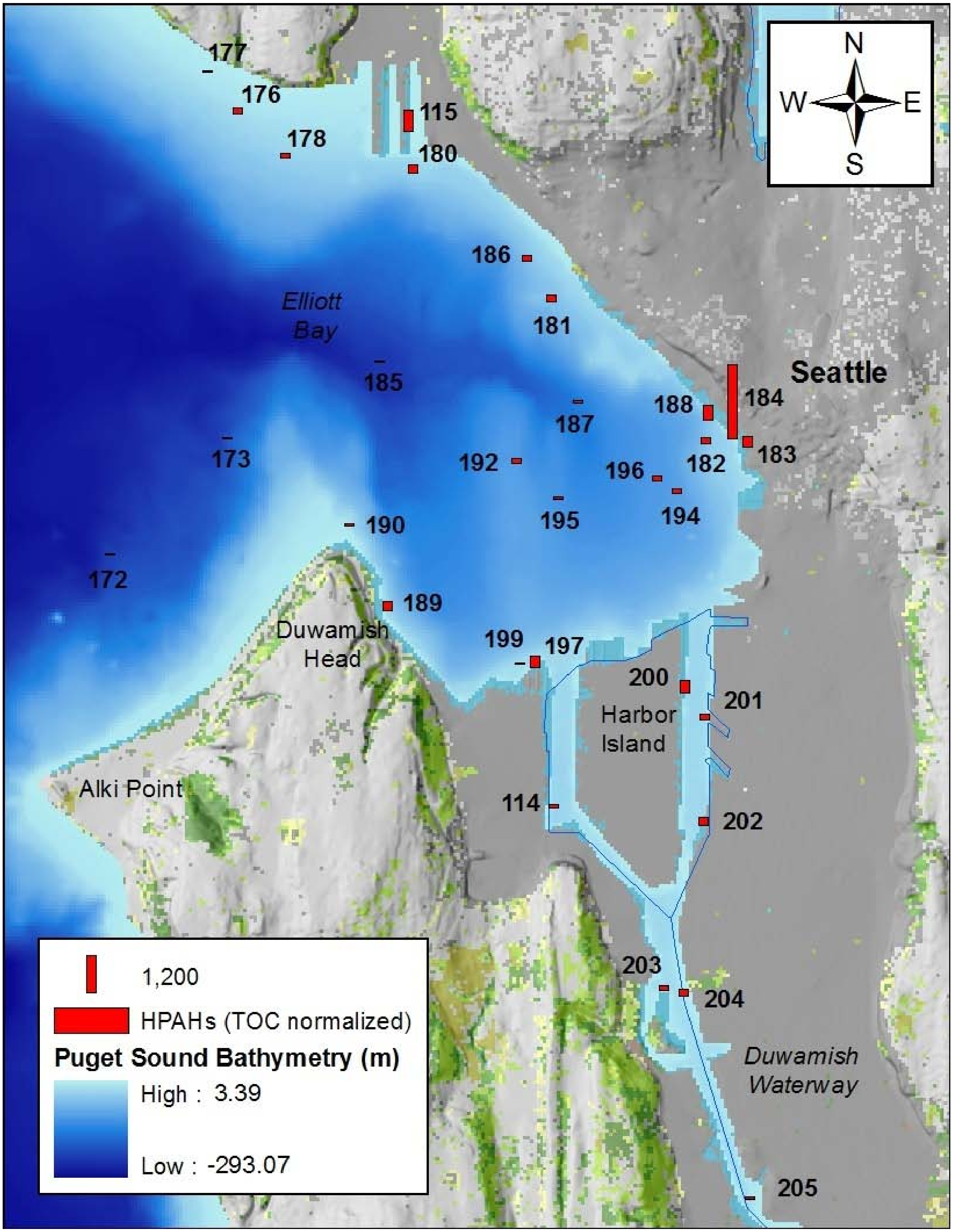

Figure 12. Spatial patterns in TOC-normalized Total HPAH (sum of 9 HPAH compounds) for the 2007 Urban Waters Initiative sediment study. The Sediment Quality Standard for Total HPAH is 960 ppm organic carbon.

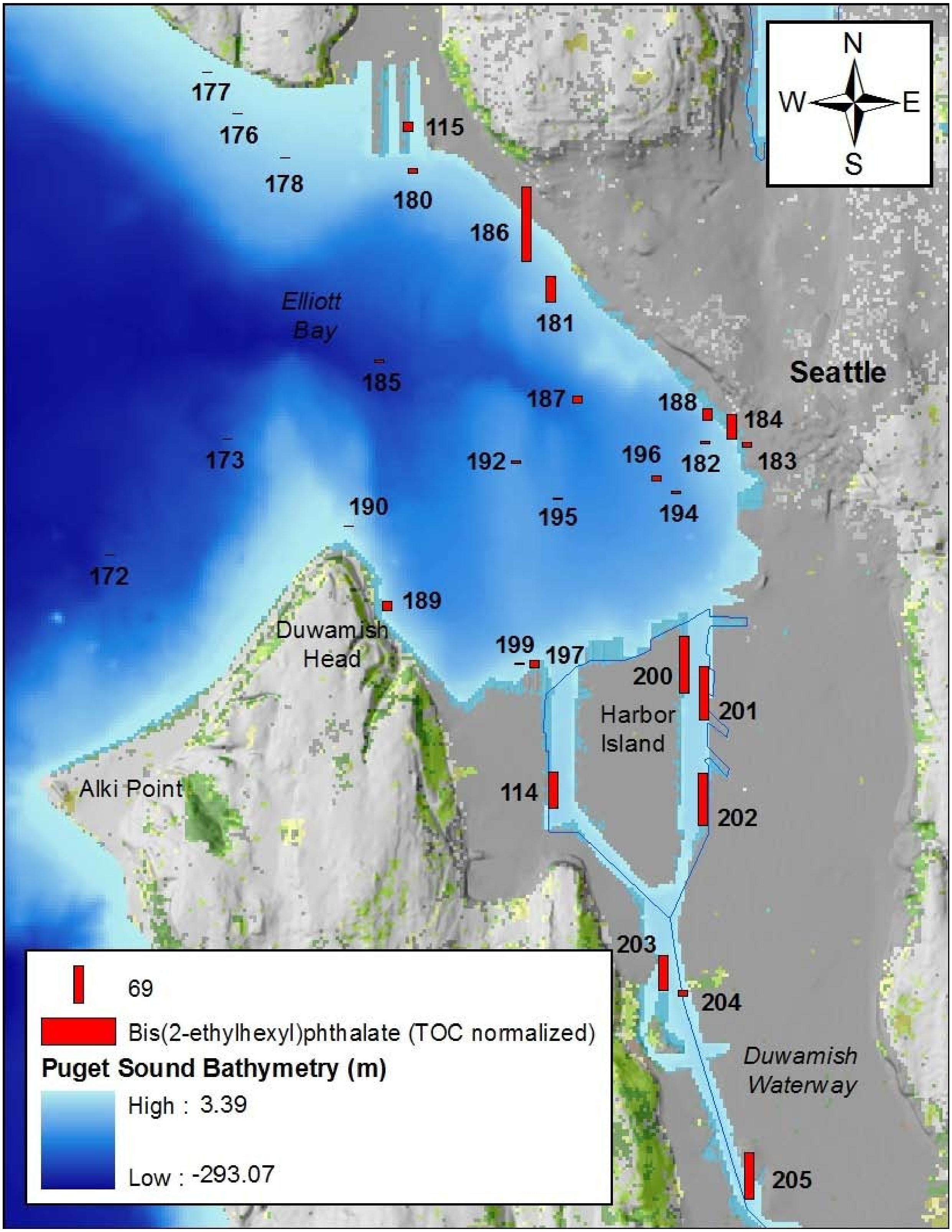

Figure 13. Spatial patterns in TOC-normalized Bis(2-ethylhexyl) phthalate for the 2007 Urban Waters Initiative sediment study. The Sediment Quality Standard for Bis(2-ethylhexyl) phthalate is 2.88 ppm organic carbon.

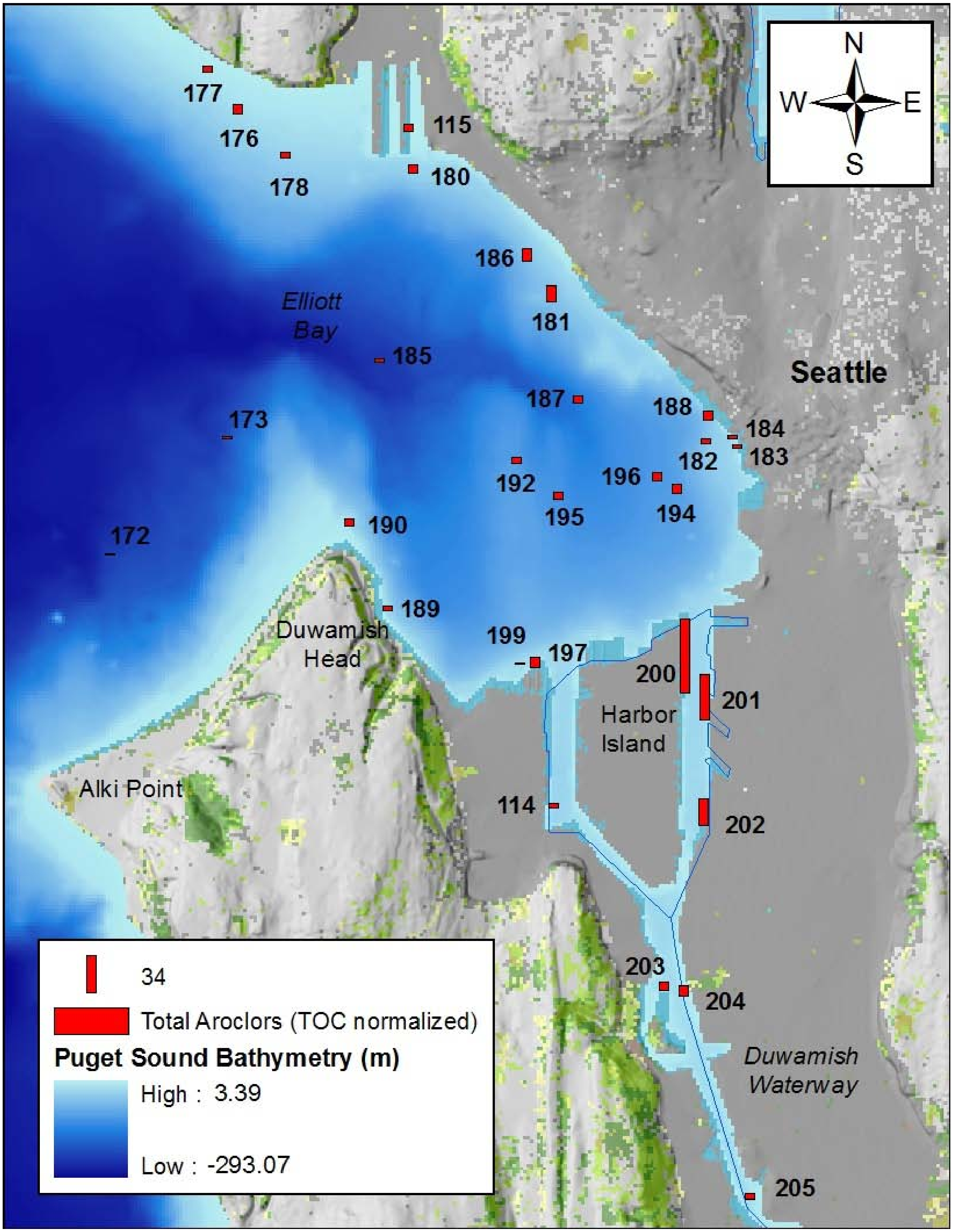

Figure 14. Spatial patterns in TOC-normalized Total PCB Aroclors for the 2007 Urban Waters Initiative sediment study. The Sediment Quality Standard for Total PCB is 12 ppm organic carbon.

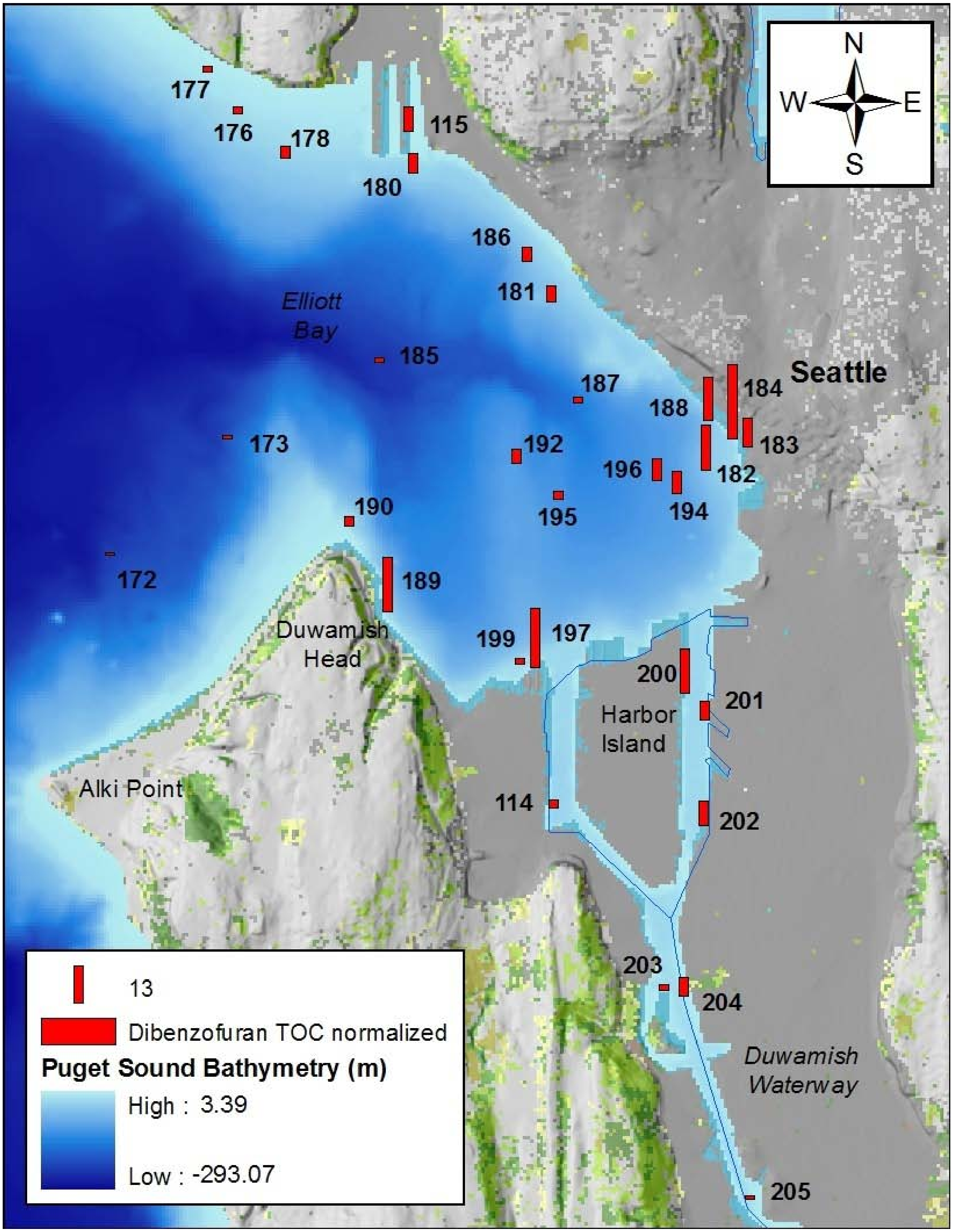

Figure 15. Spatial patterns in TOC-normalized Dibenzofuran for the 2007 Urban Waters Initiative sediment study. The Sediment Quality Standard for Dibenzofuran is 4 ppm organic carbon.

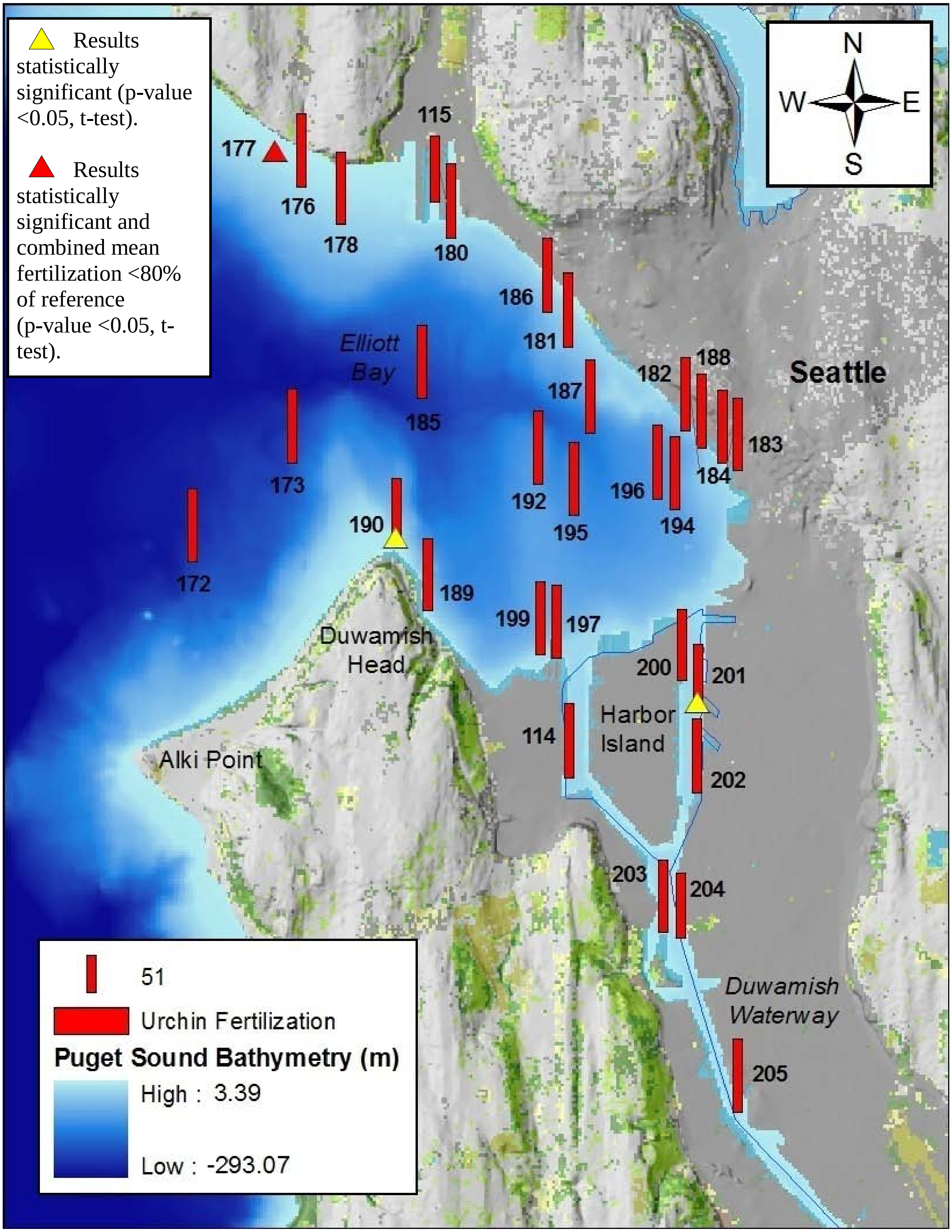

Figure 16. Spatial patterns in toxicity determined with the sea urchin *Strongylocentrotus purpuratus* for the 2007 Urban Waters Initiative sediment study.

