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Sediment Quality in Commencement Bay


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Anthropogenic: Caused by humans.

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.

Benthic invertebrates (or benthos): Sediment-dwelling invertebrates, organisms that live on or in marine sediments.

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 that 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.

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) that feed at the bottom of a waterbody.

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

ERM quotient: Ratio of a chemical concentration to the respective Effects Range-Median (ERM) sediment quality guideline for that chemical.

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.

Invertebrates: Animals without backbones (e.g., crustaceans, worms, clams).

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

Multidimensional scaling: A mathematical method that 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.

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, these are any unconfined and diffuse source of contamination and often unregulated.

Pielou's Evenness (J'): An index of the equitability (evenness) of the distribution of individuals among species in a sample.

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.

Spatial extent: An estimate of the size of area affected by a measure or variable of environmental quality, usually expressed as percentage of the total survey area.

SQS quotient: Ratio of a chemical concentration to the respective Washington State Sediment Quality Standard (SQS).

Stratum (plural, strata): Segment(s) of the study area with a defined set of characteristics.

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

Taxa richness: Number of different taxa.

Taxa: Plural of taxon.

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

Temporal: Relating to changes over time.

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

Acronyms and Abbreviations

Ag	Silver
ANOSIM	Analysis of Similarity
ANOVA	Analysis of Variance
As	Arsenic
ASARCO	American Smelting and Refining Company
ASE	Accelerated solvent extraction
ASTM	American Society for Testing and Materials
BNA	Base/Neutral/Acid semivolatile organic compounds
Cd	Cadmium
CDF	Cumulative distribution function
CI	Confidence interval
Cu	Copper
CSL	Washington State Cleanup Screening Levels defined in SMS
CVAA	Cold vapor atomic absorption
DGPS	Differential Global Positioning System
DMMP	Dredged Material Management Program
DQO	Decision Quality Objective
EAP	Ecology's Environmental Assessment Program
Ecology	Washington State Department of Ecology
EIM	Ecology's Environmental Information Management System
EMAP	U.S. EPA's Environmental Monitoring and Assessment Program
EPA	U.S. Environmental Protection Agency
ERL	NOAA's Effects Range Low sediment quality guideline
ERM	NOAA's Effects Range Median sediment quality guideline
GC/ECD	Gas chromatography/electron capture detection
GC/MS	Gas chromatography/mass spectrometry
GC-DDC/ECD	Gas chromatography dual dissimilarity column/electron capture detection
GIS	Geographic Information System
GPC	Gel permeation chromatography
GRTS	Generalized random tessellation stratified survey design
Hg	Mercury
Hg+	Mercury ion
HPAH	High molecular weight PAH
ICPMS	Inductively coupled plasma/mass spectrometry
LPAH	Low molecular weight PAH
MDS	Non-metric multidimensional scaling
MEL	Ecology's Manchester Environmental Laboratory
MESA	NOAA's Marine Ecosystems Analysis project
MQO	Measurement Quality Objective
NCA	U.S. EPA's National Coastal Assessment program
NOAA	National Oceanic and Atmospheric Administration
NS&T	NOAA's National Status and Trends program
PAH	Polycyclic aromatic hydrocarbon or polynuclear aromatic hydrocarbon (synonymous)

Pb	Lead
PBDE	Polybrominated diphenyl ether
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)
PSAT	Puget Sound Action Team
PSDDA	Puget Sound Dredged Disposal Analysis program
PSEP	U.S. EPA's Puget Sound Estuary Program
PSP	Puget Sound Partnership
QA	Quality assurance
QA/QC	Quality assurance/quality control
QAPP	Quality assurance project plan
QC	Quality control
RCW	Revised Code of Washington
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
SMS	Sediment Management Standards (Washington State Sediment Management Standards, Chapter 173-204 WAC)
SOP	Standard operating procedures
SQG	Sediment quality guideline
SQGQ	Sediment quality guidelines quotient
SQS	Washington State Sediment Quality Standards defined in SMS
SQTI	Sediment Quality Triad Index
TBA	Tetrabutylammonium hydrogen sulfate
TOC	Total organic carbon
U.S. EPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
UWI	Urban Waters Initiative
WAC	Washington Administrative Code
WSRT	Wilcoxon signed ranks test
Zn	Zinc

Units of Measure

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

Abstract

The Urban Waters Initiative (UWI) is a multi-agency program to reduce toxic chemical pollution in selected urban bays of Puget Sound. As part of the UWI, the Washington State Department of Ecology is assessing sediment quality throughout those bays to determine current conditions and compare them to past conditions. These bay-scale assessments provide information to environmental managers concerned whether and how the collective effects of multiple localized cleanups and source controls improve bay-wide conditions over time. In 2008 Ecology sampled Commencement Bay, including adjoining waterways.

The UWI sediment surveys are part of the Sediment Component of the Puget Sound Assessment and Monitoring Program (PSAMP). The sampling design enables assessment of sediment conditions on several spatial scales, from bay-wide to Sound-wide. The PSAMP sediment monitoring program developed baseline conditions from 1997-2003 surveys for comparison to current UWI results. The program uses a multiple-variable Sediment Quality Triad Index that combines measures of exposure (sediment contamination), response (toxicity), and biological effects (benthic invertebrates) to classify sediment quality on a 4-level scale from high quality to degraded.

In 2008, approximately 15% of Commencement Bay had contaminated sediments and 35% had adversely affected benthic communities. About 12% of the area had both. None of the sediments were highly toxic in two kinds of laboratory tests. Overall, 61% of the area had high sediment quality.

Comparisons with similar data from 1999 showed:

- Decreased sediment contamination by numerous toxics, primarily polycyclic aromatic hydrocarbons and metals.
- Increased contamination by phthalates.
- Slightly decreased toxicity.
- Improved benthic community health in the waterways, but deterioration in the central-southeastern bay.
- Shifts from both degraded conditions and high sediment quality to intermediate conditions, possibly reflecting both positive effects of numerous cleanups and source controls and negative effects of habitat changes in the central-southeastern portion of the bay.

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Executive Summary

As part of the Urban Waters Initiative (UWI), site managers, planners, and engineers in the Washington State Department of Ecology (Ecology) are working with local governments near Puget Sound's urban bays to reduce toxic chemical pollution. Numerous activities have been completed or are underway to help reduce pollution entering the urban bays of the Sound. As part of the Initiative, Ecology's marine biologists are assessing sediment quality throughout selected urban bays that adjoin Puget Sound, including Elliott Bay and Commencement Bay. Commencement Bay, including the adjoining waterways, was sampled in 2008, the second year of these assessments. Monitoring results are being compared to results from previous surveys to provide information on whether the combined effects of environmental regulation, source control, and localized cleanup efforts have had positive impacts bay-wide and to describe the nature of changes, if any.

The specific objectives of the UWI study in Commencement Bay were to:

1. Assess the current conditions in the area, particularly the overall spatial extent of sediment degradation.
2. Determine whether there had been changes in the incidence, spatial extent and spatial patterns in measures of degraded sediment quality over time.
3. Compare estimates of the extent of sediment quality degradation in Commencement Bay with similar estimates for the other regions of the Sound and throughout the entire Sound.

Surface sediments from 30 sampling locations (i.e., stations) selected by statistical random design were sampled throughout all reaches of the bay and the adjoining industrial waterways in June of 2008. Each was analyzed to measure three different indicators of sediment quality: sediment chemistry, sediment toxicity, and the composition of benthic (bottom-dwelling) invertebrate assemblages. These three indicators were then combined into Ecology's Sediment Quality Triad Index (SQTI), an important, multi-variable indicator of sediment quality in Puget Sound.

Results of the 2008 UWI study were compared to results from a joint Ecology/NOAA survey of the same area conducted in 1999 to determine what changes, if any, had taken place in the interim and the magnitude of any changes. Bay-wide sediment quality was also compared with baseline conditions previously estimated by Ecology for adjoining central Puget Sound, other regions and all of Puget Sound using the SQTI and with historical data collected in the early 1980s.

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 Commencement Bay

The probability-based sample design enabled estimation of spatial extent of sediment quality degradation for each sediment parameter measured and for the measures combined in the SQTI. Spatial extent was estimated as both area (km^2) and the proportion of the total 24.06 km^2 study area. Station area-weightings were unequal and defined by the statistical study design.

Sediment Contamination

Sediment samples were analyzed for more than 130 potentially toxic contaminants, among them metals, polycyclic aromatic hydrocarbons (PAHs), phthalates, and chlorinated hydrocarbons, such as numerous pesticides and polychlorinated biphenyls (PCBs).

Spatial Extent

- There were eight stations (27%) that were chemically contaminated. Therefore, approximately 3.7 km^2 or 15.5% of the total study area was chemically contaminated with one or more chemicals exceeding Washington State Sediment Quality Standards (SQS) sediment management criteria. The SQS values were exceeded for 19 of 41 chemicals or chemical groups for which there are State criteria.
- Cleanup Screening Level (CSL) sediment management criteria were exceeded at four stations (13%), representing 13.1% of the study area. (CSL values generally are higher than the corresponding SQS values.) These are the stations where ecological risks were highest.
- Six samples exceeding SQS criteria did so for a single chemical or chemical group. Most chemicals or chemical groups exceeded their respective SQS values in only one or two samples each. Mixtures of metals and organic compounds were found in all 30 samples. The chemical that exceeded its SQS most frequently was butylbenzylphthalate.
- No SQS were exceeded at 22 of the 30 stations (73%), representing almost 85% of the study area. Therefore, chemical contamination did not represent a high toxicological threat to the local benthos in the majority of the bay.
- The toxicological risks of the presence of mixtures of chemicals were very low in 19 stations, slightly elevated in 9 stations, moderate in 1 station, and high in 1 station. The latter two stations were in Thea Foss Waterway.

Geographic Patterns

- Sediments in the northeast portion of the bay were very muddy (>90% silt-clay); sediments tended to be sandiest in the central-southeast portions of the bay.
- Total organic carbon (TOC) was lower in the Blair Waterway and central inner and outer portions of Commencement Bay than elsewhere in the study area. TOC was particularly high in the inner portion of Thea Foss Waterway.
- The eight stations that were chemically contaminated occurred in several areas, including the Thea Foss Waterway, Hylebos Waterway, the mouth of the Middle Waterway, and off the Tacoma shoreline.

- Two stations in the Thea Foss waterway were most contaminated. They had 11 and 14 chemical concentrations, respectively, that exceeded the State criteria. In general, contaminant concentrations were highest in the Thea Foss and Hylebos Waterways and lowest in the outer bay.
- Each chemical and chemical class that exceeded the State criteria had unique, but sometimes overlapping, geographic patterns in their distributions in the study area.
- Due to considerable amounts of cleanup over the past 25 years, these spatial patterns are somewhat different from what was reported in sediment quality studies conducted there by NOAA in the early 1980s and by the joint Ecology/NOAA survey in 1999.

Sediment Toxicity

- Based on the results of the lethal and sublethal toxicity tests performed, no stations had toxic sediments in 2008. Therefore, both the incidence and spatial extent of toxicity were zero in each test and both tests combined.

Invertebrate Communities

- There were wide ranges in total abundance and taxa richness among stations. Most stations had relatively high numbers of dominant taxa.
- The annelids and molluscs were the most abundant groups, followed by the arthropods, echinoderms, and miscellaneous taxa. Arthropod abundance was relatively low at most stations. Echinoderms were absent from seven stations, miscellaneous taxa were absent from three stations, and arthropods were absent from one station.
- There were four distinct assemblages of benthic species among the 30 stations. Species composition of the assemblages was primarily related to differences in water depth and to a lesser degree TOC and percent fines concentrations. One station in Thea Foss Waterway had a unique assemblage dominated by oligochaetes.
- The benthic invertebrate assemblages were considered to be adversely affected at 12 stations, representing 8.5 km^2 and about 35% of the study area.
- Adversely affected benthic invertebrate communities often had low taxa richness and supported large numbers of pollution-tolerant species.

Sediment Quality Triad Index

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

- Fifteen of the 30 stations, representing about 14.7 km^2 (60.9% of the study area), had high sediment quality, as gauged by the SQTI.
- Ten stations, representing 6.6 km^2 (27.4% of area), had intermediate/high sediment quality, with degradation in one of the triad elements.

- Five stations, representing 2.8 km^2 (11.7% of area), had intermediate/degraded sediment quality, with degradation in two of the triad elements.
- None of the stations or area sampled in 2008 had degraded sediment quality as measured with all three triad elements.