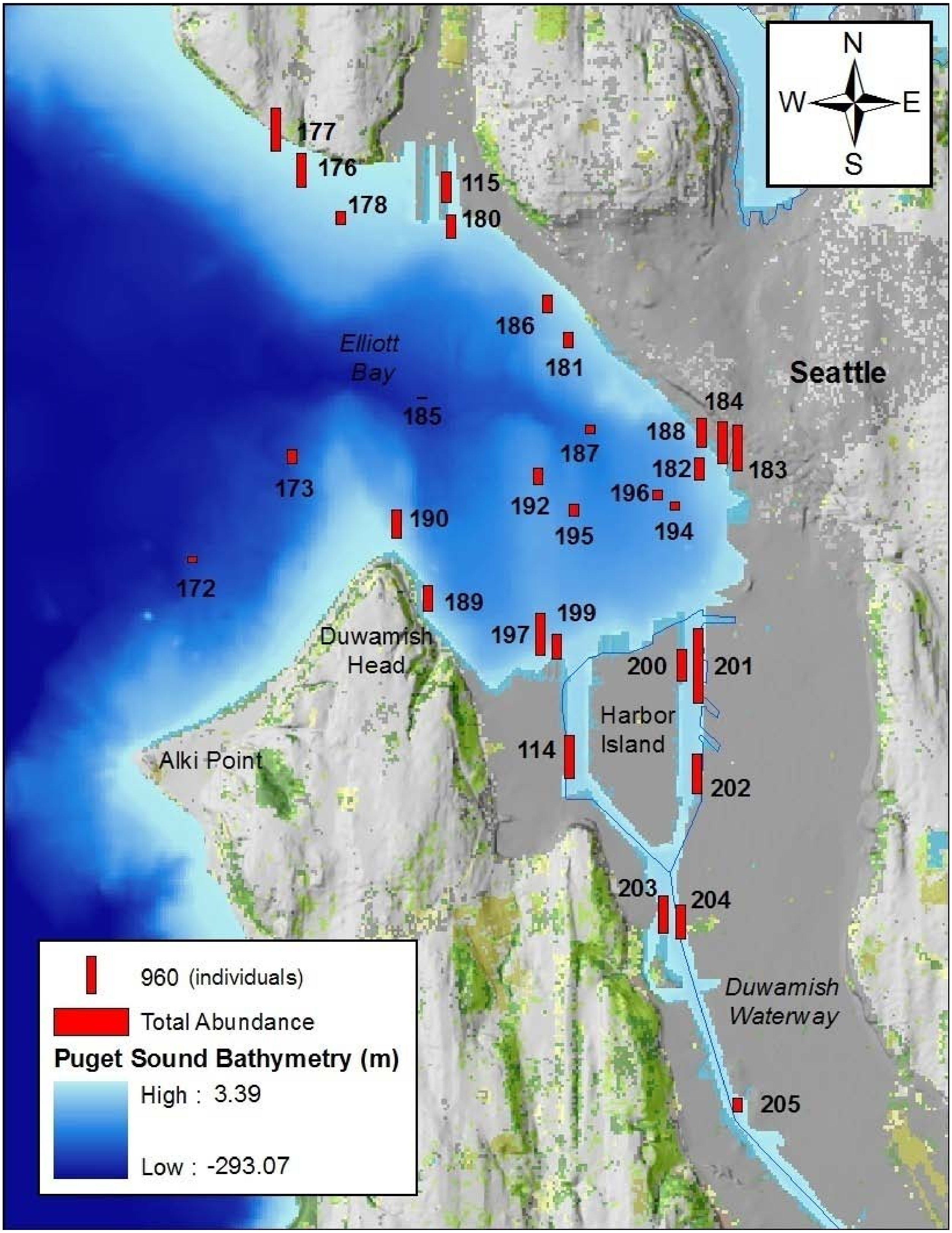

Figure 17. Total abundance of all benthic organisms at 30 sediment stations sampled for the 2007 Urban Waters Initiative sediment study.

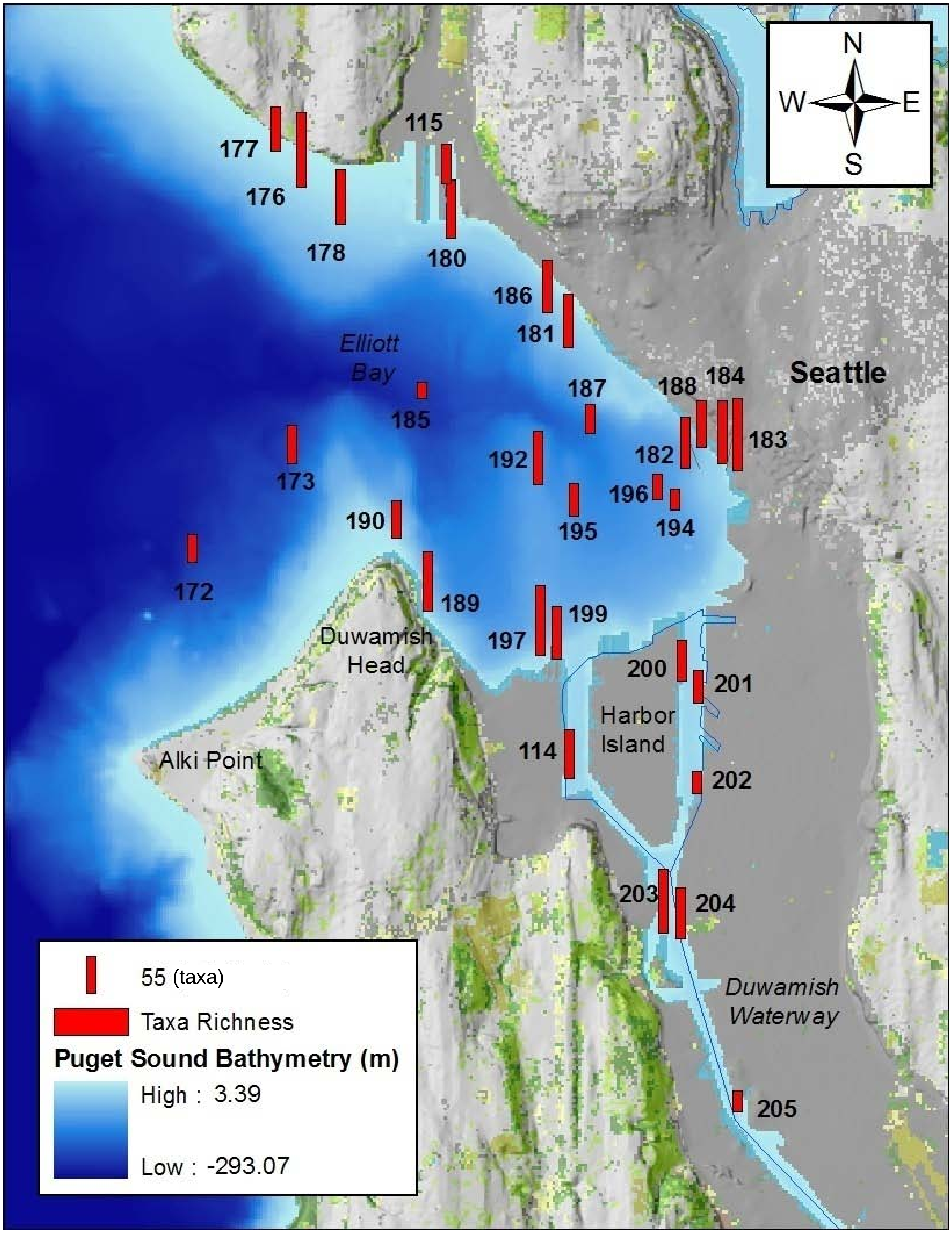

Figure 18. Taxa richness at 30 sediment stations sampled for the 2007 Urban Waters Initiative sediment study.

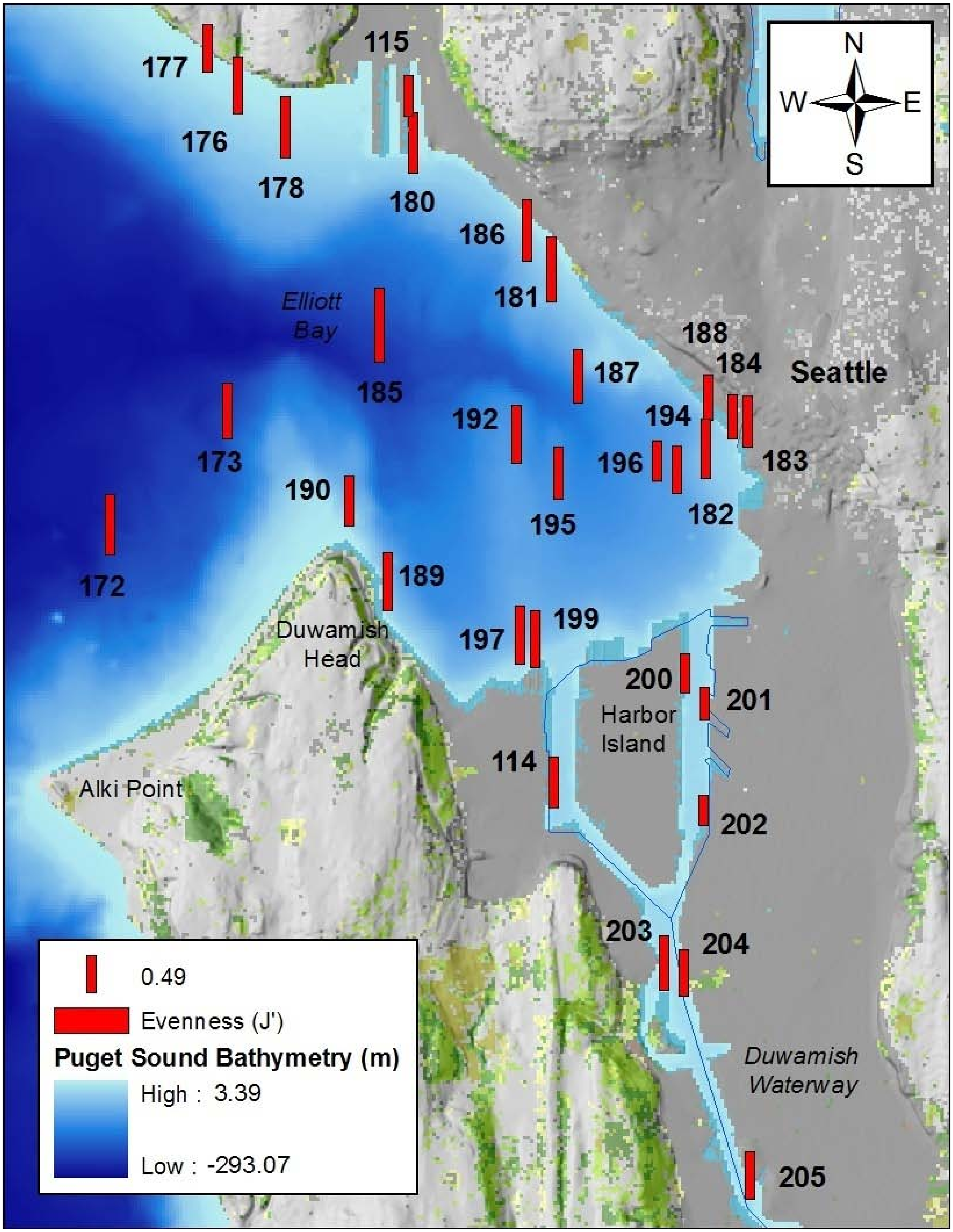

Figure 19. Pielou's evenness index values for the benthos at 30 sediment stations sampled for the 2007 Urban Waters Initiative sediment study.

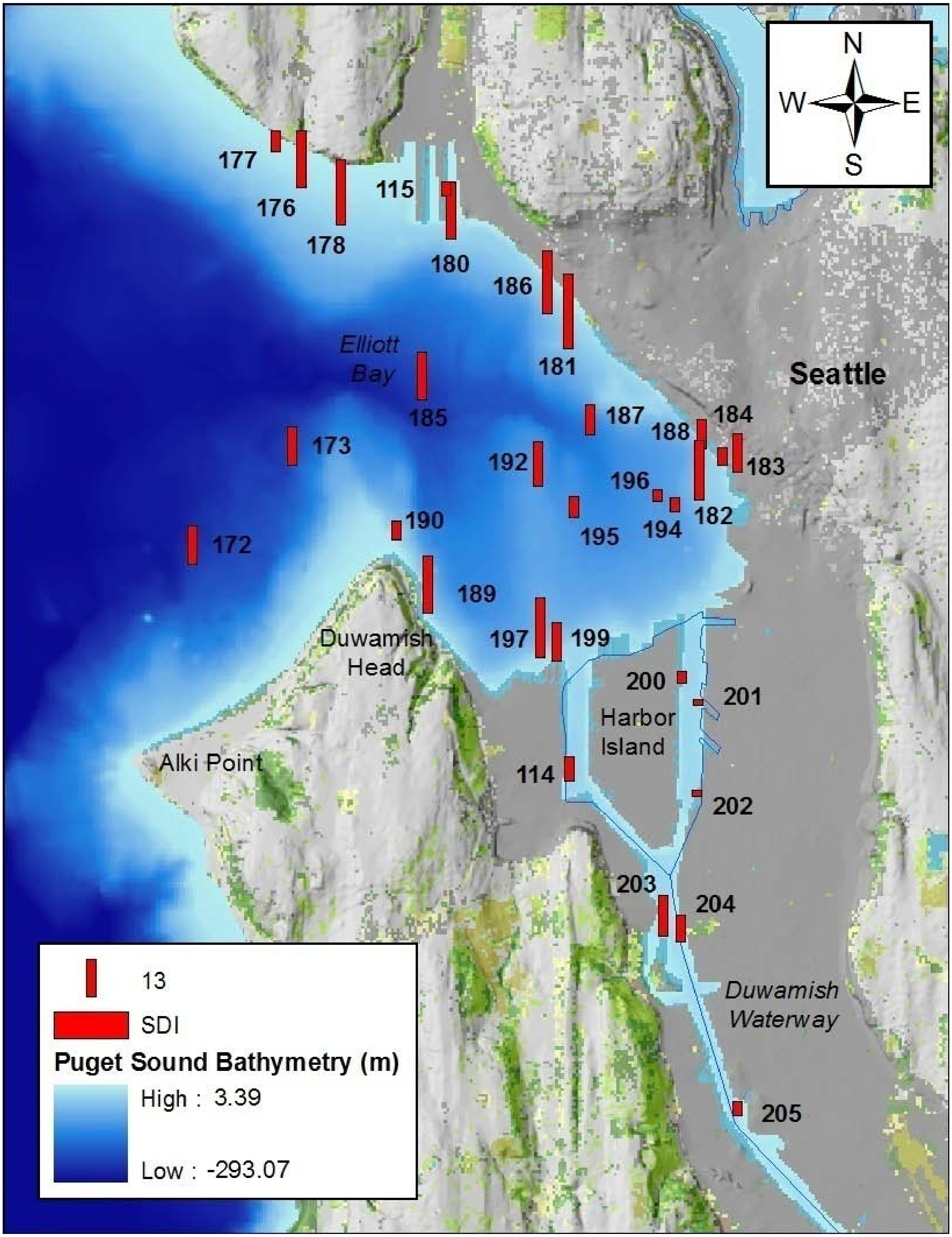

Figure 20. Swartz' dominance index (SDI) values for the benthos at 30 sediment stations sampled for the 2007 Urban Waters Initiative sediment study.

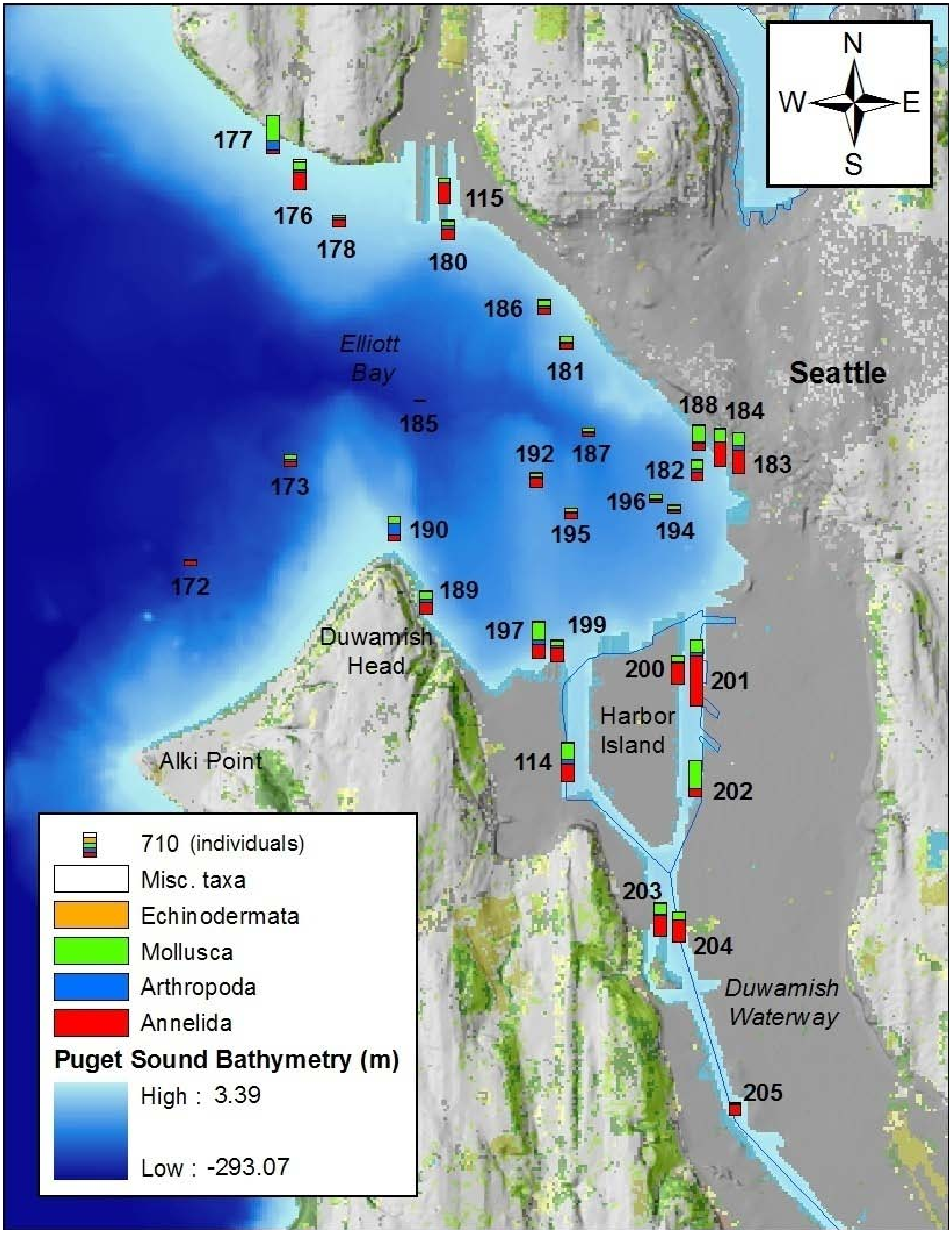

Figure 21. Abundance of each major benthic taxonomic group at 30 sediment stations sampled for the 2007 Urban Waters Initiative sediment study.