Comparison to 1999 Conditions

Overall, there was a mixture of temporal trends between 1999 and 2008. Most measures indicated improvements (decreases) in sediment contamination by metals and PAHs on a bay-wide scale. Bis(2-ethylhexyl)phthalate contamination increased. One test of toxicity indicated a slight improvement, whereas another test indicated no change, with no highly significant responses in either survey. The proportion of the study area with adversely affected benthos increased. The following changes were found.

Sediment Contamination

- *Metals:* The concentrations of arsenic, copper, lead, mercury, nickel, silver, tin, and zinc decreased significantly. There were no statistically significant changes in the levels of cadmium or chromium.
- *PAHs:* The concentrations of most PAHs decreased. There were no changes in the levels of acenaphthylene or benzo(b)fluoranthene.
- *PCBs:* There were too few detected results in either 1999 or 2008 to conduct a statistical comparison.
- *Phthalates:* Bis(2-ethylhexyl)phthalate concentrations increased.
- *Chlorinated pesticides, other organic compounds (BNAs):* There were too few detected results in either 1999 or 2008 to conduct a statistical comparison.
- *Comparison to sediment quality standards:* Relative to the SQS values, there were seven stations that were contaminated in 1999 and eight in 2008. There were no statistically significant changes in numbers of stations, proportion of area, and number of chemicals exceeding their respective SQS, with the exception of an increase in the proportion of area for which the SQS for bis(2-ethylhexyl)phthalate was exceeded.
- The incidence of contamination by one or more chemicals or chemical classes relative to the NOAA Effects Range Median (ERM) sediment quality guideline values declined from 44% of stations in the early 1980s to 24% in 1999 and 13% in 2008.

Sediment Toxicity

- Sediment toxicity, as measured by the one sublethal toxicity test common to both surveys, decreased from one station representing less than 1% of the study area in 1999 to none in 2008. A test of acute toxicity indicated none of the samples was toxic in either 1999 or 2008.

Invertebrate Communities

- Some indices of benthic invertebrate community health improved from 1999 to 2008. At six stations in the waterways, the condition of the benthos improved from affected to unaffected; and at four other stations in the waterways, the benthic communities showed signs of improvement but were still classified as adversely affected. However, at four stations in the south-central portion of the bay the benthic communities showed signs of degradation and were classified as adversely affected.
- The numbers of stations classified as adversely affected decreased slightly from 1999 to 2008; however, the affected area increased substantially.

Sediment Quality Triad Index

- Sediment quality, as measured by the SQTI, improved for 3.7% of the study area (6 stations), remained the same for 44.0% (13 stations), and declined for 22.4% (6 stations). The five stations not sampled in 1999 account for the remaining 29.8% of study area. Most of the improvements were in the waterways.
- Sediment quality in the outer and northern portions of the bay and along the Tacoma waterfront, already high, remained high.
- Sediment quality declined at five stations in the central-southeastern portion of the bay due primarily to adversely affected invertebrates.
- Increased levels of bis(2-ethylhexyl)phthalate resulted in decreases in sediment quality at several stations.
- No sediment was classified as degraded in 2008. In 1999, a single station in the Thea Foss Waterway, representing 0.5% of the study area, had degraded sediment. In 2008, sediment quality at that station was intermediate/high.

Sediment Quality at Different Spatial Scales

The 2008 UWI Commencement Bay sampling frame is nested within the PSAMP Sediment Component's Central Region, which aligns well 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 comparisons of sediment quality at several spatial scales and between urbanized vs. non-urbanized areas.

- High sediment quality was found in a much smaller proportion of the Commencement Bay study area 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.

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 by:

- Determining the current status of and temporal trends in sediment quality in major geographic regions and habitat types in the Sound.
- Determining the degree and nature of changes in sediment quality over time as estimates of the effectiveness of the collective efforts to improve the quality of the environment.
- Relying upon multiple complimentary indices to classify sediment quality in the Sound.
- Estimating and reporting sediment quality for spatial scales ranging from individual stations, waterways and reaches to entire bays and the entire Puget Sound.
- Relying upon the current state of the science methods and criteria for classification of sediment quality and striving to improve those methods and criteria.
- Communicating results to PSP members and other stakeholders via multiple kinds of oral presentations and written reports.

Recommendations

A number of recommended changes in sediment quality monitoring could be made to improve the program at all scales, from bay-wide to Puget Sound-wide. Included are specific recommendations to:

- Continue the existing PSAMP and UWI programs, and expand the urban bays sampling into other large urban bays, smaller urban bays, and some selected rural bays. Resample the large urban bays at approximately 6-year intervals.
- Refine the sediment chemistry, toxicity, and benthic indices to improve their effectiveness and predictive abilities specifically in Puget Sound.
- Integrate sediment monitoring with other ecosystem monitoring, including other components of PSAMP and regional stormwater monitoring.

Introduction

Problem Statement

Commencement Bay and the adjoining waterways have long been known to be adversely affected by toxic chemicals (Malins et al., 1982; Chapman et al., 1982; Long, 1982; Singleton, 2008). Since the early 1980s, the nearshore tideflats and waterways at Tacoma have been among the highest-priority Superfund sites in the country (Singleton, 2008; U.S. EPA, 2009). High concentrations of contaminants were found in sediments, the water column, benthic invertebrates, demersal fish, marine birds, and marine mammals (Long, 1988). These chemicals had accumulated over decades in the sediments (Long, 1988). Over the years, new sites and sources of contamination have been identified for cleanup (Singleton, 2008). Because of the long history and degree of contamination, there is also concern over post-cleanup recontamination and resuspension of contaminants by disturbance (Singleton, 2008).

Millions of dollars have been spent to clean up the most contaminated sites, and most of the cleanups are nearing completion (Singleton, 2008). 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. The topic of interest in this report is whether sediment quality throughout the bay has changed over time, particularly the past 10 years, and in what ways.

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 three waterbodies initially targeted by the Washington legislature are Elliott Bay and its adjoining waterways, Commencement Bay and its adjoining waterways, and the Spokane River.

The Ecology Urban Waters Initiative (UWI) 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 assessing sediment quality in these urban bays. In 2008, the second year of these assessments, Commencement Bay (including the adjoining waterways) was sampled.[1] In this report, monitoring results are compared to results from previous studies to provide information on whether and how changes in sediment quality have occurred, bay-wide.

[1] A report on bay-wide sediment assessment of Elliott Bay and the adjoining waterways of the lower Duwamish River conducted in 2007 has been published (Partridge et al., 2009).

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 changes in sediment contamination, toxicity, and benthos. Armed with such information, managers may direct further research and monitoring efforts to understand the 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

Commencement Bay is part of Puget Sound. It adjoins Puget Sound in the southern reaches of the Central Basin (also known as the Main Basin). The northern boundary of the study area is a straight line from Browns Point to Point Defiance (Figure 1). The City and Port of Tacoma define the study-area boundaries to the northeast, east, and south. Included in the study area are the major industrial waterways (Thea Foss, Middle, Sitcum, Blair, and Hylebos Waterways), though not the lower Puyallup River or Puyallup Waterway. Excluded was an area off the Ruston shoreline that was previously observed to be composed mainly of ground ASARCO slag that could not be sampled efficiently with our grab sampler.

Water circulation in the bay is driven by a combination of tidal hydraulic pumping through the Tacoma Narrows, two-layered estuarine flow through the Main Basin and Colvos Passage, prevailing southwesterly winds, and freshwater input (Ebbesmeyer et al., 1986). The Puyallup River is the main freshwater source, entering Commencement Bay on the eastern shore. Several small streams also provide freshwater to the bay via several waterways that were dredged historical creekbeds.

The study area hosts a variety of urban and industrial activities, multiple stormwater and sewage outfalls, Superfund sites, dredged-materials disposal site, and a busy port. Potential sources of toxicants to the bay include a municipal wastewater treatment facility, a pulp and paper plant, log storage and shipment, chlorine gas production, oil and asphalt refining, metals production, plywood production, marinas, pleasure boats, boat repair yards, barge fabrication and repair, automobile shipments and storage, and stormwater from surface streets, parking lots, railroad lines, and highways.

Resources at Risk

A wide variety of marine and estuarine biological resources and humans are at risk from chemical contamination of the sediments in Commencement Bay (Long, 1985). The soft sediments are a key habitat for numerous benthic invertebrates that depend upon uncontaminated conditions, including crabs, shrimp, other crustaceans, polychaete worms, and large and small bivalves. Many of the crustaceans that live near the bottom in association with sea grasses are important prey for demersal fish species in Puget Sound (Simenstad et al., 1979). Demersal fish, such as sole and flounder, are important sources of nutrition for larger predatory fish, seals, orcas, octopus, marine birds, and human anglers. Commencement Bay hosts important native tribal subsistence and commercial fisheries for migratory salmon and a recreational fishery for other species (EVS, 1995; U.S. EPA, 2009).

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 Commencement Bay. 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 Commencement Bay 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 for this report (Appendix A[2]).

All of the data from the historical research, collectively, served to identify (1) those areas of Commencement Bay where problems of chemical contamination were greatest and (2) which chemicals were detected most often. Metals, polycyclic aromatic hydrocarbons (PAHs), and phthalates are some of the chemicals that were most often detected in Commencement Bay sediments. Maps depicting measured concentrations for several metals and organic compounds relevant to this Urban Waters 2008 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 (80 studies) was compared to Washington State regulatory sediment criteria promulgated by Ecology for 47 chemicals or chemical groups (Ecology, 1995). Of the 47 Sediment Quality Standards (SQS), 46 were exceeded at one or more of 758 stations in the historical data for this region (Appendix A). Chlorobenzenes, total polychlorinated biphenyls (PCBs), mercury, and phthalates exceeded SQS criteria most frequently; only the SQS for diethylphthalate was not exceeded. Of the 47 Cleanup Screening Levels (CSL), 42 were exceeded at one or more of 564 stations. The CSL were not exceeded for

[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, National Marine Fisheries Service, National Oceanic and Atmospheric Administration), as well as from peer-reviewed journals.

anthracene, fluoranthene, and several phthalates (diethyl-, di-n-butyl-, and di-n-octyl-). Generally, the CSL values are higher than the SQS values.

Summary of Historical NOAA and U.S. EPA Studies

The National Oceanic and Atmospheric Administration (NOAA), through its Marine EcoSystems Analysis (MESA) Puget Sound project, generated considerable information on sediment contamination and its effects on the biota in the Commencement 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, 2000; Long and Sloane, 2005; Long et al., 1996, 2000, 2003; Turgeon et al., 1998). Many of the methods used in the MESA studies were sufficiently similar to those still used by Ecology in the current Puget Sound Assessment and Monitoring Program (PSAMP) monitoring to warrant qualitative comparisons.

Some of the more significant chemical and toxicity data from the MESA studies are summarized in Appendix A.

The MESA study in Commencement Bay included chemical analyses of surficial sediments in all of the waterways, off the shorelines of the bay, and in the mouth of the bay near the boundary with the Main Basin (Malins et al., 1980, 1982; Long, 1982). These studies found that sediments were most contaminated in the waterways, especially the Hylebos Waterway and City Waterway (now known as Thea Foss Waterway) (Appendix A). Substantial numbers and percentages of samples were contaminated. Each of the urban bays of Puget Sound had its own unique chemical signature based on the history of inputs, and Commencement Bay was 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.

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

Sediments in the waterways other than Hylebos and City generally had lower levels of contamination. Conditions tended to improve in these other waterways and off downtown Tacoma, Ruston, and Point Defiance, and to a lesser degree seaward toward Browns Point. Often, the lowest chemical concentrations were found in the center and mouth of the bay. High concentrations of metals often were found off the Ruston shoreline in chunks of ASARCO copper-smelter slag and were assumed to be inert (Long, *pers. comm.*).

The NOAA/MESA Project also funded four studies of the toxicity of sediments in Puget Sound. They were conducted in four sequential phases and spanned the years of 1981 – 1983 (Chapman et al., 1982, 1983, 1984a, 1984b). Three of the four phases involved Commencement Bay.

In the exploratory Phase I, a wide variety of test species was used to measure a variety of kinds of endpoints, most of which were not used again in Puget Sound. None of the acute tests showed any significant mortality in any of the samples from Commencement Bay. However, a test of metabolic respiration in an oligochaete worm showed significant decreases in 46% of the samples, and significant cell and chromosomal damage were observed in the genotoxicity test in 32% of the samples (Chapman et al., 1982). Samples which showed significant toxicity were from stations scattered throughout the waterways and off the Ruston shoreline.