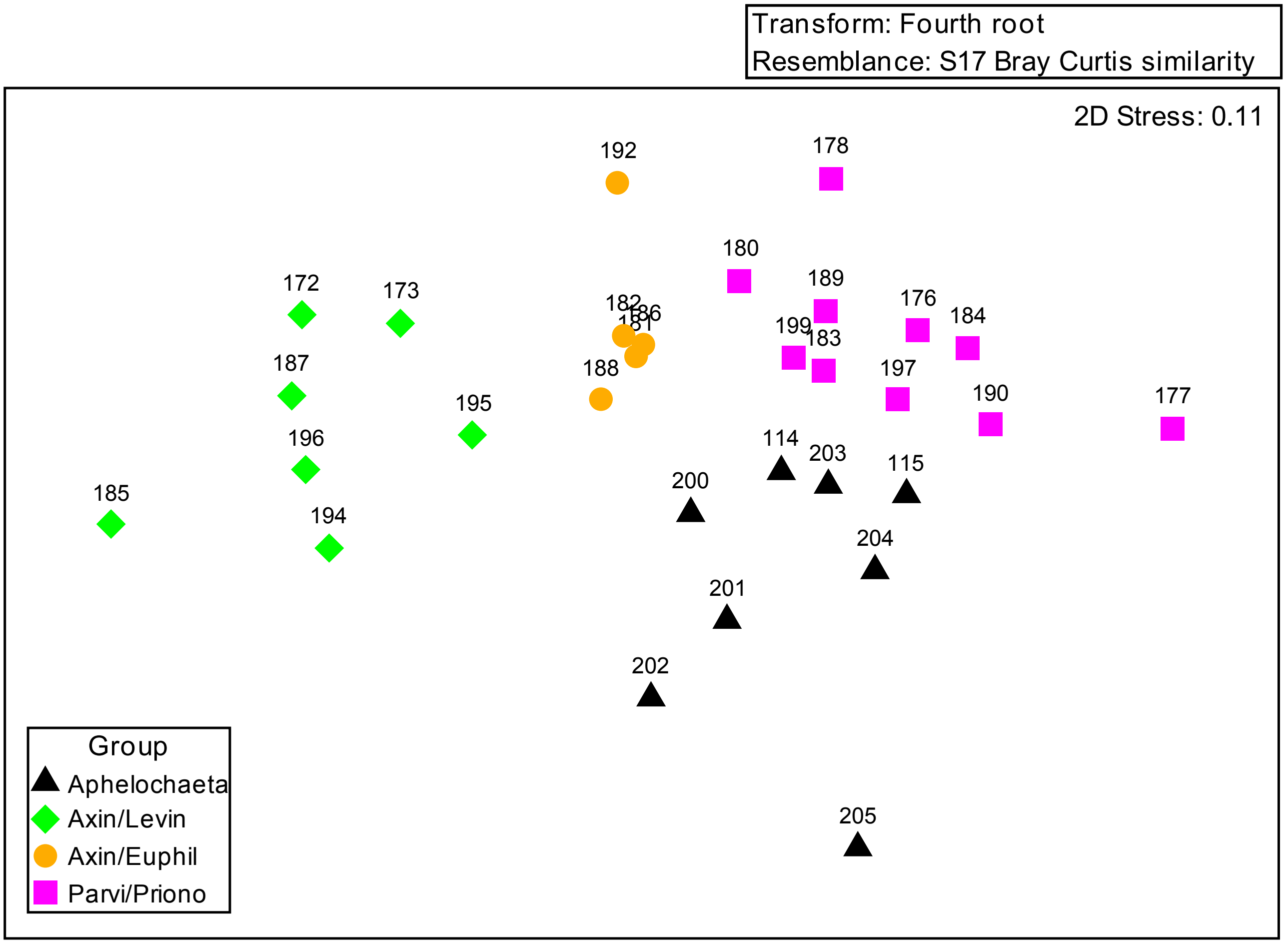

Figure 22. Multidimensional scaling (MDS) map of benthic invertebrate assemblages at 30 sediment stations sampled for the 2007 Urban Waters Initiative sediment study, based on Bray-Curtis similarities of 4th-root-transformed species abundances (all species included). Degree of similarity between assemblages is depicted by relative distance in this two-dimensional map. Assemblages are labeled with the dominant taxa on which they were based (see text). The groups also had similar depth and sediment characteristics (see text). Station numbers are indicated above the symbols.

Assemblages from stations in the waterways and at Pier 90 were dominated by the stress-tolerant polychaete, *Aphelochaeta glandaria*. (See text, Figure 23.) Assemblages dominated by bivalve species *Axinopsida serricata* and the polychaetes *Levinsenia gracilis*, *Aricidea lopezi*, and *Cossura* spp. were from stations located in the outer and central inner portions of Elliott Bay. The other assemblage groups were from shallower stations around the rim of Elliott Bay (dominated by the bivalve *Parvilucina tenuisculpta* and the polychaete *Prionospio steenstrupi*) and in the eastern portion of the bay (dominated by the bivalve *Axinopsida serricata* and the ostracod *Euphilomedes producta*).

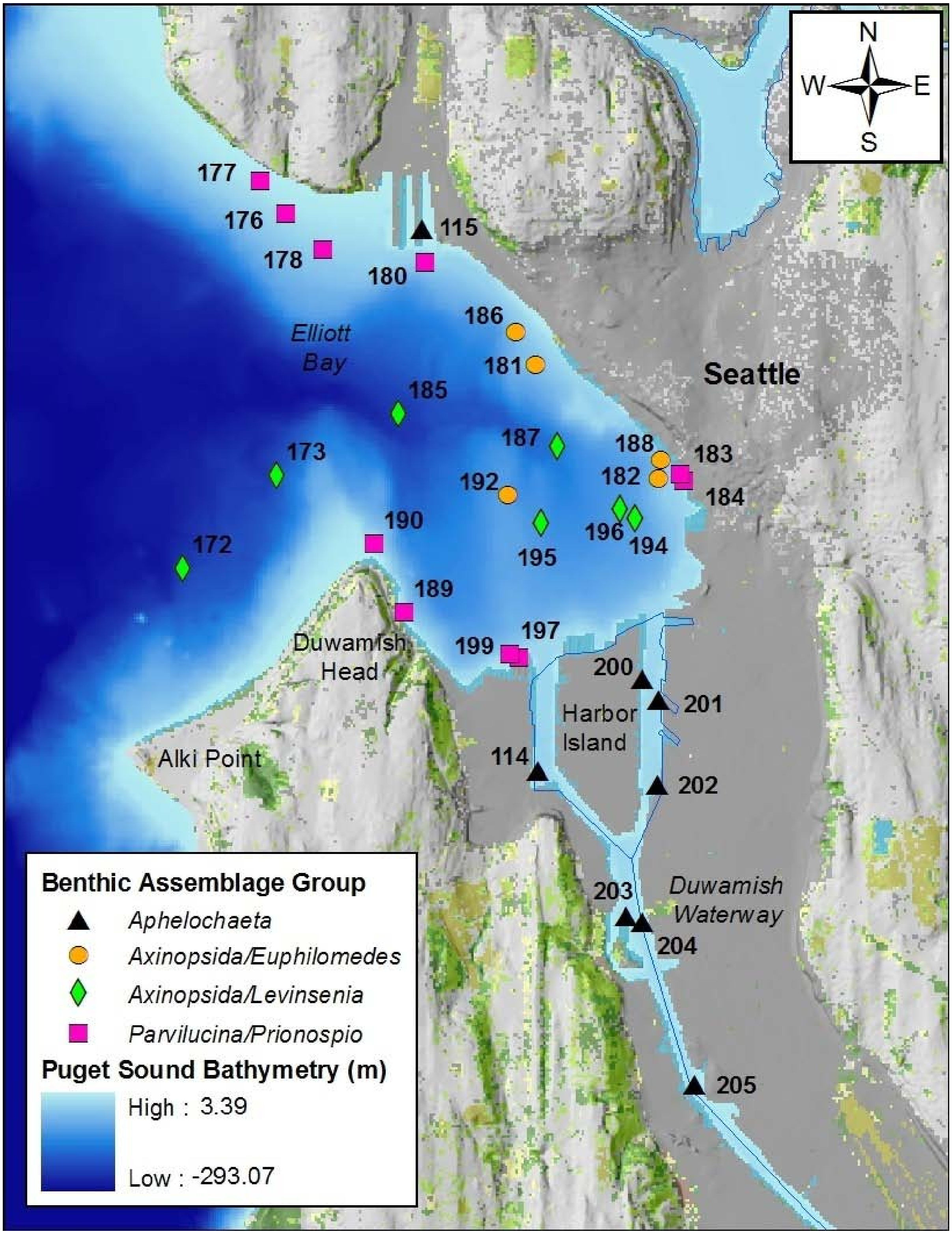

Figure 23. Benthic invertebrate assemblage groups at 30 sediment stations sampled for the 2007 Urban Waters Initiative sediment study. Groups are labeled with the dominant taxa (see text). These assemblage groups differed from each other primarily on dominant taxa, depth, and sediment characteristics. Station numbers are indicated beside the symbols.

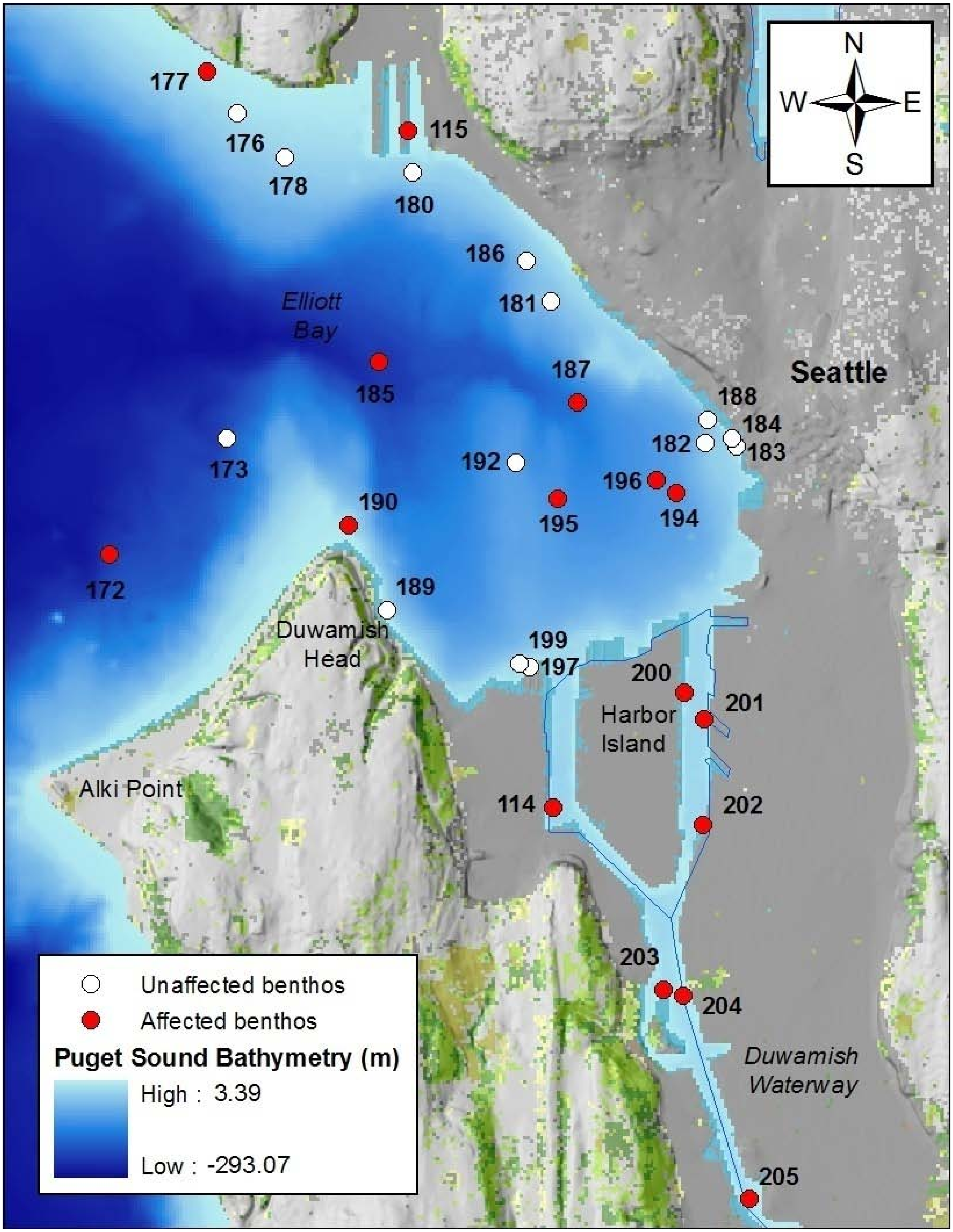

Figure 24. Spatial distribution of stations in the 2007 Urban Waters Initiative sediment study at which the benthos was classified as unaffected or adversely affected.

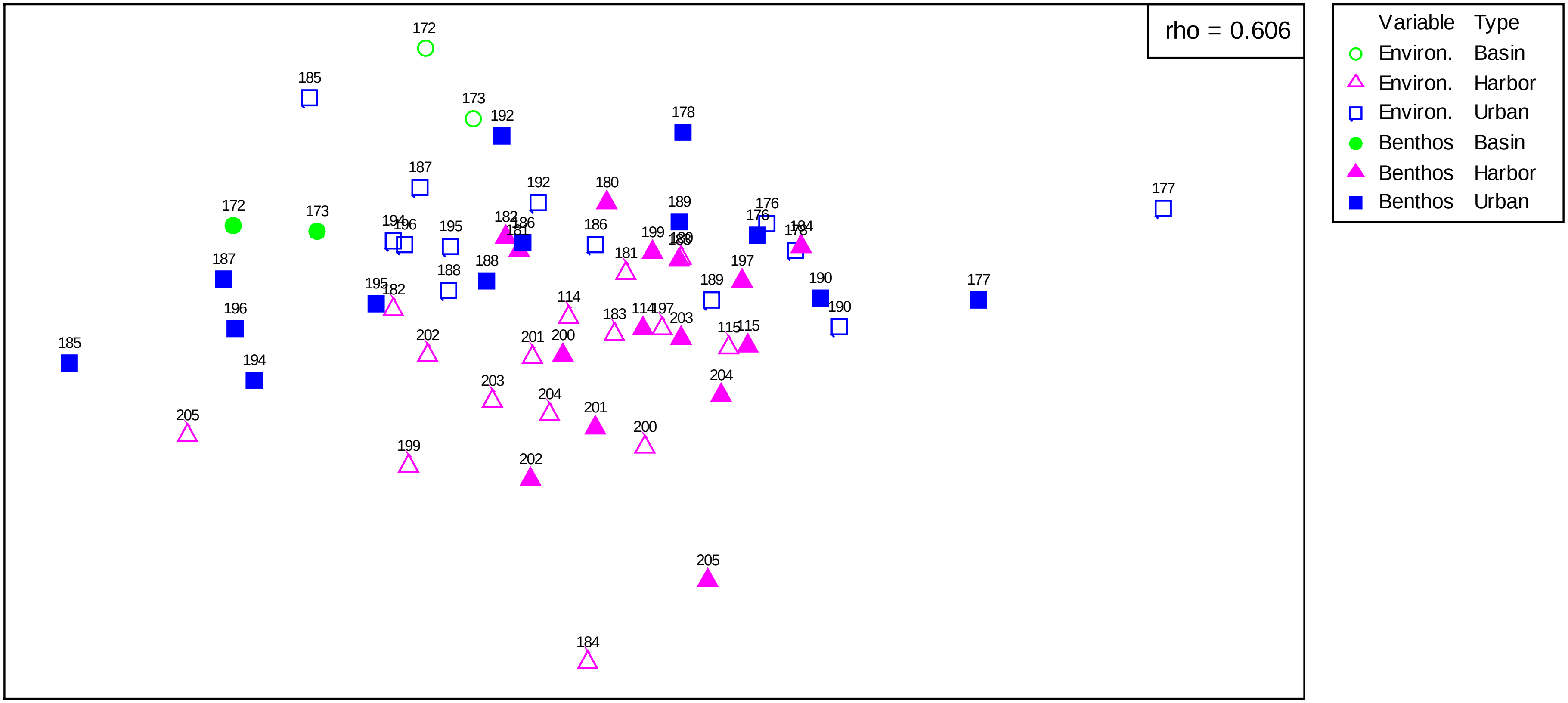

Figure 25. Multidimensional scaling (MDS) map of environmental variables overlaid on map of benthic invertebrate assemblages at 30 sediment stations sampled for the 2007 Urban Waters Initiative sediment study. The benthos map is based on Bray-Curtis similarities of 4^{th}-root-transformed species abundances (all species included). The map of the environmental variables is based on Euclidean distances of normalized environmental variables. Station numbers are indicated above the symbols. Relative distance indicates degree of similarity (among benthic assemblages or among environmental variables). Spearman rank correlation (rho) between the matrices of similarities and distances is 0.606.

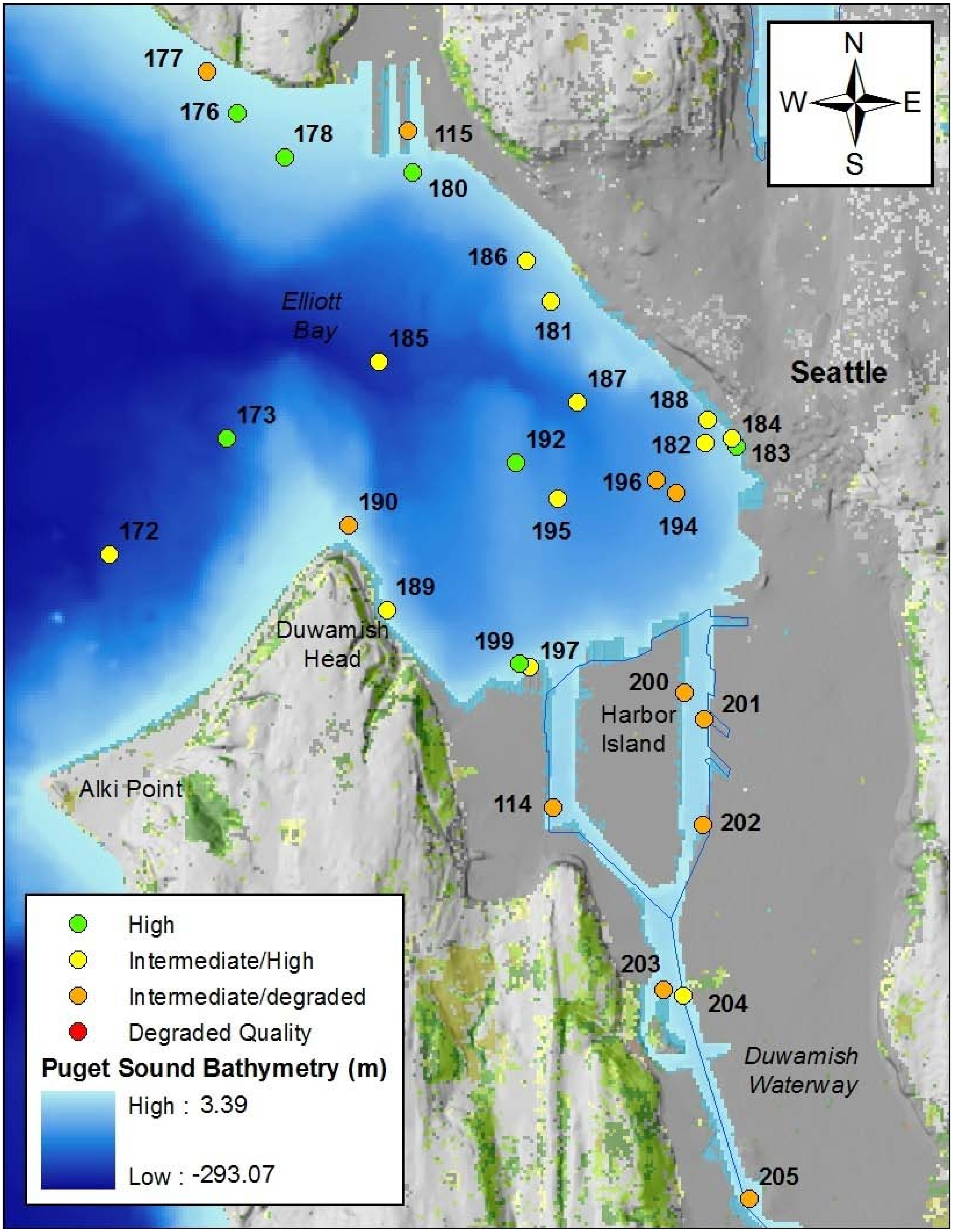

Figure 26. Spatial distribution of stations in the 2007 Urban Waters Initiative sediment study classified as one of four possible categories with the Sediment Quality Triad Index.

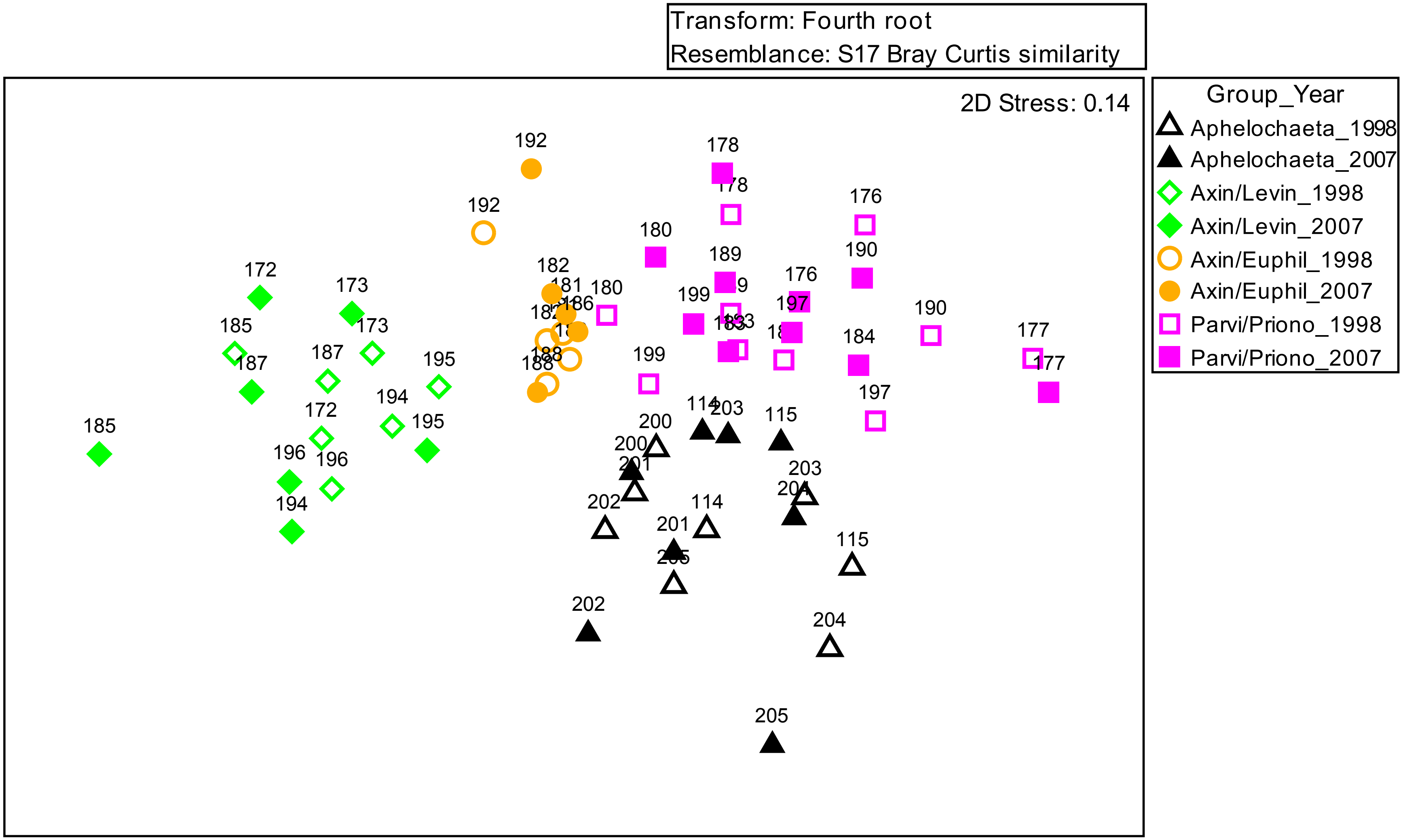

Figure 27. Multidimensional scaling (MDS) map of benthic invertebrate assemblages at 30 sediment stations sampled for the 2007 Urban Waters Initiative and for the 1998 PSAMP/NOAA survey, based on Bray-Curtis similarities of 4^{th}-root-transformed species abundances (all species included). Groups of assemblages are labeled with the dominant taxa (see text). Station numbers are indicated above the symbols. Degree of similarity or dissimilarity between assemblages is depicted by relative closeness or distance in this two-dimensional map.

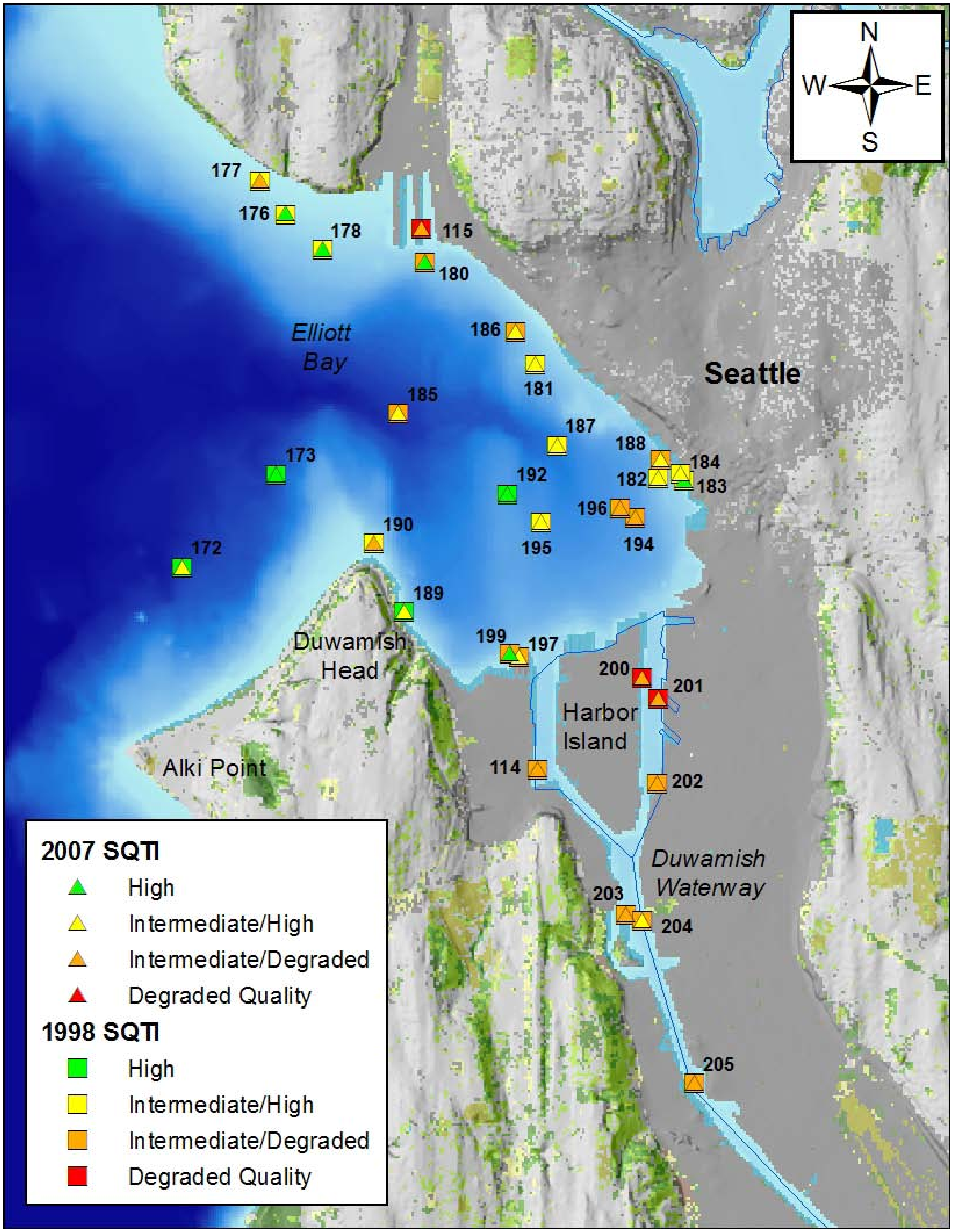

Figure 28. Classification of sediment quality at sampling stations in 2007 compared to 1998, according to the Sediment Quality Triad Index (SQTI).

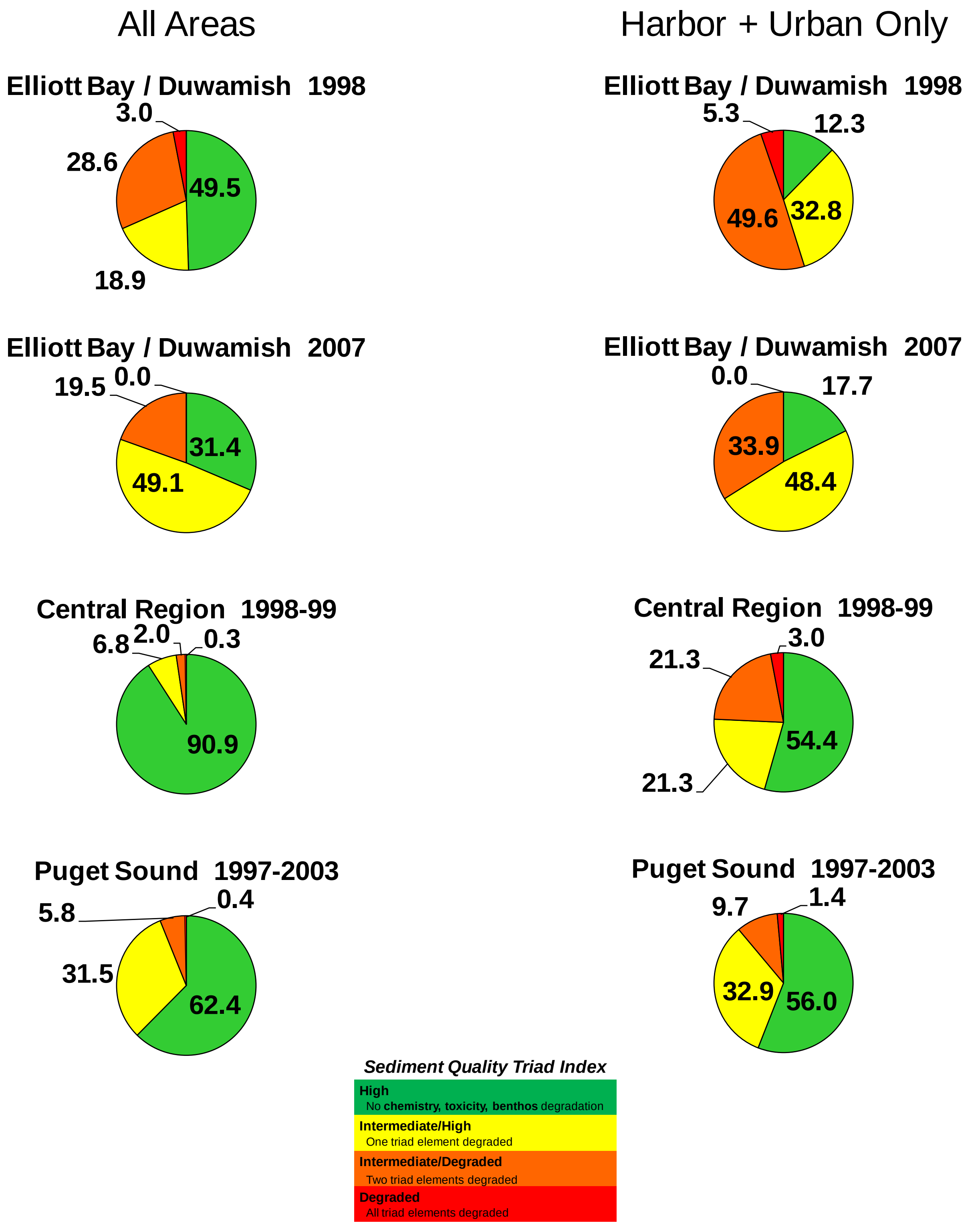

Figure 29. Spatial extent (% of area) of sediment quality by Sediment Quality Triad Index categories for the Elliott Bay/lower Duwamish area in 1998 and 2007, PSAMP Central Sound region (1998-1999), and all of Puget Sound (1997-2003). The pie charts on the left depict spatial extent for all PSAMP "strata" types. The pie charts on the right depict spatial extent for harbor and urban areas only.

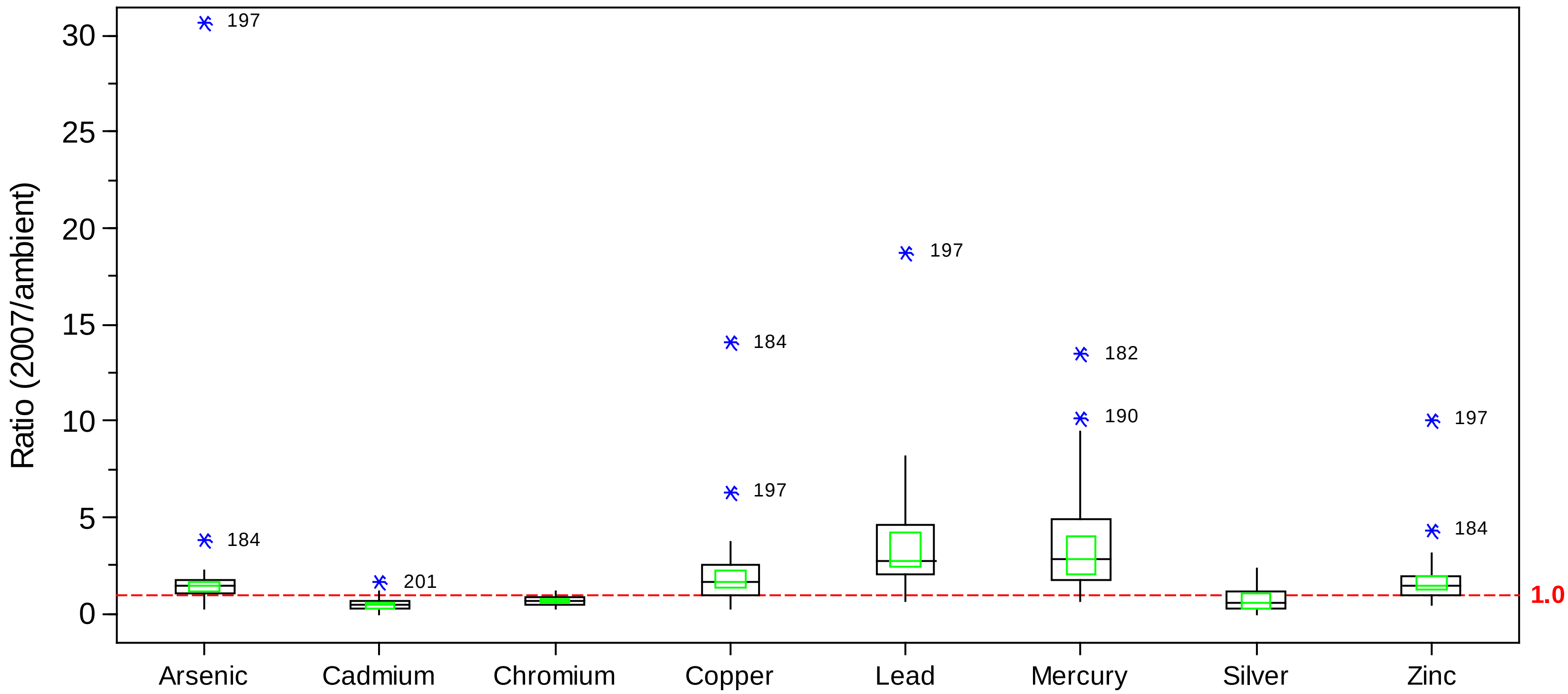

Figure 30. Comparison of 2007 Urban Waters Initiative sediment metals concentrations to 1997-2003 PSAMP ambient means. Outliers are labeled with station numbers.

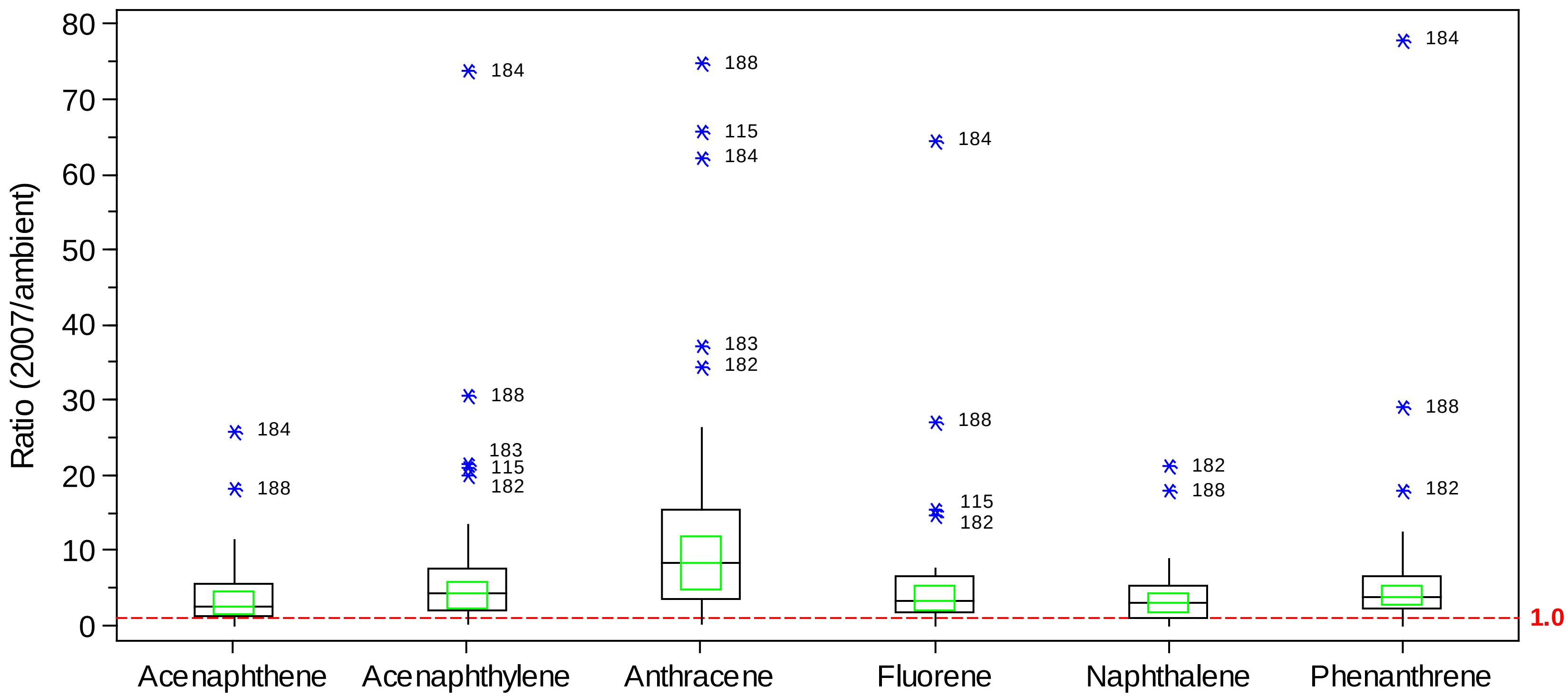

Figure 31. Comparison of 2007 Urban Waters Initiative sediment LPAH concentrations to 1997-2003 PSAMP ambient means. Outliers are labeled with station numbers.