Phase II was a field experiment to determine possible methods for measuring reproductive effects with many kinds of experimental tests (Chapman et al., 1983). Sediment samples were collected at 22 selected stations throughout Puget Sound, 10 of which were scattered throughout Commencement Bay and the adjoining waterways. In tests of morphological abnormalities of oyster embryos exposed to sediment/water mixtures, the most toxic samples were those from Hylebos and City Waterways (Chapman et al., 1983). Surf smelt tests indicated that the most toxic samples occurred in sediments from Hylebos, Blair, and City Waterways.

Sediment toxicity was determined in northern Puget Sound during Phase III (Chapman et al., 1984a). The triad approach now used regularly nationwide and in other countries to assess sediment quality was debuted as Phase IV in 1985 with data from Elliott and Commencement Bays and other Puget Sound areas (Chapman et al., 1984b; Long and Chapman, 1985).

The U.S. Environmental Protection Agency (U.S. EPA) lab in Newport, OR, also studied Commencement Bay in the 1980s. They tested sediments throughout the bay and the waterways with the estuarine amphipod *Rhepoxynius abronius* (Swartz et al., 1982). Among 175 samples tested during four periods, the incidence of toxicity was 58%. In 10 of 66 samples from the Hylebos Waterway the survival rate in the tests was zero. The only other areas in which zero survival was observed in the samples were Blair Waterway, City Waterway, and the other waterways. The numbers of resident amphipods and of amphipod species were lowest (often zero) in the benthic samples from the waterways that were most toxic in the laboratory tests.

Brief Overview of Cleanups in Commencement Bay

Commencement Bay Nearshore/Tideflats Superfund Sites

In the early 1980s, several portions of Commencement Bay and adjoining waterways were placed on the Superfund National Priorities List (Singleton, 2008; U.S. EPA, 2009). By 2007, 19 sediment cleanup sites under federal or Washington state jurisdiction were identified (Singleton, 2008). As of 2009, the cleanups and remediation have been completed for the Middle, St. Paul, and Sitcum Waterways (U.S. EPA, 2009). Most of the remediation and cleanups have been completed in the Hylebos and Thea Foss Waterways (U.S. EPA, 2009). In the Thea Foss Waterway, there is concern over re-contamination (Singleton, 2008; U.S. EPA, 2009). Source-control efforts continue.

Cleanups and remediations have employed various methods, depending on such factors as source, location, depth, and type of contamination. Cleanup methods have included active management (e.g., dredging, capping) and passive management (allowing nature to take its course, i.e., burial by natural sedimentation).

ASARCO Superfund Sites

Portions of the remediation and cleanups have been completed at the ASARCO (American Smelting and Refining Company) Superfund sites (U.S. EPA, 2009). Offshore of the smelter site, some of the sediment has been capped. Additional work to be done include dredging contaminated sediments from offshore and from the yacht basin, as well as capping of sediments with clean sand (U.S. EPA, 2009).

Rehabilitation[3]

Ecology began a process of contamination source discovery in Commencement Bay in the early 1990s to support the U.S. EPA Commencement Bay Nearshore/Tideflats Superfund project. Rapid industrialization beginning in the 1870s had resulted in many areas of abandoned and contaminated property. The Urban Bay Action Team went through a process of inspecting active facilities and doing historical research on former facilities and abandoned properties to determine what were the sources of contamination entering Commencement Bay. These discovery processes resulted in the establishment of dozens of cleanup sites and, working with the City of Tacoma, the establishment of a very robust stormwater source control program.

Cleanups along Thea Foss Waterway also created a platform upon which the City could attract new development to the downtown area. Many new residential, commercial, and arts-related developments have resulted in the resurrection of a formerly run-down and abandoned downtown core. The University of Washington has established a Tacoma campus that is growing rapidly. Cleanup of waterway sediments and upland properties have included habitat restoration and new habitat creation. Ecology has also contributed to this resurgence by providing state remedial action grant funds to local government to help pay for the much needed cleanups.

Resources

Detailed information on cleanup, source-control, and rehabilitation efforts are given in these websites:

Urban Waters Initiative:
www.ecy.wa.gov/urbanwaters/commencementbay.html

Ecology's Toxics Cleanup Program:
www.ecy.wa.gov/programs/tcp/sites/commBay/commBay.html

U.S. EPA's Superfund Program:
http://yosemite.epa.gov/R10/CLEANUP.NSF/7d19cd587dff1eee8825685f007d56b7/e8d62480494ad483882564f80082a1c0!OpenDocument

[3] This section contributed by M. Coleman, Washington State Department of Ecology.

NOAA's Damage Assessment, Remediation, and Restoration Program (DARRP):
www.darrp.noaa.gov/northwest/cbay/restore.html
www.cbrestoration.noaa.gov/projects.html

Sediment Phthalates Work Group
www.ecy.wa.gov/programs/tcp/smu/phthalates/phthalates_hp.htm

City of Tacoma Public Works:
www.cityoftacoma.org/Page.aspx?hid=939

City of Tacoma Environmental Stewardship Project:
www.cityoftacoma.org/Page.aspx?hid=10501

Port of Tacoma:
www.portoftacoma.com/Page.aspx?cid=1717

Citizens for a Healthy Bay:
www.healthybay.org/cleanup/our-bays-superfund-cleanup

Friends of the Hylebos - Hylebos Creek Conservation Initiative:
www.hylebos.org/programs/conservation-initiative

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Methods

Sample Design

Sediment monitoring for the UWI uses the design and methods of the PSAMP Marine Sediment Monitoring Component (Dutch et al., 2009). PSAMP uses a probability-based sampling design to assess sediment quality in Puget Sound at multiple geographic scales. Sediments are sampled for chemistry, toxicity, and sediment-dwelling invertebrate communities (called benthic invertebrates or benthos) to characterize the extent of degraded sediment quality over a given area.

To characterize change over time, samples for the UWI study were collected at sites sampled a decade earlier as part of the 1997-1999 joint NOAA-Ecology survey of Puget Sound known as PSAMP/NOAA. Twenty-five stations had been selected in Commencement Bay under a stratified random design and sampled in 1999 as part of PSAMP/NOAA. All 25 PSAMP/NOAA sample stations in Commencement Bay were re-sampled in June 2008 for the UWI survey.

To achieve a total UWI sample size of 30 for characterization of current (2008) conditions in Commencement Bay, five additional random sites were selected from the PSAMP Spatial focus studies sample draw (Dutch et al., 2009).[4]

The 2008 UWI sediment survey area covered an estimated 24.06 km^2. Because the population of interest was soft sediments, the area of Commencement Bay offshore from Ruston was not included in the sample frame (Figure 1). Attempts had been made to sample that area previously, and it was found to be unsamplable because of the slag from the former ASARCO mill.

The 2008 UWI Commencement Bay study area is nested within (contained within) the current PSAMP Sediment Component sample frame, which is divided into multidensity categories forming eight "regions" (Figure 2) and five anthropogenic-use/geomorphological "strata"[5] (Figure 3), based on the original PSAMP/NOAA strata. Commencement Bay lies within the PSAMP Central Region, which aligns 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 total Puget Sound sampling frame. This nested series of sampling frames enables comparisons of sediment quality at several spatial scales.

The Commencement Bay UWI survey included areas characterized in PSAMP as industrialized harbors (2.25 km^2) and urban bays (21.8 km^2). Of the 30 UWI sampling sites, 12 were located in the harbor stratum and 18 in the urban stratum (Table 1, Figure 4).

[4] The current PSAMP design uses a spatially-balanced, generalized random tessellation stratified (GRTS) multi-density survey design, as described by Stevens (1997) and Stevens and Olsen (1999, 2003, 2004). Details of this design are described in the PSAMP Sediment Component Quality Assurance Project Plan (QAPP) (Dutch et al., 2009).

[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 strict statistical sampling-design sense, but they are defined subpopulations with specified characteristics. In that sense, they are called strata in this report.

The sample design enables estimation of spatial or areal extent of environmental conditions. For a specified condition (e.g., sediment mercury concentration above 0.41 ug/g), the proportion of the study area with that condition is estimated by summing the amounts of area represented by individual samples with that condition and dividing by the total area.

Because sample locations were originally selected at random within PSAMP/NOAA strata, the sample weights, or estimated amounts of area represented by the stations, 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 estimated amount of area represented.

The majority of field and analytical methods used in the 2008 UWI survey were the same as those used in PSAMP/NOAA (Dutch et al., 1998, 2009); therefore, most of the data collected in the two surveys should be comparable. Specifically, the sampling and laboratory methods; including processing and identification of benthic invertebrates were the same. Most of the sampling personnel, laboratories, and taxonomists were the same. The same critical values or criteria were used during the interpretation of the data. As described in more detail in the comparisons of the 1999 and 2008 data (Results and Discussion), the integration of the chemistry, toxicity, and benthos elements of the Sediment Quality Triad Index for the 2008 data was somewhat different than for the PSAMP/NOAA survey. Therefore, the PSAMP/NOAA data were reassessed using the same methods and station weights as for the 2008 data (Weakland et al., 2009).

Field Sampling

Collection of sediments for chemistry, toxicity, and benthic invertebrates followed the protocols specified in the PSAMP Sediment Component QAPP (Dutch et al., 2009) to ensure compatibility with data from the PSAMP/NOAA study. The QAPP for Ecology's sediment quality monitoring in the PSAMP has been issued several times to update the information (Dutch et al., 1998, 2004, 2009). The methods are based on the Puget Sound Estuary Program (PSEP) Protocols (PSEP 1987, 1996a; http://psparchives.com/our_work/science/protocols.htm).

Sediments were collected during June 2008 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 (below Mean Lower Low Water), the operating limit of the sampling vessel.

Physical and Chemical Analyses

Grain size analyses were conducted by Analytical Resources, Incorporated (ARI) in Tukwila, Washington, using the modified PSEP protocol for analysis of marine sediments with salt correction (PSEP, 1986), as specified in the QAPP (Dutch et al., 2009). Case narratives for the grain size analyses, including quality assurance procedures, are included in the 2008 ARI laboratory report (Appendix E). The data met or exceeded Ecology's quality assurance criteria and therefore were acceptable.

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). Laboratory analytical methods and reporting limits for quantification of chemical concentrations followed those specified in the QAPP (Table 3; PSEP, 1986, 1996b,c; Dutch et al., 2009).

Analytical procedures provided data quality that met or exceeded objective performance criteria specified in the QAPP (Table 3; Dutch et al., 2009), including analyses of blanks and standard reference materials; therefore, the data were accepted. 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.

Toxicity Testing

Amphipod (*Eohaustorius estuarius*) Survival in Solid Phase Sediments

Amphipod survival tests were conducted by CANTEST Ltd., in Burnaby, British Columbia, Canada. Methods used in these 10-day amphipod survival tests complied with recommendations of ASTM (1993) for marine and estuarine amphipods, PSEP (1995), and DeWitt et al. (1989) for *E. estuarius*. Detailed methods for this toxicity test, as well as quality assurance procedures, are included in the 2008 CANTEST laboratory report (Electronic Appendix G; CANTEST Ltd., 2008). The data met or exceeded Ecology's quality assurance criteria and therefore were acceptable.

Sea Urchin (*Strongylocentrotus purpuratus*) Fertilization in Porewater

Tests of fertilization success with sea urchin gametes in sediment porewaters were conducted by the U. S. Geological Survey (USGS), using methods largely developed by the laboratory in Corpus Christi, TX (Carr and Chapman, 1995; Carr, 1998). These methods were developed initially for *Arbacia punctulata* along southeastern U.S. estuaries, but adapted for use in the Pacific Northwest with *Strongylocentrotus purpuratus*. Sediment pore water was extracted with a pneumatic apparatus and was stored frozen until just prior to testing. *S. purpuratus* gametes were exposed to porewaters at 12 °C for 20 minutes to determine toxicity. Each sample was tested with 100%, 50%, and 25% porewater concentrations to determine the percentages of eggs that were successfully fertilized. Detailed methods for this toxicity test, as well as quality assurance procedures, are included in the U. S. Geological Survey (USGS) laboratory report (Electronic Appendix H; USGS, 2009). The data met or exceeded Ecology's quality assurance criteria and therefore were acceptable.

Benthic Community Analyses

All animals retained on a 1-mm screen were identified to the species level, where possible, and counted. The methods and procedures for processing, analysis, and quality assurance of the benthic invertebrate samples were those described in the QAPP (Dutch et al., 2009) and therefore were acceptable.