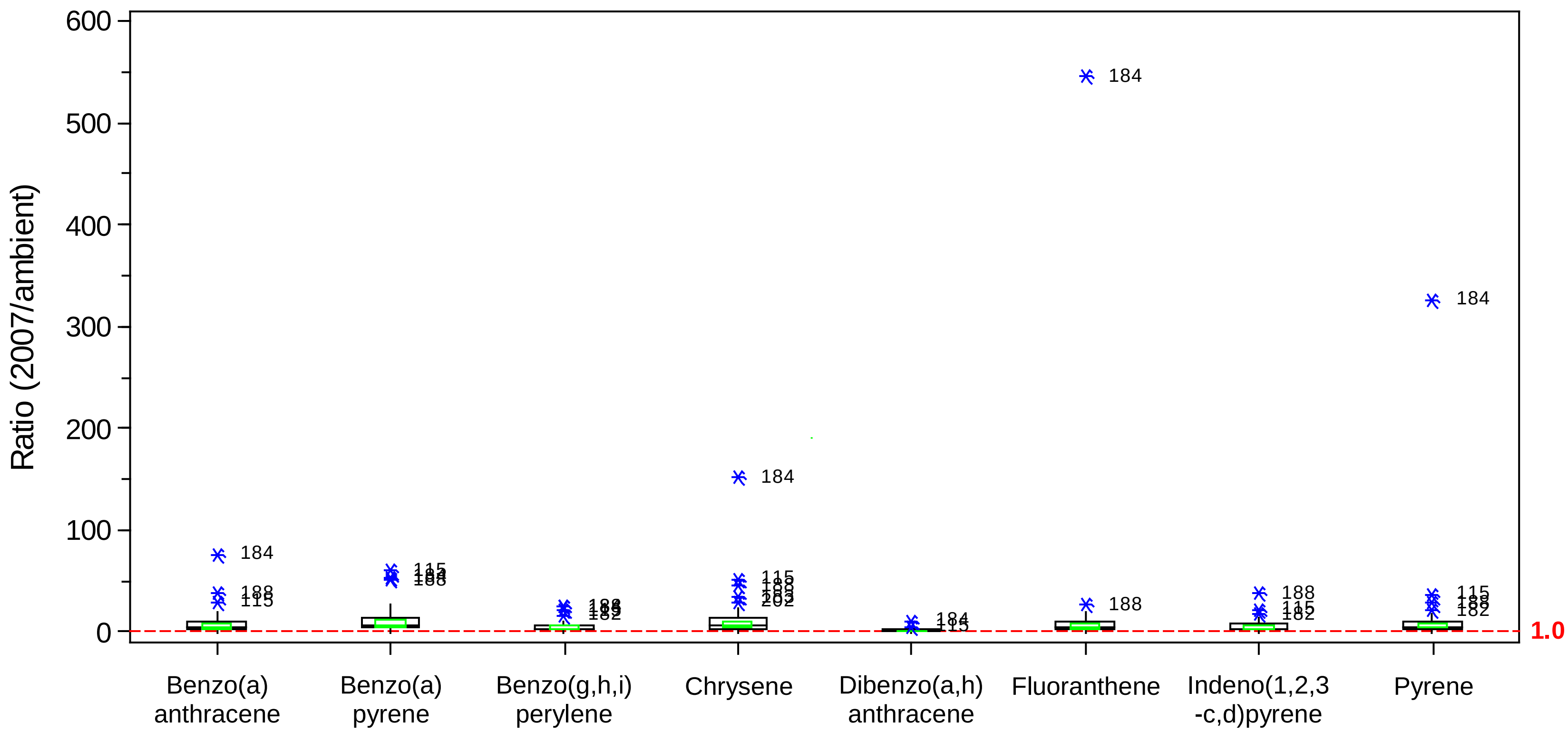

Figure 32. Comparison of 2007 Urban Waters Initiative sediment HPAH concentrations to 1997-2003 PSAMP ambient means. Outliers are labeled with station numbers.

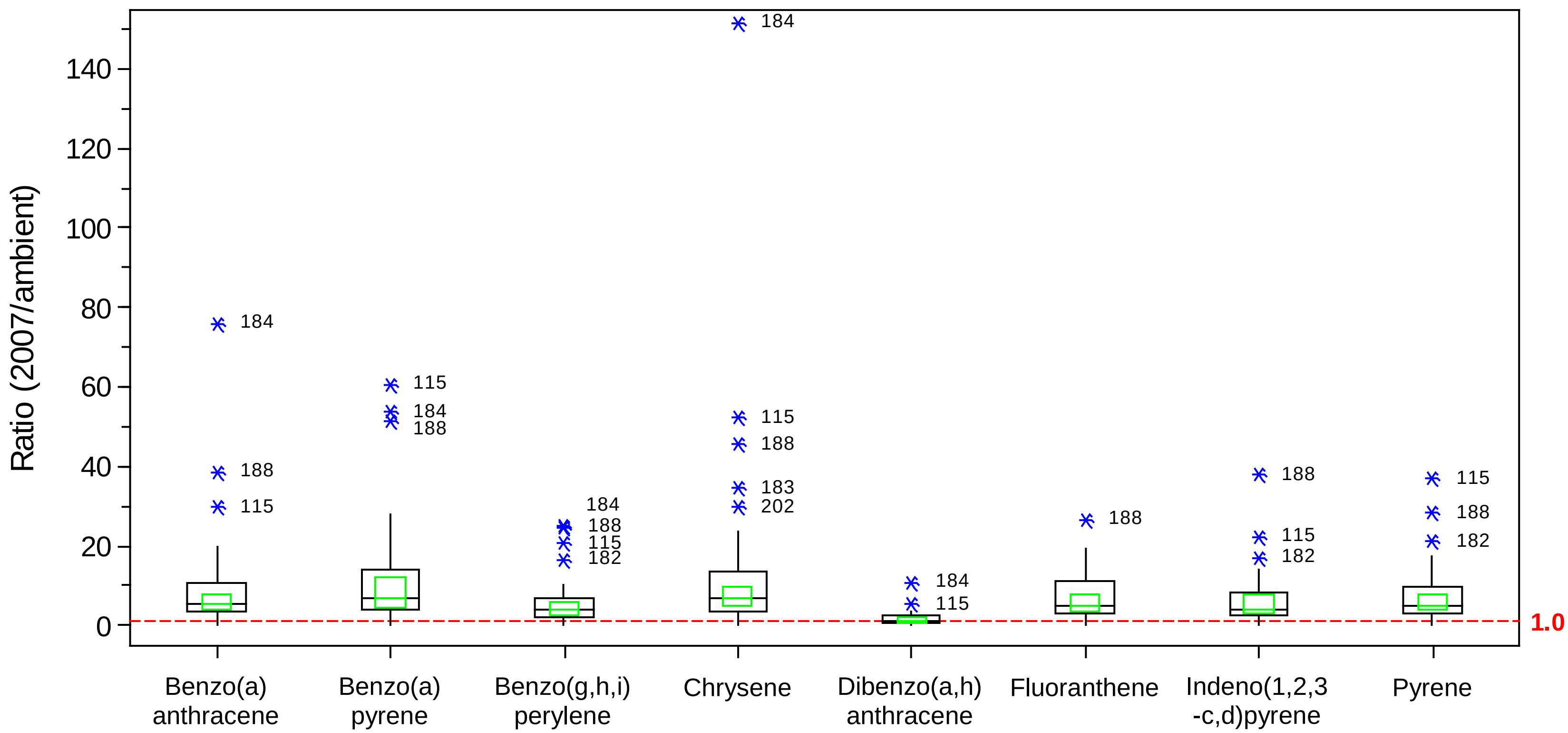

Figure 33. Comparison of 2007 Urban Waters Initiative sediment HPAH concentrations to 1997-2003 PSAMP ambient means, zoomed-in to smaller scale. Outliers are labeled with station numbers.

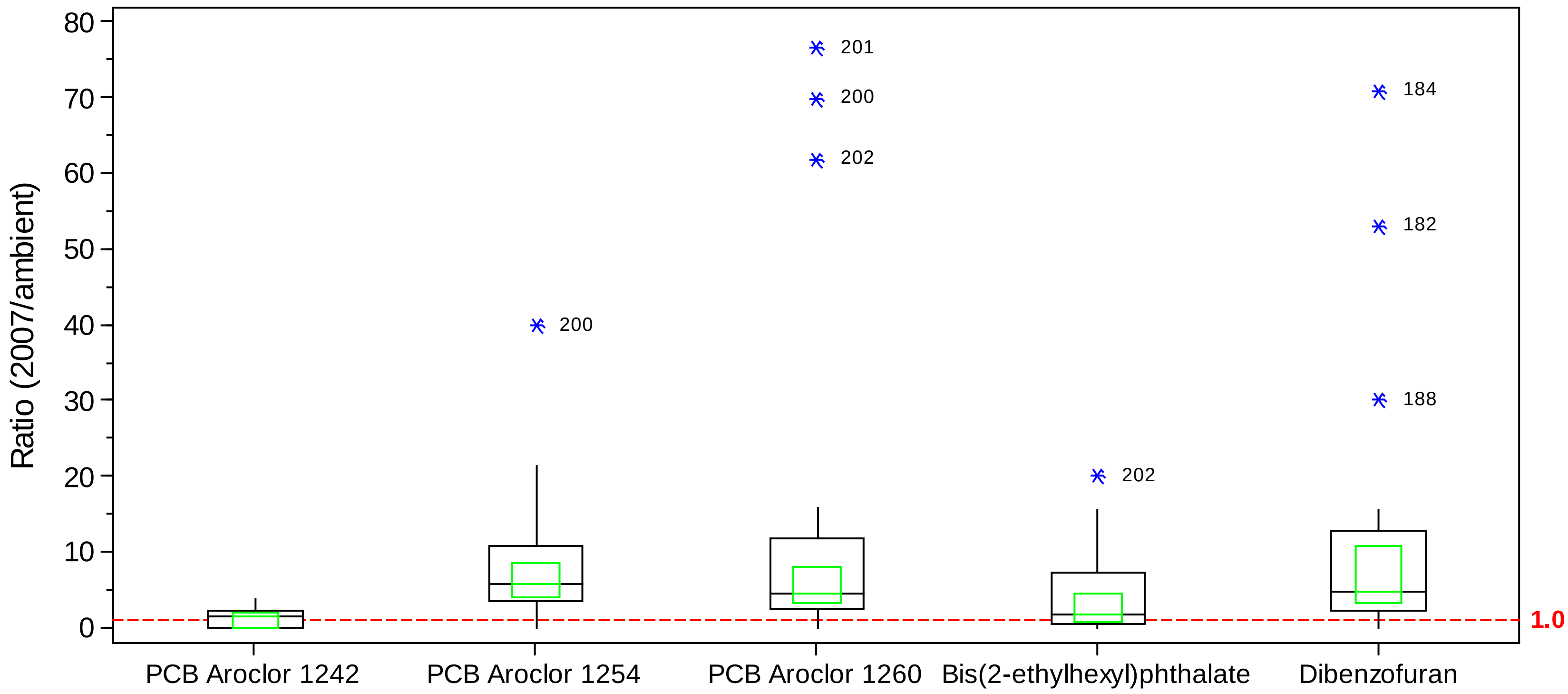

Figure 34. Comparison of 2007 Urban Waters Initiative sediment contaminant concentrations to 1997-2003 PSAMP ambient means. Outliers are labeled with station numbers.

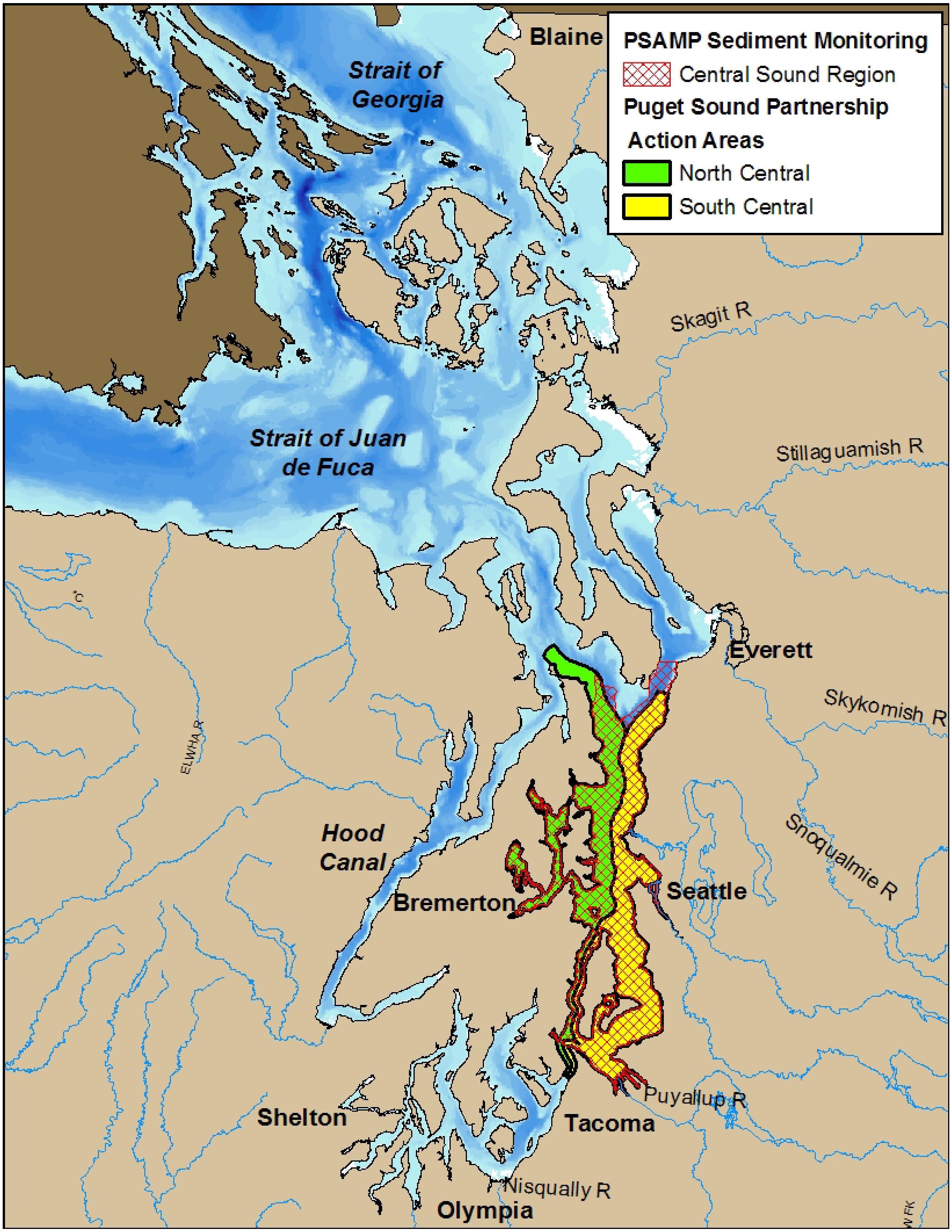

Figure 35. Overlap of PSAMP sediment monitoring Central Sound region and Puget Sound Partnership South Central and North Central Action Areas.

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Tables

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Table 1. Station numbers, names, "stratum" types, and sample weights for the 2007 Urban Waters Initiative sediment study.

Station Number	Location	"Stratum" Type (Multidensity Category)	Area represented (km^2)
114	West Waterway, Terminal 5	Harbor	0.36
115	Elliott Bay, east side of Pier 90	Harbor	0.44
172	West of Duwamish Head	Basin	5.58
173	Northwest of Duwamish Head	Basin	5.58
176	Elliott Bay, west of EB Marina	Urban	0.42
177	Magnolia Bluff	Urban	0.42
178	Elliott Bay, south of EB Marina	Urban	0.42
180	Elliott Bay, Piers 89-90	Harbor	0.44
181	Elliott Bay, west of Piers 70-71	Harbor	0.44
182	Elliott Bay, west of Pier 54	Harbor	0.11
183	Elliott Bay, Pier 54	Harbor	0.11
184	Elliott Bay, Pier 55	Harbor	0.11
185	North of Duwamish Head	Urban	1.04
186	Elliott Bay, west of Denny Way	Urban	1.04
187	Elliott Bay, west of Pier 59	Urban	1.04
188	Elliott Bay, west of Pier 57	Urban	1.04
189	Elliott Bay, east of Duwamish Head	Urban	0.93
190	Elliott Bay, Duwamish Head	Urban	0.93
192	Elliott Bay, central	Urban	0.93
194	Elliott Bay, west of Pier 48	Urban	0.97
195	Elliott Bay, west of Pier 48	Urban	0.97
196	Elliott Bay, west of Yesler Way	Urban	0.97
197	Elliott Bay, south	Harbor	0.36
199	Elliott Bay, south	Harbor	0.36
200	East Waterway, Terminal 18	Harbor	0.18
201	East Waterway, Pier 32	Harbor	0.18
202	East Waterway, south end	Harbor	0.18
203	Duwamish River, North	Harbor	0.25
204	Duwamish River, North	Harbor	0.25
205	Duwamish River, SW of Slip 2	Harbor	0.25
Overall	Sampling "stratum" type	Number of stations	Area (km^2)
	Basin	2	11.16
	Harbor	15	4.02
	Urban	13	11.13
	Total	30	26.32

Table 2. Chemical and physical parameters measured in sediments collected for the 2007 Urban Waters Initiative study.

Related Parameters
Grain Size
Total Organic Carbon

Priority Pollutant Metals
- Arsenic
- Cadmium
- Chromium
- Copper
- Lead
- Mercury
- Nickel
- Selenium
- Silver
- Zinc

Trace Elements
- Tin

Organics

Chlorinated Alkenes
- Hexachlorobutadiene

Chlorinated and Nitro-Substituted Phenols
- Pentachlorophenol

Chlorinated Aromatic Compounds
- 1,2,4-Trichlorobenzene
- 1,2-Dichlorobenzene
- 1,3-Dichlorobenzene
- 1,4-Dichlorobenzene
- 2-Chloronaphthalene
- Hexachlorobenzene

Chlorinated Pesticides
- 2,4'-DDD
- 2,4'-DDE
- 2,4'-DDT
- 4,4'-DDD
- 4,4'-DDE
- 4,4'-DDT
- Aldrin

Chlorinated Pesticides (continued)
- Cis-Chlordane
- Dieldrin
- Endosulfan I
- Endosulfan II
- Endosulfan Sulfate
- Endrin
- Endrin Aldehyde
- Endrin Ketone
- Gamma-BHC (Lindane)
- Heptachlor
- Heptachlor Epoxide
- Mirex
- Oxychlordane
- Toxaphene
- Trans-Chlordane (Gamma)

Polynuclear Aromatic Hydrocarbons
LPAH
- 1,6,7-Trimethylnaphthalene
- 1-Methylnaphthalene
- 1-Methylphenanthrene
- 2,6-Dimethylnaphthalene
- 2-Methylnaphthalene
- Acenaphthene
- Acenaphthylene
- Anthracene
- Biphenyl
- Dibenzothiophene
- Fluorene
- Naphthalene
- Phenanthrene
- Retene

HPAH
- Benzo(a)anthracene
- Benzo(a)pyrene
- Benzo(b)fluoranthene
- Benzo(e)pyrene
- Benzo(g,h,i)perylene
- Benzo(k)fluoranthene
- Chrysene
- Dibenzo(a,h)anthracene

HPAH (continued)
- Fluoranthene
- Indeno(1,2,3-c,d)pyrene
- Perylene
- Pyrene

Miscellaneous Extractable Compounds
- Benzoic Acid
- Benzyl Alcohol
- Beta-coprostanol
- Carbazole
- Cholesterol
- Dibenzofuran
- Isophorone

Organonitrogen Compounds
- Caffeine
- N-Nitrosodiphenylamine

Phenols
- 2,4-Dimethylphenol
- 2-Methylphenol
- 4-Methylphenol
- Phenol
- P-nonylphenol

Phthalate Esters
- Bis(2-Ethylhexyl) Phthalate
- Butylbenzylphthalate
- Diethylphthalate
- Dimethylphthalate
- Di-N-Butylphthalate
- Di-N-Octyl Phthalate

Polychlorinated Biphenyls (PCB)
PCB Congeners
- PCB Congener 8
- PCB Congener 18
- PCB Congener 28
- PCB Congener 44
- PCB Congener 52
- PCB Congener 66

PCB Congeners (continued)
- PCB Congener 77
- PCB Congener 101
- PCB Congener 105
- PCB Congener 118
- PCB Congener 126
- PCB Congener 128
- PCB Congener 138
- PCB Congener 153
- PCB Congener 169
- PCB Congener 170
- PCB Congener 180
- PCB Congener 187
- PCB Congener 195
- PCB Congener 206
- PCB Congener 209

PCB Aroclors
- PCB Aroclor 1016
- PCB Aroclor 1221
- PCB Aroclor 1232
- PCB Aroclor 1242
- PCB Aroclor 1248
- PCB Aroclor 1254
- PCB Aroclor 1260
- PCB Aroclor 1262
- PCB Aroclor 1268

Polybrominated Diphenylethers (PBDEs)
PBDE Congeners
- PBDE- 47
- PBDE- 66
- PBDE- 71
- PBDE- 99
- PBDE-100
- PBDE-138
- PBDE-153
- PBDE-154
- PBDE-183
- PBDE-184
- PBDE-191
- PBDE-209

Table 3. Laboratory analytical methods and reporting limits for the 2007 Urban Waters Initiative sediment study.

Parameter	Extraction Method	Clean-Up Method	Analysis Method	Technique/ Instrument	Required Reporting Limit
Grain Size	N/A	N/A	PSEP, 1986	Sieve-pipette method	>2000 to <3.9 microns
Total Organic Carbon	Drying sediment material	N/A	PSEP, 1986	Non-dispersive infrared detector	0.1%
Metals except mercury	EPA 3050B	N/A	EPA 200.8	ICP-MS	0.1 mg/kg dry weight (0.2 for Sn, 0.5 for Cr and Se, 5.0 for Zn)
Mercury	EPA 245.5	N/A	EPA 245.5	CVAA	0.005 mg/kg dry weight
Base/Neutral/Acid Organic Compounds (BNA)	EPA 3541	No cleanup performed	EPA 8270	Capillary GC/MS	20 µg/kg dry weight (for ≥ 50% solids)
Polynuclear Aromatic Hydrocarbons (PAH)	EPA 3545	EPA 3630C	EPA 8270 with isotopic dilution	Capillary GC/MS, GC/MS-SIM	0.5-2.0 µg/kg dry weight
Chlorinated Pesticides	EPA 3545B	EPA 3620 and EPA 3665	EPA 8081 and EPA 8082	GC-DDC/ECD	1 µg/kg dry weight (20 for Toxaphene)
PCB Aroclors	EPA 3545B	EPA 3620 and EPA 3665	EPA 8081 and EPA 8082	GC-DDC/ECD	10 µg/kg dry weight
PCB Congeners	EPA 3545B	EPA 3620 and EPA 3665	EPA 8081 and EPA 8082	GC-DDC/ECD	1 µg/kg dry weight
PBDE	EPA 3545B	EPA 3620, EPA 3660 and EPA 3665	EPA 8270 with isotopic dilution	Capillary GC/MS, GC/MS-SIM	1 µg/kg dry weight

Table 4. Benthic infaunal indices calculated to characterize the infaunal invertebrate assemblages identified for the 2007 Urban Waters Initiative sediment study.

Infaunal index	Definition	Calculation
Total Abundance	A measure of density equal to the total number of organisms per sample area.	Sum of all organisms counted in each sample.
Major Taxa Abundance	A measure of density equal to the total number of organisms in each major taxa group (Annelida, Mollusca, Echinodermata, Arthropoda, Miscellaneous Taxa) per sample area.	Sum of all organisms counted in each major taxa group per sample.
Taxa Richness	Total number of taxa (taxa = lowest level of identification for each organism) per sample area.	Sum of all taxa identified in each sample.
Pielou's Evenness (J') (Pielou, 1966)	Relates the observed diversity in benthic assemblages as a proportion of the maximum possible diversity for the data set (the equitability (evenness) of the distribution of individuals among species).	$J' = H'/\log S$, where $H' = -\sum_{i=1}^{S} p_i \log p_i$, where p_i = the proportion of the assemblage that belongs to the i^{th} species ($p_i = n_i/N$, where n_i = the number of individuals in the i^{th} species and N= total number of individuals) and S= the total number of species (H' is the Shannon-Wiener diversity index).
Swartz' Dominance Index (SDI) (Swartz et al., 1982)	The minimum number of taxa whose combined abundance accounted for 75 percent of the total abundance in each sample.	Sum of the minimum number of taxa whose combined abundance accounted for 75 percent of the total abundance in each sample.

Table 5. Sediment types characterizing 30 samples collected for the 2007 Urban Waters Initiative sediment study.

Sediment type	Percent sand	Percent silt+clay	Range of percent gravel for sediment type	No. of stations with this sediment type	Area (km^2)	Percent of total study area
Sand	> 80	< 20	0.1 - 1.5	6	2.7	10.1
Silty sand	60 to 80	20 to >40	0.1 - 25.8	5	3.0	11.5
Mixed	20 to < 60	40 to 80	0.3 - 2.7	14	11.0	41.9
Silt + clay	< 20	> 80	0.0 - 0.2	5	9.6	36.5

Table 6. Summary statistics for TOC concentrations for sediment monitoring "strata" types in the 2007 Urban Waters Initiative sediment study.

"Stratum" type	N	Minimum	Maximum	Mean	Standard deviation	Median
Entire study area	30	0.2	5.8	1.7	1.2	1.7
Basin	2	1.9	2.3	2.1	0.2	2.1
Harbor	15	0.5	5.8	2.0	1.4	1.6
Urban	13	0.16	2.44	1.2	0.9	0.9

Table 7. Summary statistics for concentrations of metals and organic compounds from sediments collected for the 2007 Urban Waters Initiative sediment study. RL = reporting limit; ND = nondetect; CDF = cumulative distribution function.

Parameter Code	N	# Detects	# ND	# ND > highest detect	Mean*	Std. Dev.*	Median*	Minimum*	Maximum (detected)	Max RL (ND)	Notes (see bottom)	50th %-ile estimated from CDF (ND=0)	90th %-ile estimated from CDF (ND=0)
Priority Pollutant Metals (mg/kg dry weight)													
Arsenic	30	30	0	0	14.69	32.59	9.07	1.74	186		1	8.87	10.54
Cadmium	30	25	5	0	0.2769	0.1882	0.245	0.0585	0.91	0.1		0.25	0.4
Chromium	30	30	0	0	30.02	9.23	28.7	14.1	49.9		1	37.0	41.8
Copper	30	30	0	0	56.1	63.7	41.3	5.7	352		1	38.5	66.9
Lead	30	30	0	0	39.2	34.58	27.7	6.75	188		1	26.5	48.6
Mercury	30	30	0	0	0.251	0.1992	0.1785	0.044	0.853		1	0.167	0.507
Nickel	30	30	0	0	24.19	10.99	22	5.77	64		1	31.2	35.8
Selenium	30	11	19	0	0.439	0.193	0.397	0.1712	0.99	0.5		0.65	0.91
Silver	30	26	4	0	0.4345	0.3539	0.305	0.0479	1.31	0.1		0.29	0.79
Zinc	30	30	0	0	106.1	100.3	84.4	27	577		1	83.3	109.4
Trace Elements													
Tin	30	30	0	0	8.06	23.27	2.84	0.48	130		1	2.6	6
Organic Compounds (µg/kg dry weight)													
Chlorinated Alkanes													
Hexachlorobutadiene	30	0	30	30						72	2		
Chlorinated and Nitro-substituted Phenols													
Pentachlorophenol	30	0	30	30						289	2		
Chlorinated Aromatic Compounds													
1,2,4-Trichlorobenzene	30	2	28	17					12	72	3,5		
1,2-Dichlorobenzene	30	0	30	30						72	2		
1,3-Dichlorobenzene	30	1	29	29						72	3,4		
1,4-Dichlorobenzene	30	15	15	0	15.65	25.53	7.82	3.2	137	72			11.47
2-Chloronaphthalene	30	0	30	30						5.3	2		
Hexachlorobenzene	30	0	30	30						72	2		

Parameter Code	N	# Detects	# ND	# ND > highest detect	Mean*	Std. Dev.*	Median*	Minimum*	Maximum (detected)	Max RL (ND)	Notes (see bottom)	50th %-ile estimated from CDF (ND=0)	90th %-ile estimated from CDF (ND=0)
Chlorinated Pesticides													
2,4'-DDD	30	6	24	0	0.3066	0.4943	0.1202	0.0183	2.4	0.53			0.54
2,4'-DDE	30	0	30	30						2.5	2		
2,4'-DDT	30	1	29	0					0.64	0.53	5		
4,4'-DDD	30	24	6	0	2.126	2.092	1.45	0.244	7.9	0.53			4.26
4,4'-DDE	30	23	7	0	1.236	0.947	0.945	0.289	3.8	0.86		0.65	1.7
4,4'-DDT	30	25	5	0	15.7	73.4	1.3	0.1	404	0.53		0.87	3.33
Aldrin	30	0	30	30						0.53	2		
Cis-chlordane (Alpha-chlordane)	30	3	27	0	0.2778	0.131	0.2365	0.1315	0.75	0.53			
Dieldrin	30	0	30	30						0.53	2		
Endosulfan I	30	0	30	30						0.53	2		
Endosulfan II	30	0	30	30						1.6	2		
Endosulfan Sulfate	30	1	29	1					0.67	0.89	3,5		
Endrin	30	0	30	30						0.53	2		
Endrin Aldehyde	30	0	30	30						0.53	2		
Endrin Ketone	30	0	30	30						35	2		
Gamma-BHC (Lindane)	30	0	30	30						0.53	2		
Heptachlor	30	0	30	30						0.53	2		
Heptachlor Epoxide	30	0	30	30						0.53	2		
Hexachlorobenzene	30	1	29	0					1.1	0.53	5		0.58
Mirex	30	0	30	30						0.53	2		
Oxychlordane	30	0	30	30						0.53	2		
Toxaphene	30	0	30	30						107	2		
Trans-Chlordane (Gamma)	30	6	24	1	0.3936	0.1987	0.3362	0.1719	0.94	1.6	3		

Parameter Code	N	# Detects	# ND	# ND > highest detect	Mean*	Std. Dev.*	Median*	Minimum*	Maximum (detected)	Max RL (ND)	Notes (see bottom)	50th %-ile estimated from CDF (ND=0)	90th %-ile estimated from CDF (ND=0)
Polynuclear Aromatic Hydrocarbons (PAH)													
LPAH													
1,6,7-Trimethylnaphthalene	30	30	0	0	15.61	9.69	13.5	4.3	50		1	15.6	20
1-Methylnaphthalene	30	30	0	0	40.37	40.15	30.5	1.6	186		1	30.9	55.8
2,6-Dimethylnaphthalene	30	30	0	0	58.94	50.03	51.5	6.5	229		1	52.4	77.7
2-Methylnaphthalene	30	30	0	0	66.6	67.2	47	2.6	307		1	45.5	85.8
2-Methylphenanthrene	30	30	0	0	95.3	192.3	53.5	1.1	1070		1	53.1	82.7
Acenaphthene	30	30	0	0	55.4	68.6	33	1.1	319		1	11.7	81.6
Acenaphthylene	30	30	0	0	149.6	240.5	72.5	4.3	1240		1	27.9	148.4
Anthracene	30	30	0	0	271.9	352.3	147.5	3.5	1320		1	42.9	272.7
Biphenyl	30	28	2	0	27.44	29.54	18.5	2.81	114	9.6		14.5	34.4
Dibenzothiophene	30	30	0	0	51.2	135.8	17	0.6	749		1	12.4	30.3
Fluorene	30	30	0	0	103.1	184	50	1.9	970		1	22.8	111.1
Naphthalene	30	28	2	0	192.4	212.4	136	13.1	938	32		67.2	300.7
Phenanthrene	30	30	0	0	467	865	228	5	4660		1	116.3	470.3
Retene	30	30	0	0	154.9	160.2	103.5	0.5	780		1	157.4	300.0
HPAH													
Benzo(a)anthracene	30	30	0	0	279.1	391	147	3.4	1970		1	63.9	235.9
Benzo(a)pyrene	30	30	0	0	406.1	493.6	216	4.9	1890		1	95.7	435.8
Benzo(b)fluoranthene	29	29	0	0	626	937	280	9	4680		1	268.6	1237.8
Benzo[e]pyrene	29	29	0	0	251.2	270.6	152	4.6	1110		1	69.8	294.3
Benzo(g,h,i)perylene	30	30	0	0	238.4	256.4	147	4.3	947		1	95.6	262.1
Benzo(k)fluoranthene	30	30	0	0	226.7	308.5	110.5	3.7	1450		1	49.7	215.7
Chrysene	30	30	0	0	595	1054	260	5	5570		1	99.5	371.4
Dibenzo(a,h)anthracene	30	30	0	0	52.7	57	34.5	1	298		1	17.8	68.1
Fluoranthene	30	30	0	0	1870	7311	387	10	40500		1	164.3	584.9

Parameter Code	N	# Detects	# ND	# ND > highest detect	Mean*	Std. Dev.*	Median*	Minimum*	Maximum (detected)	Max RL (ND)	Notes (see bottom)	50th %-ile estimated from CDF (ND=0)	90th %-ile estimated from CDF (ND=0)
HPAH (continued)													
Indeno(1,2,3-c,d)pyrene	30	30	0	0	232.8	267	133.5	4	1300		1	92.5	298.4
Perylene	29	29	0	0	223.9	157.4	204	7.2	556		1	149.6	352.4
Pyrene	30	30	0	0	1454	4587	403	10	25500		1	187.9	724.2
Miscellaneous Extractable Compounds													
Beta-coprostanol	30	19	11	0	980	1569	291	48	6150	1280		408.4	860.8
Carbazole	29	28	1	0	45.84	49.98	26	2.74	201	3		9.2	53.1
Cholesterol	30	30	0	0	7976	9246	3285	784	39600		1	3436.9	14238
Dibenzofuran	30	29	1	0	125.8	181.9	57	3.2	831	11		21.9	150.8
Isophorone	30	21	9	0	55.38	52.07	28	6.85	164	97		42.4	128.8
Organonitrogen Compounds													
Caffeine	30	0	30	30						72	2		
N-Nitrosodiphenylamine	30	0	30	30						144	2		
Phenols													
P-nonylphenol	30	0	30	30						144	2		
Phthalate Esters													
Bis(2-Ethylhexyl) Phthalate	30	24	6	0	481	623	181	11	2150	65			584.4
Butylbenzylphthalate	30	2	28	8					86	143	3,5		
Diethylphthalate	30	0	30	30						144	2		
Dimethylphthalate	30	2	28	0					262	144	5		
Di-N-Butylphthalate	30	6	24	0	47	136.7	7.2	2.1	610	286			
Di-N-Octyl Phthalate	30	0	30	30						144	2		
Polychlorinated Biphenyls (PCB)													
PCB Congeners													
PCB Congener 8	30	14	16	0	0.5387	0.2951	0.4269	0.2022	1.3	0.53			0.68
PCB Congener 18	30	8	22	0	0.4279	0.4225	0.2631	0.0714	1.8	0.53			
PCB Congener 28	30	20	10	0	1.144	0.807	0.935	0.303	3.3	0.53		0.67	1.44

Parameter Code	N	# Detects	# ND	# ND > highest detect	Mean*	Std. Dev.*	Median*	Minimum*	Maximum (detected)	Max RL (ND)	Notes (see bottom)	50th %-ile estimated from CDF (ND=0)	90th %-ile estimated from CDF (ND=0)
PCB Congeners (cont.)													
PCB Congener 44	30	22	8	0	1.13	0.96	0.895	0.239	4.7	0.53		0.54	1.38
PCB Congener 52	30	26	4	0	2.093	2.247	1.5	0.344	11	0.53		0.87	2.21
PCB Congener 66	30	25	5	0	1.618	1.224	1.25	0.31	5	0.53		0.74	2.40
PCB Congener 77	30	25	5	0	1.898	2.196	0.995	0.196	8.9	0.53		0.68	2.82
PCB Congener 101	30	27	3	0	4.482	4.195	3.15	0.607	17	0.52		2.15	6.22
PCB Congener 105	30	26	4	0	1.657	1.162	1.2	0.405	4.6	0.53		0.83	2.45
PCB Congener 118	30	27	3	0	3.626	2.571	2.8	0.779	11	0.52		2.27	5.67
PCB Congener 126	30	1	29	23					0.49	0.53	3,5		
PCB Congener 128	30	23	7	0	1.142	0.922	0.835	0.227	3.6	0.53		0.58	1.74
PCB Congener 138	30	27	3	0	7.62	8.61	4.4	0.68	31	0.52		3.07	11.35
PCB Congener 153	30	28	2	0	9.97	14.38	4.15	0.51	55	0.52		2.90	11.56
PCB Congener 169	30	0	30	30						0.53	2		
PCB Congener 170	30	26	4	0	3.638	5.438	1.5	0.237	21	0.53		0.76	4.69
PCB Congener 180	30	27	3	0	6.98	10.84	2.65	0.34	42	0.53		1.67	9.09
PCB Congener 187	30	27	3	0	3.88	5.5	1.75	0.25	22	0.52		1.62	4.97
PCB Congener 195	30	11	19	0	0.624	0.989	0.198	0.033	3.9	0.53			0.80
PCB Congener 206	30	16	14	0	0.831	0.619	0.589	0.204	2.4	0.53		0.57	1.86
PCB Aroclors													
PCB Aroclor 1016	30	0	30	30						21	2		
PCB Aroclor 1221	30	0	30	30						21	2		
PCB Aroclor 1232	30	0	30	30						21	2		
PCB Aroclor 1242	30	18	12	0	11.7	5.7	10.5	4.84	26	11			14.5
PCB Aroclor 1248	30	0	30	30						102	2		
PCB Aroclor 1254	30	27	3	0	54.39	52.74	39.5	7.88	271	10		25.1	69
PCB Aroclor 1260	30	26	4	0	84.2	138.2	31	3.6	529	11		21.5	94.1
PCB Aroclor 1262	30	0	30	30						297	2		
PCB Aroclor 1268	30	0	30	30						11	2		

Parameter Code	N	# Detects	# ND	# ND > highest detect	Mean*	Std. Dev.*	Median*	Minimum*	Maximum (detected)	Max RL (ND)	Notes (see bottom)	50th %-ile estimated from CDF (ND=0)	90th %-ile estimated from CDF (ND=0)
Polybrominated Diphenylethers (PBDE)													
PBDE- 47	29	23	6	0	1.563	1.884	0.86	0.093	7.3	0.2		1.16	1.85
PBDE- 49	25	9	16	0	0.818	1.839	0.148	0.007	8.9	0.21		0.3	0.84
PBDE- 66	30	0	30	30						0.21	2		
PBDE- 71	30	0	30	30						0.21	2		
PBDE- 99	30	13	17	0	0.598	0.853	0.237	0.035	4.4	0.21		0.79	1.34
PBDE-100	30	1	29	0					0.32	0.21	5		
PBDE-138	30	0	30	30						0.43	2		
PBDE-153	30	0	30	30						0.43	2		
PBDE-154	30	1	29	29						0.43	3,4		
PBDE-183	30	1	29	0					0.88	0.43	5		
PBDE-184	30	0	30	30						0.43	2		
PBDE-191	30	0	30	30						0.86	2		
PBDE-209	28	6	22	0	6.59	7.23	3.47	0.97	27	5.3		0.07	25.2

Notes
*: Estimated by ROS when nondetects present.
1: All values detected (no nondetects).
2: All nondetect.
3: Nondetects higher than the maximum detect are set to missing values.
4: All nondetects are higher than the maximum detect.
5: Too few detected observations for regression.