Data Analyses

Sediment Chemistry Comparison to Regulatory Sediment-Quality Standards

Sediment contaminant concentrations were compared to the Washington State Sediment Management Standards[6] (SMS) (Ecology, 1995) applicable to those contaminants. Nondetects were treated as specified in Ecology (1995). Samples in which none of the Sediment Quality Standard (SQS) values were exceeded were classified as not contaminated. Samples in which one or more of these 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 (Long et al., 2006). Mean ERM quotients were compared to toxicity risk tables of Long et al. (2000) to gauge the degree of contamination by chemical mixtures at each station.

Data for six organic compounds were excluded from the analyses because of the relatively low reliability of the analytical results for these substances. These six compounds were benzoic acid, benzyl alcohol, phenol, 2-methylphenol, 4-methylphenol, and 2,4-dimethylphenol. The laboratory methods used for PSAMP and UWI are intended to analyze large suites of base/neutral/acid (BNA) organic compounds and are not optimized for these specific compounds (Huntamer, *pers. comm.*). The analytical precision and detection limits attained by the lab for analyses of these compounds were highly variable, and in 1999 there were indications of

[6] The Washington State regulatory sediment criteria (Sediment Management Standards; Ecology, 1995) 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 invertebrates are expected always to occur. The Cleanup Screening Levels (CSL) are concentration levels above which at least moderate adverse biological effects are expected to occur. CSL values generally are higher than SQS values for the same chemical.

laboratory contamination in some samples, thereby precluding confidence in the reported concentrations.

Benthic Community Analysis

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

Non-metric multidimensional scaling (MDS) and cluster analyses were conducted in PRIMER v.6 (PRIMER-E Ltd., 2006) to provide graphical depictions of the relative degree of similarity among the benthic assemblages (Clarke and Warwick, 2001). For some analyses, "rare" taxa were excluded based on the following: If the mean abundance over all samples from both years was less than 1, the taxon was excluded. Similarities among samples were determined using the Bray-Curtis similarity measure calculated on 4^{th}-root-transformed abundance data. Two-dimensional maps depicting the relative sample similarities were generated by the MDS ordination algorithm. Cluster analysis dendrograms were generated using group average linkage.

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 benthic communities of each biogeographic area; therefore, application of indices from other regions to Puget Sound benthic communities is not warranted.

Benthic data from this survey were interpreted qualitatively using best professional judgment based on more than ten years of experience with hundreds of samples collected in Puget Sound. Best professional judgment took into account the nine benthic measures mentioned above, presence/absence and abundance of known stress-tolerant and stress-sensitive species (e.g., Diaz and Rosenberg, 1995), and habitat characteristics (depth, salinity, grain size).

The values of the nine benthic invertebrate 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 ranges did not by themselves provide any judgment value as to whether the benthic community was "adversely affected." Classification of the benthic assemblages in Commencement Bay was based on knowledge of and experience with Puget Sound overall, and did not attempt to separate natural and anthropogenic stressors.

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

The use of best professional judgment by benthic experts for assessing the condition of benthic communities has been validated by Teixeira et al. (in press) as “a viable means for calibrating indices of ecosystem condition.” For example, six benthic experts, using their individual methods, classified multiple assemblages similarly with data from southern California (Bay et al., 2007).

Sediment Quality Triad Index (SQTI)

The data from chemical analyses, toxicity tests, and benthic invertebrate assemblage analyses conducted for the 2008 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 in 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). Equal weight is given to each element of the triad. 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 measures indicating unaffected assemblages).
- **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 benthos).
- **Intermediate/degraded quality:** Sediments with degradation in two of the 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(s), and affected benthos (number and diversity of benthic organisms depressed relative to uncontaminated sediments, or benthic assemblage 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 1999 and 2008 results are given in the electronic Appendices D (physical parameters) and I (benthos) of this report.

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).

Comparisons of 2008 Results to 1999 Results

To determine whether parameter values bay-wide had increased, decreased, or remained the same from 1999 to 2008, a weight-of-evidence approach was used. No single statistical hypothesis test combines the attributes of repeated measures, unequal weights, and (for chemistry results) censoring of nondetects. 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.

While 25 stations from 1999 were resampled in 2008, five additional stations were sampled in 2008 to increase the total sample size to 30. Paired comparisons were conducted for resampled stations only. Unpaired comparisons were conducted for all stations and for just the resampled stations. Station weights were adjusted, depending on the number of stations used. In most cases, the analytical results were the same for only resampled stations and all stations.

For sediment chemistry results with nondetects present, nondetects were handled by one of several procedures (set to zero, set to the reporting limit, or censored), depending on the test capabilities. Test results that were consistent were used in the weight-of-evidence. Results that were inconsistent (different answers for different treatments of nondetects) were considered inconclusive and were not used.

Cumulative distribution functions (CDF) and 95% confidence bands, based on Horvitz-Thompson estimates of variance for the unequally weighted samples, were generated to describe the distribution of spatial extent of each parameter of interest. CDFs for 1999 and 2008 (weighted, unpaired) were compared with the Wald F test (Kincaid, 2000, 2006), using a function developed by the U.S. EPA (Diaz-Ramos et al., 1996; U.S. EPA, 2007) and written for the S-PLUS statistical software language (Insightful Corporation, 2005). Nondetects were set to zero for CDF analyses.

Weighted paired differences (for the 25 resampled stations only) 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). For sediment chemistry results with nondetects present, unweighted paired differences 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 Kruskal-Wallis test or the Mann-Whitney test was used to compare the (unpaired) medians of unweighted samples.

Comparisons of Proportions

Fisher’s exact test was to compare the numbers of stations in 1999 vs. 2008 meeting a single criterion, such as sediment contaminant concentration exceeding (worse than) the SQS.

The two-proportion test (normal approximation) was used to compare the proportions of area in 1999 vs. 2008 meeting a single criterion, such as sediment contaminant concentration exceeding (worse than) the SQS.

The chi-square test of homogeneity was used to compare the 1999 and 2008 multinomial distributions of grain size (proportions of gravel, sand, silt, and clay) and Sediment Quality Triad Index classifications (number of stations meeting criteria for 0, 1, 2, or 3 triad elements).

Comparisons of 1999 and 2008 Results to Earlier Results

NOAA, through its Marine EcoSystems Analysis (MESA) Puget Sound project, generated considerable information on sediment contamination and its effects on the biota in the Commencement 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, 2000; Long and Sloane, 2005; Long et al., 1996, 2000, 2003; Turgeon et al., 1998). Many of the methods used in the MESA studies were sufficiently similar to those used in the 1997-1999 PSAMP/NOAA survey and in the current Urban Waters sediment monitoring to warrant qualitative comparisons among the three periods.