Table 8. Number of 2007 Urban Waters Initiative sediment study samples exceeding Washington State sediment-quality standards[a] and estimated spatial extent of chemical contamination. Total sampling area = 26.32 km^2.

Analyte	Criterion	> SQS[b]				Criterion	> CSL[b]			
		No.	Area (Km^2)	% of Total Area	Sample Number		No.	Area (Km^2)	% of Total Area	Sample Number
Trace Metals (ppm dry weight)										
Arsenic	57	1	0.36	1.37	197	93	1	0.36	1.37	197
Cadmium	5.1	criterion not exceeded				6.7	criterion not exceeded			
Chromium	260	criterion not exceeded				270	criterion not exceeded			
Copper	390	criterion not exceeded				390	criterion not exceeded			
Lead	450	criterion not exceeded				530	criterion not exceeded			
Mercury	0.41	5	4.03	15.31	182, 188, 190, 194, 196	0.59	4	3.06	11.61	182, 188, 190, 194
Silver	6.1	criterion not exceeded				6.1	criterion not exceeded			
Zinc	410	1	0.36	1.37	197	960	criterion not exceeded			
Combined total for any individual trace metals	n.a.	6	4.39	16.68	182, 188, 190, 194, 196, 197	n.a.	5	3.42	12.98	182, 188, 190, 194, 197
Organic Compounds										
LPAH (ppm organic carbon)										
2-Methylnaphthalene	38	criterion not exceeded				64	criterion not exceeded			
Acenaphthene	16	criterion not exceeded				57	criterion not exceeded			
Acenaphthylene	66	criterion not exceeded				66	criterion not exceeded			
Anthracene	220	criterion not exceeded				1200	criterion not exceeded			
Fluorene	23	1	0.11	0.42	184	79	criterion not exceeded			
Naphthalene	99	criterion not exceeded				170	criterion not exceeded			
Phenanthrene	100	1	0.11	0.42	184	480	criterion not exceeded			
Combined total for any individual LPAH	n.a.	1	0.11	0.42	184	n.a.	criteria not exceeded			
Total LPAH (ppm organic carbon)										
Sum of 6 LPAH (WA Ch. 173-204 RCW)	370	criterion not exceeded				780	criterion not exceeded			
HPAH (ppm organic carbon)										
Benzo(a)anthracene	110	criterion not exceeded				270	criterion not exceeded			
Benzo(a)pyrene	99	1	0.36	1.37	115	210	criterion not exceeded			
Benzo(g,h,i)perylene	31	2	1.48	5.62	115, 188	78	criterion not exceeded			
Chrysene	110	1	0.11	0.42	184	460	criterion not exceeded			
Dibenzo(a,h)anthracene	12	criterion not exceeded				33	criterion not exceeded			
Fluoranthene	160	1	0.11	0.42	184	1200	1	0.11	0.42	184
Indeno(1,2,3-c,d)pyrene	34	2	1.48	5.62	115, 188	88	criterion not exceeded			
Pyrene	1000	criterion not exceeded				1400	criterion not exceeded			

Analyte	Criterion	> SQS[b]				Criterion	> CSL[b]			
		No.	Area (Km^2)	% of Total Area	Sample Number		No.	Area (Km^2)	% of Total Area	Sample Number
HPAH (continued)										
Total Benzofluoranthenes	230	criterion not exceeded				450	criterion not exceeded			
Combined total for any individual HPAH	n.a.	3	1.59	6.04	115, 184, 188	n.a.	1	0.11	0.42	184
Total HPAH (ppm organic carbon)										
Sum of 9 HPAH (WA Ch. 173-204 RCW)	960	1	0.11	0.42	184	5300	criterion not exceeded			
All PAHs (ppm organic carbon)										
Combined total for any individual PAH	n.a.	3	1.59	6.04	115, 184, 188	n.a.	1	0.11	0.42	184
Phenols (ppb dry weight)										
Pentachlorophenol	360	criterion not exceeded				690	criterion not exceeded			
Phthalate Esters (ppm organic carbon)										
Bis(2-Ethylhexyl) Phthalate	47	8	2.88	10.94	114, 181, 186, 200, 201, 202, 203, 205	78	5	1.83	6.95	186, 200, 201, 202, 205
Butylbenzylphthalate	4.9	1		1.67	181	64	criterion not exceeded			
Diethylphthalate	61	criterion not exceeded				110	criterion not exceeded			
Dimethylphthalate	53	criterion not exceeded				53	criterion not exceeded			
Di-N-Butyl Phthalate	220	criterion not exceeded				1700	criterion not exceeded			
Di-N-Octyl Phthalate	58	criterion not exceeded				4500	criterion not exceeded			
Combined total for any individual phthalate esters	n.a.	8	2.88	10.94	114, 181, 186, 200, 201, 202, 203, 205	n.a.	5	1.83	6.95	186, 200, 201, 202, 205
Total PCB (ppm organic carbon)										
Total Aroclors (WA Ch. 173-204 RCW)	12	4	0.98	3.72	181, 200, 201, 202	65	1	0.18	0.68	200
Miscellaneous Compounds (ppm organic carbon)										
1,2-Dichlorobenzene	2.3	criterion not exceeded				2.3	criterion not exceeded			
1,2,4-Trichlorobenzene	0.81	1	0.18	0.68	200	1.8	criterion not exceeded			
1,4-Dichlorobenzene	3.1	2	0.36	1.37	200, 201	9	criterion not exceeded			
Dibenzofuran	15	4	1.51	5.75	182, 184, 189, 197	58	criterion not exceeded			
Hexachlorobenzene	0.38	criterion not exceeded				2.3	criterion not exceeded			
Hexachlorobutadiene	3.9	criterion not exceeded				6.2	criterion not exceeded			
N-Nitrosodiphenylamine	11	criterion not exceeded				11	criterion not exceeded			

Analyte	Criterion	> SQS[b]				Criterion	> CSL[b]			
		No.	Area (Km^2)	% of Total Area	Sample Number		No.	Area (Km^2)	% of Total Area	Sample Number
***Combined total for all individual chemicals (metals and organics)**	n.a.	17	9.00	34.21	114, 115, 181, 182, 184, 186, 188, 189, 190, 194, 196, 197, 200, 201, 202, 203, 205	n.a.	11	5.36	20.35	182, 184, 186, 188, 190, 194, 197, 200, 201, 202, 205

[a] Excluding Benzoic Acid, Benzyl Alcohol, Phenol, 2-Methylphenol, 4-Methylphenol, and 2,4-Dimethylphenol.
[b] SQS = Sediment Quality Standard, CSL = Cleanup Screening Levels (Washington State Sediment Management Standards - Chapter 173-204 WAC).

Table 9. Samples from the 2007 Urban Waters Initiative sediment study in which Washington State sediment quality standards[a] were exceeded. The mean ERM quotient is the average of all chemical concentrations divided by their respective ERMs[b].

Sample	Sample location	Sampled-weighted area (km^2)	Mean ERM quotient	Number of SQSs exceeded	Chemicals exceeding SQSs	Number of CSLs exceeded	Chemicals exceeding CSLs
114	West Waterway, Terminal 5	0.36	0.07	1	Bis(2-Ethylhexyl) Phthalate	0	
115	Elliott Bay, east side of Pier 90	0.44	0.40	3	Benzo(a)pyrene, Benzo(g,h,i)perylene, Indeno(1,2,3-c,d)pyrene	0	
172	West of Duwamish Head	5.58	0.08	No WA standards exceeded			
173	Northwest of Duwamish Head	5.58	0.08	No WA standards exceeded			
176	Elliott Bay, west of EB Marina	0.42	0.05	No WA standards exceeded			
177	Magnolia Bluff	0.42	0.02	No WA standards exceeded			
178	Elliott Bay, south of EB Marina	0.42	0.03	No WA standards exceeded			
180	Elliott Bay, Piers 89-90	0.44	0.11	No WA standards exceeded			
181	Elliott Bay, west of Piers 70-71	0.44	0.18	3	Butylbenzylphthalate, Bis(2-Ethylhexyl) Phthalate, Total Aroclors	0	
182	Elliott Bay, west of Pier 54	0.11	0.38	2	Dibenzofuran, Mercury	1	Mercury
183	Elliott Bay, Pier 54	0.11	0.22	No WA standards exceeded			

Sample	Sample location	Sampled-weighted area (km^2)	Mean ERM quotient	Number of SQSs exceeded	Chemicals exceeding SQSs	Number of CSLs exceeded	Chemicals exceeding CSLs
184	Elliott Bay, Pier 55	0.11	1.57	6	Chrysene, Dibenzofuran, Fluoranthene, Fluorene, Phenanthrene, Total HPAHs	1	Fluoranthene
185	North of Duwamish Head	1.04	0.10	No WA standards exceeded			
186	Elliott Bay, W. of Denny Way	1.04	0.11	1	Bis(2-Ethylhexyl) Phthalate	1	Bis(2-Ethylhexyl) Phthalate
187	Elliott Bay, west of Pier 59	1.04	0.11	No WA standards exceeded			
188	Elliott Bay, west of Pier 57	1.04	0.51	3	Mercury, Benzo(g,h,i)perylene, Indeno(1,2,3-c,d)pyrene	1	Mercury
189	Elliott Bay, east of Duwamish Head	0.93	0.13	1	Dibenzofuran	0	
190	Elliott Bay, Duwamish Head	0.93	0.06	1	Mercury	1	Mercury
192	Elliott Bay, central	0.93	0.08	No WA standards exceeded			
194	Elliott Bay, west of Pier 48	0.97	0.25	1	Mercury	1	Mercury
195	Elliott Bay, west of Pier 48	0.97	0.48	No WA standards exceeded			
196	Elliott Bay, west of Yesler Way	0.97	0.20	1	Mercury	0	

Sample	Sample location	Sampled-weighted area (km^2)	Mean ERM quotient	Number of SQSs exceeded	Chemicals exceeding SQSs	Number of CSLs exceeded	Chemicals exceeding CSLs
197	Elliott Bay, south	0.36	0.32	3	Arsenic, Dibenzofuran, Zinc	1	Arsenic
199	Elliott Bay, south	0.36	0.12	No WA standards exceeded			
200	East Waterway, Terminal 18	0.18	0.28	4	1,4-Dichlorobenzene, 1,2,4-Trichlorobenzene, Bis(2-Ethylhexyl) Phthalate, Total Aroclors	2	Bis(2-Ethylhexyl) Phthalate, Total Aroclors
201	East Waterway, Pier 32	0.18	0.28	3	1,4-Dichlorobenzene, Bis(2-Ethylhexyl) Phthalate, Total Aroclors	1	Bis(2-Ethylhexyl) Phthalate
202	East Waterway, south end	0.18	0.37	2	Bis(2-Ethylhexyl) Phthalate, Total Aroclors	1	Bis(2-Ethylhexyl) Phthalate
203	Duwamish River, North	0.25	0.10	1	Bis(2-Ethylhexyl) Phthalate	0	
204	Duwamish River, North	0.25	0.18	No WA standards exceeded			
205	Duwamish River, SW of Slip 2	0.25	0.09	1	Bis(2-Ethylhexyl) Phthalate	1	Bis(2-Ethylhexyl) Phthalate

[a] Chapter 173-204 WAC (Washington State Department of Ecology, 1995).
[b] ERM = Effects Range–Median sediment-quality guideline (Long et al., 1995).

Table 10. Summary statistics for mean ERM quotients for samples from the 2007 Urban Waters Initiative sediment study.

"Stratum" type	N	Minimum	Maximum	Median	Average
Entire study area	30	0.02	1.57	0.13	0.23
Basin	2	0.08	0.08	0.08	0.08
Harbor	15	0.07	1.57	0.22	0.31
Urban	13	0.02	0.51	0.11	0.17

Table 11. Results of sea urchin fertilization tests in undiluted and diluted porewaters from 30 sediment samples for the 2007 Urban Waters Initiative sediment study. Data are expressed as mean percent fertilization and as percentage of control response. Tests were performed with *Strongylocentrotus purpuratus*.

Station	Location	100% porewater			50% porewater			25% porewater		
		Mean fertilization (%)	Mean fertilization as % of control	Statistical significance (p value <0.05, t-test)	Mean fertilization (%)	Mean fertilization as % of control	Statistical significance (p value <0.05, t-test)	Mean fertilization (%)	Mean fertilization as % of control	Statistical significance (p value <0.05, t-test)
114	West Waterway, Terminal 5	99.0	101.7		95.6	104.3		96.8	104.4	
115	Elliott Bay, east side of Pier 90	87.6	90.0		86.0	93.8		95.2	102.7	
172	West of Duwamish Head	98.6	101.3		96.6	105.3		96.6	104.2	
173	Northwest of Duwamish Head	99.8	102.6		98.6	107.5		99.0	106.8	
176	Elliott Bay, west of EB Marina	98.4	101.1		92.8	101.2		93.4	100.8	
177	Magnolia Bluff	0.2	0.2	**	0.4	0.4	**	18.2	19.6	**
178	Elliott Bay, south of EB Marina	96.6	99.3		91.6	99.9		92.6	99.9	
180	Elliott Bay, Piers 89-90	98.8	101.5		97.0	105.8		98.0	105.7	
181	Elliott Bay, west of Piers 70-71	99.6	102.4		98.4	107.3		97.6	105.3	
182	Elliott Bay, west of Pier 54	98.2	100.9		97.8	106.7		98.4	106.1	
183	Elliott Bay, Pier 54	98.0	100.7		94.4	102.9		95.8	103.3	
184	Elliott Bay, Pier 55	98.0	100.7		91.2	99.5		87.0	93.9	
185	North of Duwamish Head	99.2	102.0		98.0	106.9		91.6	98.8	
186	Elliott Bay, west of Denny Way	99.2	102.0		94.4	102.9		92.8	100.1	
187	Elliott Bay, west of Pier 59	98.2	100.9		98.8	107.7		96.8	104.4	
188	Elliott Bay, west of Pier 57	99.5	102.3		98.4	107.3		96.0	103.6	
189	Elliott Bay, east of Duwamish	96.6	99.3		95.0	103.6		91.2	98.4	
190	Elliott Bay, Duwamish Head	79.4	81.6		98.8	107.7		97.0	104.6	
192	Elliott Bay, central	99.0	101.7		95.2	103.8		96.4	104.0	
194	Elliott Bay, west of Pier 48	98.7	101.4		96.7	105.4		95.3	102.8	
195	Elliott Bay, west of Pier 48	98.4	101.1		95.8	104.4		95.4	102.9	
196	Elliott Bay, west of Yesler Way	99.6	102.4		98.4	107.3		97.2	104.9	
197	Elliott Bay, south	99.0	101.7		98.0	106.9		97.6	105.3	
199	Elliott Bay, south	98.2	100.9		99.0	108.0		98.2	105.9	
200	East Waterway, Terminal 18	95.0	97.6		96.4	105.1		94.2	101.6	
201	East Waterway, Pier 32	78.4	80.6	**	97.6	106.4		94.2	101.6	
202	East Waterway, south end	98.8	101.5		97.2	106.0		96.2	103.8	
203	Duwamish River, North	97.6	100.3		96.2	104.9		96.0	103.6	
204	Duwamish River, North	87.2	89.6		96.4	105.1		95.8	103.3	
205	Duwamish River, SW of Slip 2	98.2	100.9		94.0	102.5		87.8	94.7	

Table 12. Total abundance, taxa richness, Pielou's Evenness, and Swartz' Dominance Index calculated for the 2007 Urban Waters Initiative sediment study.

Station	Location	Total Abundance	Taxa Richness	Pielou's Evenness (J')	Swartz' Dominance Index
114	West Waterway, Terminal 5	1109	71	0.66	8
115	Elliott Bay, east side of Pier 90	760	58	0.53	5
172	West of Duwamish Head	172	41	0.79	13
173	Northwest of Duwamish Head	355	58	0.73	13
176	Elliott Bay, west of EB Marina	845	110	0.75	19
177	Magnolia Bluff	1110	66	0.62	7
178	Elliott Bay, south of EB Marina	341	81	0.80	22
180	Elliott Bay, Piers 89-90	572	85	0.79	19
181	Elliott Bay, west of Piers 70-71	383	79	0.85	25
182	Elliott Bay, west of Pier 54	579	76	0.78	20
183	Elliott Bay, Pier 54	1191	107	0.67	13
184	Elliott Bay, Pier 55	1087	92	0.58	6
185	North of Duwamish Head	33	24	0.97	16
186	Elliott Bay, west of Denny Way	435	76	0.80	21
187	Elliott Bay, west of Pier 59	209	42	0.70	10
188	Elliott Bay, west of Pier 57	758	69	0.59	10
189	Elliott Bay, east of Duwamish Head	647	87	0.76	19
190	Elliott Bay, Duwamish Head	701	55	0.65	6
192	Elliott Bay, central	430	80	0.76	15
194	Elliott Bay, west of Pier 48	228	31	0.62	5
195	Elliott Bay, west of Pier 48	297	47	0.69	7
196	Elliott Bay, west of Yesler Way	237	38	0.53	4
197	Elliott Bay, south	625	77	0.75	13
199	Elliott Bay, south	1083	104	0.75	20
200	East Waterway, Terminal 18	800	60	0.52	4
201	East Waterway, Pier 32	1912	49	0.42	2
202	East Waterway, south end	1022	32	0.40	2
203	Duwamish River, North	980	95	0.70	14
204	Duwamish River, North	869	75	0.60	9
205	Duwamish River, SW of Slip 2	369	32	0.63	5
	Mean	671	67	0.68	12
	Median	636	70	0.69	12
	Min	33	24	0.40	2
	Max	1912	110	0.97	25
	Range	1879	86	0.57	23

Table 13. Total abundance, major taxa abundance, and major taxa percent abundance calculated for the 2007 Urban Waters Initiative sediment study.

Station	Total abundance	Annelida	Annelida % of total abundance	Arthropoda	Arthropoda % of total abundance	Echino-dermata	Echino-dermata % of total abundance	Mollusca	Mollusca % of total abundance	Misc. taxa	Misc. taxa % of total abundance
114	1109	479	43.19	134	12.08	9	0.81	475	42.83	12	1.08
115	760	608	80.00	9	1.18	0	0.00	143	18.82	0	0.00
172	172	128	74.42	16	9.30	6	3.49	13	7.56	9	5.23
173	355	145	40.85	64	18.03	5	1.41	130	36.62	11	3.10
176	845	501	59.29	52	6.15	9	1.07	231	27.34	52	6.15
177	1110	110	9.91	270	24.32	0	0.00	728	65.59	2	0.18
178	341	200	58.65	63	18.48	4	1.17	70	20.53	4	1.17
180	572	321	56.12	83	14.51	1	0.17	157	27.45	10	1.75
181	383	174	45.43	53	13.84	0	0.00	140	36.55	16	4.18
182	579	233	40.24	107	18.48	2	0.35	212	36.61	25	4.32
183	1191	675	56.68	128	10.75	5	0.42	369	30.98	14	1.18
184	1087	704	64.77	5	0.46	11	1.01	360	33.12	7	0.64
185	33	16	48.48	8	24.24	0	0.00	8	24.24	1	3.03
186	435	186	42.76	72	16.55	1	0.23	165	37.93	11	2.53
187	209	96	45.93	18	8.61	4	1.91	90	43.06	1	0.48
188	758	217	28.63	41	5.41	0	0.00	465	61.35	35	4.62
189	647	327	50.54	94	14.53	7	1.08	203	31.38	16	2.47
190	701	144	20.54	337	48.07	0	0.00	203	28.96	17	2.43
192	430	284	66.05	39	9.07	8	1.86	94	21.86	5	1.16
194	228	81	35.53	19	8.33	0	0.00	126	55.26	2	0.88
195	297	166	55.89	29	9.76	0	0.00	94	31.65	8	2.69
196	237	76	32.07	12	5.06	0	0.00	146	61.60	3	1.27

Station	Total abundance	Annelida	Annelida % of total abundance	Arthropoda	Arthropoda % of total abundance	Echino-dermata	Echino-dermata % of total abundance	Mollusca	Mollusca % of total abundance	Misc. taxa	Misc. taxa % of total abundance
197	625	396	63.36	56	8.96	0	0.00	154	24.64	19	3.04
199	1083	400	36.93	129	11.91	27	2.49	504	46.54	23	2.12
200	800	584	73.00	32	4.00	1	0.13	174	21.75	9	1.13
201	1912	1427	74.63	115	6.01	0	0.00	367	19.19	3	0.16
202	1022	214	20.94	5	0.49	1	0.10	801	78.38	1	0.10
203	980	613	62.55	49	5.00	7	0.71	299	30.51	12	1.22
204	869	632	72.73	14	1.61	0	0.00	219	25.20	4	0.46
205	369	329	89.16	2	0.54	0	0.00	38	10.30	0	0.00
Mean	671	349	51.64	69	11.19	4	0.61	239	34.59	11	1.96
Median	636	259	53.22	51	9.19	1	0.15	170	31.18	9	1.25
Min	33	16	9.91	2	0.46	0	0.00	8	7.56	0	0.00
Max	1912	1427	89.16	337	48.07	27	3.49	801	78.38	52	6.15
Range	1879	1411	79.25	335	47.61	27	3.49	793	70.82	52	6.15

Table 14. Major taxa abundance and number of species over 30 samples in 2007 Urban Waters Initiative sediment study.

Phylum	Abundance	Percent	Number of Species*	Percent
Annelida	26641	55.1%	208	54.0%
Arthropoda	5634	11.7%	78	20.3%
Echinodermata	223	0.5%	14	3.6%
Mollusca	15312	31.7%	62	16.1%
Miscellaneous	507	1.0%	0	0.0%
Total	48317	100.0%	385	100.0%

Table 15. Condition of benthic invertebrate communities in the 2007 Urban Waters Initiative sediment study.

Station	Location	Condition of Benthos
114	West Waterway, Terminal 5	Affected
115	Elliott Bay, east side of Pier 90	Affected
172	West of Duwamish Head	Affected
177	Magnolia Bluff	Affected
185	North of Duwamish Head	Affected
187	Elliott Bay, west of Pier 59	Affected
190	Elliott Bay, Duwamish Head	Affected
194	Elliott Bay, west of Pier 48	Affected
195	Elliott Bay, west of Pier 48	Affected
196	Elliott Bay, west of Yesler Way	Affected
200	East Waterway, Terminal 18	Affected
201	East Waterway, Pier 32	Affected
202	East Waterway, south end	Affected
203	Duwamish River, North	Affected
204	Duwamish River, North	Affected
205	Duwamish River, SW of Slip 2	Affected
173	Northwest of Duwamish Head	Unaffected
176	Elliott Bay, west of EB Marina	Unaffected
178	Elliott Bay, south of EB Marina	Unaffected
180	Elliott Bay, Piers 89-90	Unaffected
181	Elliott Bay, west of Piers 70-71	Unaffected
182	Elliott Bay, west of Pier 54	Unaffected
183	Elliott Bay, Pier 54	Unaffected
184	Elliott Bay, Pier 55	Unaffected
186	Elliott Bay, west of Denny Way	Unaffected
188	Elliott Bay, west of Pier 57	Unaffected
189	Elliott Bay, east of Duwamish Head	Unaffected
192	Elliott Bay, central	Unaffected
197	Elliott Bay, south	Unaffected
199	Elliott Bay, south	Unaffected

Table 16. Estimated incidence and spatial extent of degraded sediments in the 2007 Urban Waters Initiative sediment study, as measured with the Sediment Quality Triad Index.

Sediment Quality Triad Index Category	Incidence		Spatial extent	
	No. (%) of stations		km^2 (%) of study area	
Total Study Area	30	(100.0)	26.32	(100.0)
High[1]	7	(23.3)	8.26	(31.4)
Intermediate/high[2]	12	(40.0)	12.92	(49.1)
Chemistry	7	(23.3)	4.03	(15.3)
Toxicity	0	(0.0)	0	(0.0)
Benthos	5	(16.7)	8.88	(33.8)
Intermediate/degraded[3]	11	(36.7)	5.13	(19.5)
Chemistry/toxicity	0	(0.0)	0	(0.0)
Chemistry/benthos	10	(33.3)	4.72	(17.9)
Benthos/toxicity	1	(3.3)	0.42	(1.6)
Degraded[4]	0	(0.0)	0	(0.0)
By Triad Element[5]				
Chemistry	17	(56.7)	8.75	(33.2)
Toxicity	1	(3.3)	0.42	(1.6)
Benthos	16	(53.3)	14.01	(53.2)

[1] No parameters impaired.
[2] One parameter impaired (chemistry, toxicity, or benthos).
[3] Two parameters impaired (chemistry, toxicity, and/or benthos).
[4] Three parameters impaired (chemistry, toxicity, and benthos).
[5] Some stations meet criteria for more than one element of triad. Some stations do not meet criteria for any elements of triad.

Table 17. Summary of statistical comparisons of 1998 PSAMP/NOAA and 2007 Urban Waters Initiative sediment grain size, TOC, and chemistry results. See Methods section of report for details of comparison methods. ↓ = decrease; ↑ = increase; -- = no change; a = all nondetect (both years); b = dependent on nondetect treatment; c = too few detected values to test; d = too few values to test.

Parameter	Paired differences weighted by area[1]	Paired differences unweighted[2]	CDF comparison weighted, unpaired[3]	Compare SQS hits # of stations[4]	Compare SQS hits % of area[5]
Grain Size					
Percent Fines	↓	↓	--		
Organic Carbon Content					
Total Organic Carbon	--	↑	↑		
Priority Pollutant Metals					
Arsenic	--	--	--	--	--
Cadmium	--	--	--	--	--
Chromium	--	--	--	--	--
Copper	--	--	--	--	--
Lead	↓	↓	--	--	--
Mercury	↓	--	--	--	--
Nickel	--	--	--		
Selenium	↑	↑	--		
Silver	↓	↓	--	--	--
Zinc	↑	↑	--	--	--
Trace Elements					
Tin	↓	↓	↓		
<u>Organic Compounds</u>					
Chlorinated Alkanes					
Hexachlorobutadiene	a	a	a	--	--
Chlorinated and Nitro-Substituted Phenols					
Pentachlorophenol	--	--	d	--	--
Chlorinated Aromatic Compounds					
1,2,4-Trichlorobenzene	b	--	c	--	--
1,2-Dichlorobenzene	c	c	c	--	--
1,3-Dichlorobenzene	b	--	c		
1,4-Dichlorobenzene	b	--	--	--	--
Chlorinated Pesticides					
2,4'-DDD	b	--	c		
2,4'-DDE	--	--	d		
2,4'-DDT	c	c	c		

Parameter	Paired differences weighted by area[1]	Paired differences unweighted[2]	CDF comparison weighted, unpaired[3]	Compare SQS hits # of stations[4]	Compare SQS hits % of area[5]
Chlorinated Pesticides (continued)					
4,4'-DDD	↓	↓	--		
4,4'-DDE	↓	↓	↓		
4,4'-DDT	--	↑	b		
Aldrin	a	a	a		
Cis-chlordane (Alpha-chlordane)	b	--	c		
Dieldrin	a	a	a		
Endosulfan I	a	a	a		
Endosulfan II	a	a	a		
Endosulfan Sulfate	c	c	c		
Endrin	a	a	a		
Endrin Aldehyde	a	a	a		
Endrin Ketone	a	a	a		
Gamma-BHC (Lindane)	a	a	a		
Heptachlor	--	--	d		
Heptachlor Epoxide	a	a	a		
Hexachlorobenzene	--	--	d	--	--
Mirex	--	--	d		
Oxychlordane	a	a	a		
Toxaphene	a	a	a		
Trans-Chlordane (Gamma)	b	--	c		
Polynuclear Aromatic Hydrocarbons					
LPAH					
1,6,7-Trimethylnaphthalene	↓	↓	↓		
1-Methylnaphthalene	--	--	--		
2,6-Dimethylnaphthalene	↑	--	--		
2-Methylnaphthalene	--	--	--	--	--
2-Methylphenanthrene	--	↓	--		
Acenaphthene	↓	↓	--	--	--
Acenaphthylene	↑	↑	--	--	--
Anthracene	--	↓	--	--	--
Biphenyl	--	↓	↓		
Dibenzothiophene	--	↓	--		
Fluorene	--	↓	--	--	--
Naphthalene	--	--	--	--	--
Phenanthrene	↓	↓	--	--	--
Retene	↑	↑	↑		
Total LPAH (sum of 6 compounds)				--	--

Parameter	Paired differences weighted by area[1]	Paired differences unweighted[2]	CDF comparison weighted, unpaired[3]	Compare SQS hits # of stations[4]	Compare SQS hits % of area[5]
HPAH					
Benzo(a)anthracene	↓	↓	--	--	--
Benzo(a)pyrene	↓	↓	--	--	--
Benzo(b)fluoranthene	↓	↓	--		
Benzo[e]pyrene	↓	↓	--		
Benzo(g,h,i)perylene	↓	↓	--	↓	↓
Benzo(k)fluoranthene	↓	↓	--		
Chrysene	--	--	--	--	--
Dibenzo(a,h)anthracene	↓	↓	--	--	--
Fluoranthene	↓	↓	--	--	--
Indeno(1,2,3-c,d)pyrene	↓	↓	--	--	--
Perylene	--	--	--		
Pyrene	↓	↓	--	--	--
Total Benzofluoranthenes				--	--
Total HPAH (sum of 9 compounds)				--	--
Miscellaneous Extractable Compounds					
Dibenzofuran	↑	--	--	--	--
Organonitrogen Compounds					
N-Nitrosodiphenylamine	c	c	c	--	--
Phenols					
P-nonylphenol	c	c	c		
Phthalate Esters					
Bis(2-Ethylhexyl) Phthalate	--	--	↑	--	--
Butylbenzylphthalate	b	--	c	--	--
Diethylphthalate	b	--	c	--	--
Dimethylphthalate	b	--	c	--	--
Di-N-Butylphthalate	b	--	c	--	--
Di-N-Octyl Phthalate	c	c	c	--	--
Polychlorinated Biphenyls (PCB)					
PCB Congeners					
PCB Congener 8	--	↓	d		
PCB Congener 18	b	--	↓		
PCB Congener 28	↓	↓	↓		
PCB Congener 44	↓	↓	↓		
PCB Congener 52	↓	↓	--		
PCB Congener 66	↓	↓	--		
PCB Congener 77	b	--	↓		
PCB Congener 101	↓	↓	--		

Parameter	Paired differences weighted by area[1]	Paired differences unweighted[2]	CDF comparison weighted, unpaired[3]	Compare SQS hits # of stations[4]	Compare SQS hits % of area[5]
PCB Congeners (continued)					
PCB Congener 105	↓	↓	↓		
PCB Congener 118	↓	↓	--		
PCB Congener 126	c	c	c		
PCB Congener 128	↓	↓	↓		
PCB Congener 138	↓	↓	--		
PCB Congener 153	↓	↓	--		
PCB Congener 170	↓	↓	--		
PCB Congener 180	↓	↓	--		
PCB Congener 187	↓	↓	--		
PCB Congener 195	--	--	b		
PCB Congener 206	b	--	b		
PCB Aroclors					
PCB Aroclor 1016	a	a	a		
PCB Aroclor 1221	a	a	a		
PCB Aroclor 1232	a	a	a		
PCB Aroclor 1242	b	--	↑		
PCB Aroclor 1248	a	a	a		
PCB Aroclor 1254	↓	↓	--		
PCB Aroclor 1260	↓	↓	--		
Total PCB Aroclors				↓	↓

[1] Wilcoxon signed rank test applied to weighted differences.
[2] Prentice-Wilcoxon test or Wilcoxon signed rank test applied to unweighted differences.
[3] Wald F test applied to CDFs (weighted).
[4] Fisher exact test.
[5] Two-proportion test.

Table 18. Summary of statistical comparisons of 1998 PSAMP/NOAA and 2007 Urban Waters Initiative benthic invertebrate measures. See Methods section of report for details of comparison methods. ↓ = decrease; ↑ = increase; -- = no change.

Parameter	Paired differences weighted by area[1]	Paired differences unweighted[2]	CDF comparison weighted, unpaired[3]
Total Abundance	↓	↓	--
Taxa Richness	--	--	--
Shannon-Wiener Diversity	↑	↑	--
Pielou’s Evenness	↑	↑	↑
Swartz’ Dominance	↑	--	--
SDI Standardized by Richness	↑	↑	--
Annelid Abundance	↓	↓	--
Arthropod Abundance	↓	↓	--
Echinoderm Abundance	--	--	possible ↑
Mollusc Abundance	↓	--	--
Abundance of Other Taxa	↑	↑	--

[1] Wilcoxon signed rank test applied to weighted differences.
[2] Wilcoxon signed rank test applied to unweighted differences.
[3] Wald F test applied to CDFs (weighted).

Table 19. Sediment Quality Triad by station, comparing 1998 and 2007 results.

Station	"Stratum" Type	Area Represented (km^2)	1998		2007	
			Triad Hits	Sediment Quality Classification	Triad Hits	Sediment Quality Classification
173	Basin	5.58		High		High
192	Urban	0.93		High		High
176	Urban	0.42	C(5)	Intermediate/High		High
178	Urban	0.42	C(1)	Intermediate/High		High
183	Harbor	0.11	C(11)	Intermediate/High		High
199	Harbor	0.36	C(2), T	Intermediate/Degraded		High
180	Harbor	0.44	C(3), T	Intermediate/Degraded		High
172	Basin	5.58		High	B	Intermediate/High
189	Urban	0.93		High	C(1)	Intermediate/High
181	Harbor	0.44	C(3)	Intermediate/High	C(3)	Intermediate/High
182	Harbor	0.11	C(4)	Intermediate/High	C(2)	Intermediate/High
184	Harbor	0.11	C(7)	Intermediate/High	C(6)	Intermediate/High
187	Urban	1.04	B	Intermediate/High	B	Intermediate/High
195	Urban	0.97	B	Intermediate/High	B	Intermediate/High
185	Urban	1.04	C(1), B	Intermediate/Degraded	B	Intermediate/High
186	Urban	1.04	C(2), B	Intermediate/Degraded	C(1)	Intermediate/High
188	Urban	1.04	C(3), B	Intermediate/Degraded	C(3)	Intermediate/High
197	Harbor	0.36	C(3), T	Intermediate/Degraded	C(3)	Intermediate/High
204	Harbor	0.25	C(2), B	Intermediate/Degraded	B	Intermediate/High
177	Urban	0.42	T	Intermediate/High	T, B	Intermediate/Degraded
190	Urban	0.93	C(1)	Intermediate/High	C(1), B	Intermediate/Degraded
114	Harbor	0.36	C(2), B	Intermediate/Degraded	C(1), B	Intermediate/Degraded
194	Urban	0.97	C(3), B	Intermediate/Degraded	C(1), B	Intermediate/Degraded
196	Urban	0.97	C(1), B	Intermediate/Degraded	C(1), B	Intermediate/Degraded

Station	"Stratum" Type	Area Represented (km^2)	1998		2007	
			Triad Hits	Sediment Quality Classification	Triad Hits	Sediment Quality Classification
202	Harbor	0.18	C(1), B	Intermediate/Degraded	C(2), B	Intermediate/Degraded
203	Harbor	0.25	C(1), B	Intermediate/Degraded	C(1), B	Intermediate/Degraded
205	Harbor	0.25	C(6), B	Intermediate/Degraded	C(1), B	Intermediate/Degraded
115	Harbor	0.44	C(2), T, B	Degraded	C(3), B	Intermediate/Degraded
200	Harbor	0.18	C(2), T, B	Degraded	C(4), B	Intermediate/Degraded
201	Harbor	0.18	C(2), T, B	Degraded	C(3), B	Intermediate/Degraded

C(#) = chemistry hit (number of chemicals > SQS).
T = toxicity hit.
B = benthos hit.

Table 20. Changes in Sediment Quality Triad Index for Elliott Bay/lower Duwamish from 1998 to 2007. ↑ = increase, ↓ = decrease, -- = no change statistically significant at α = 0.05.

Sediment Quality Triad Element	1998 # Stations	2007 # Stations	Signif. Change[1]	1998 Area (km^2)	2007 Area (km^2)	1998 % of Area	2007 % of Area	Signif. Change[2]
Chemistry > SQS	23	17	--	10.85	8.75	41.2%	33.2%	--
Toxicity	7	1	↓	2.38	0.42	9.0%	1.6%	--
Affected Benthos	15	16	--	9.16	14.01	34.8%	53.2%	--
Triad Index								
High (no triad elements)	4	7	--	13.03	8.26	49.5%	31.4%	--
Intermediate/High (1 triad element)	10	12	--	4.98	12.92	18.9%	49.1%	↑
Intermediate/Degraded (2 triad elements)	13	11	--	7.52	5.13	28.6%	19.5%	--
Degraded (all 3 triad elements)	3	0	--	0.80	0.00	3.0%	0.0%	--

[1] Fisher Exact Test.
[2] Two-Proportion Test.

Table 21. Summary of changes in Sediment Quality Triad Index in Elliott Bay/lower Duwamish from 1998 to 2007. See Figure 29.

Change in Index Categorization	All Stations			Harbor and Urban Only		
	# of Stations	Area (km^2)	% of Area	# of Stations	Area (km^2)	% of Area
Total Improvements	13	6.28	23.9%	13	6.28	41.5%
Improved One Category	11	5.48	20.8%	11	5.48	36.2%
Improved Two Categories	2	0.8	3.0%	2	0.8	5.3%
Total Declines	4	7.86	29.9%	3	2.28	15.1%
Declined One Category	4	7.86	29.9%	3	2.28	15.1%
No Change	13	12.16	46.2%	12	6.58	43.5%
Total	30	26.32	100%	28	15.16	100%

Table 22. Sediment Quality Triad Index, comparing results for 1998 PSAMP/NOAA and 2007 Urban Waters Initiative stations, PSAMP sediment monitoring Central Sound region (1998-1999), and entire Puget Sound baseline (1997-2003). Results are given for all stations and for only harbor and urban stations.

	Incidence (Percent of Stations)					Spatial Extent (Percent of Area)			
All Stations	Elliott Bay / lower Duwamish		PSAMP Central Region	Puget Sound Baseline		Elliott Bay / lower Duwamish		PSAMP Central Region	Puget Sound Baseline
	1998	2007				1998	2007		
Number of Stations:	30	30	128	381	Area (km^2):	26.32	26.32	683.92	2294.15
High	13.3%	23.3%	53.9%	52.5%		49.5%	31.4%	90.9%	62.4%
Intermediate/High	33.3%	40.0%	22.7%	31.5%		18.9%	49.1%	6.8%	31.5%
Intermediate/Degraded	43.3%	36.7%	19.5%	13.4%		28.6%	19.5%	2.0%	5.8%
Degraded	10.0%	0.0%	3.9%	2.6%		3.0%	0.0%	0.3%	0.4%
Harbor and Urban Only									
Number of Stations:	28	28	75	149	Area (km^2):	15.16	15.16	60.9	161.44
High	7.1%	21.4%	29.3%	43.6%		12.3%	17.7%	54.4%	56.0%
Intermediate/High	35.7%	39.3%	32.0%	27.5%		32.8%	48.4%	21.3%	32.9%
Intermediate/Degraded	46.4%	39.3%	32.0%	22.8%		49.6%	33.9%	21.3%	9.7%
Degraded	10.7%	0.0%	6.7%	6.0%		5.3%	0.0%	3.0%	1.4%