Results and Discussion

Site Characteristics (2008)

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).

Due to the northwest-southeast orientation of Commencement Bay, in this report the sampling stations are categorized geographically as follows (Figure 4):

- Outer Commencement Bay: Stations 222, 283, 284, 380.
- Central Commencement Bay: Stations 281, 282, 318.
- Southeast Commencement Bay: Stations 288, 289, 290.
- South Shoreline Commencement Bay: Stations 285, 286, 287.
- East Commencement Bay: Station 88.
- Northeast Commencement Bay: Stations 4, 291, 292, 293.
- Thea Foss Waterway: Stations 294, 295, 296.
- Middle Waterway: Stations 297, 298, 299.
- Blair Waterway: Stations 300, 301, 302.
- Hylebos Waterway: Stations 303, 304, 305.

Physical and Chemical Analyses (2008)

The degree and spatial patterns in chemical contamination can be influenced by both proximity to sources and by a battery of natural factors, including depth, sediment texture (grain size), and TOC content. The degree of contamination would be expected to increase with increasing station depth, percent fines, and percent TOC because all three factors would be indicative of low-energy accumulation zones.

Numerical results from the grain size, TOC, and chemical analyses are given for all stations in Appendix D Tables D-1, D-2, and D-3, respectively. Graphical summaries for each individual parameter are given in Appendix D Figures D-1 (fines), D-2 (TOC), and D-3 through D-133 (chemistry).

Station Depth

Station depths ranged from 4 to 173 meters (Figure 5**)**. There were 17 stations with water depths shallower than 35 m and 13 stations with depths greater than 60 m. As expected, stations were shallowest in the Tacoma waterways, where navigation depths are maintained by periodic dredging and around the perimeter of the bay, and deepest in the middle and outer portions of the bay.

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.

Frequency distributions of the four particle size classes (percent gravel, sand, silt, and clay) are depicted for all stations in Figure 6, and Figure 7 displays the percent fines (silt+clay content). 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.

Percent fines ranged from 18.2 to 96.4 percent. Sediments tended to be sandiest (percent fines lowest) in the western and south-central portions of the bay and at the head of the Thea Foss Waterway. Sediments were muddiest (percent fines highest) near the northern boundary of the bay and outside the Blair and Hylebos Waterways.

Four stations, collectively representing an estimated 10.4% of the study area, had sandy or silty-sand sediments (Table 5). One of those stations, representing about 3.3% of the area, had predominantly sandy sediment. That station was on a steep underwater slope along the southern shore of the bay (Figure 7). Sediments at ten stations, representing over 40% of the area, were predominantly silt+clay. The remainder, 16 stations and 49% of the area, had mixed sediment, ranging from 20% sand/80% fines to 60% sand/40% fines.

Total Organic Carbon (TOC)

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. There is empirical and experimental evidence that demonstrate that the degree of binding and bioavailability of organic toxicants in sediments can be strongly affected by high TOC content (Wenning et al., 2005).

Percent TOC concentrations are summarized in Table 6, grouped by stratum type.

TOC concentrations ranged from 0.53 to 4.74%, with mean 1.235% and standard deviation 0.78%. For two of three stations for which the TOC concentration was measured for a field split, the field split value was similar to the original. However, at the station with 4.74% TOC, the field split TOC was even higher, 8.05%. In the samples in which lab duplicate analyses were performed, the two sets of concentrations were in good agreement, indicating high precision within the analytical lab.

TOC content was considerably higher at the head of Thea Foss Waterway than elsewhere. TOC was relatively low in the Blair Waterway and at stations in the outer and southern sections of the bay, where often fines also were lowest (Figure 8).

TOC content and percent fines in freshwater, estuarine, and marine sediments are generally positively correlated. However, one station in the upper Thea Foss Waterway had high TOC and low fines. That particular station was noted during sampling as being in a bed of eelgrass and algae with really coarse sediment, lots of rotting organic debris, and very strong hydrogen sulfide odor, indicating anoxic conditions.

Chemical Contamination

Summary statistics and numbers of nondetects for each contaminant measured are given in Table 7. Table 7 also lists the 50^{th} and 90^{th} 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, indicating high precision within the analytical lab.

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 (Appendix D Table D-3). The numbers of nondetects for a given analyte ranged from occurring in no stations to occurring in all 30 stations (Table 7).

With one exception (selenium), metals and PAHs were always detected. Metals and PAHs are virtually ubiquitous in Puget Sound (Dexter et al., 1981; Long et al., 2003) and have long been known to be present in Commencement Bay (e.g., Malins et al., 1982).

PCB congeners 101, 138, and 153 were detected in 11 samples each, whereas PCB congener 169 was not detected in any sample. All of the other PCB congeners analyzed for were detected in 1 to 8 samples each.

PCB Aroclor 1254 was detected in 20 samples, and Aroclor 1260 was detected in 7 samples. With the exception of detection of Aroclor 1248 in a single sample, no other Aroclors analyzed for were detected.

PBDE congeners 47, 99, and 209 were detected in the majority of samples; BDE-47 was found in all but two samples. Other PBDE congeners analyzed for were detected in 0-5 samples each.

Bis(2-ethylhexyl)phthalate was detected in all 30 samples. Butylbenzylphthalate was detected in sediments from four of the 30 stations.

Cholesterol was detected in all but two samples, and coprostanol (beta-coprostanol) was detected in 17 of the 30 samples.

With the exception of 4,4'-DDD being detected in ten samples, chlorinated pesticides were found in 0-5 samples each. Most were not detected at all.

Incidence and Spatial Extent of Chemical Contamination

Washington State Sediment Management Standards

Sediment chemical contamination is defined and expressed as the numbers of stations (incidence) and proportion of study area (spatial extent) at which one or both of the Washington State regulatory sediment quality standards (SQS, CSL) were exceeded. Tables 8 and 9 list the stations for each analyte and analytes for each station, respectively, where SQS were exceeded in 2008.

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 based on the principles of equilibrium partitioning (U.S. EPA, 2003). Accordingly, the Washington State sediment-quality standards for PAHs, PCBs, phthalates, and miscellaneous organic compounds are expressed as TOC-normalized criteria (Ecology, 1995).

Of the 41 SQS/CSL chemicals or chemical groups for which sediment quality criteria can reliably be applied, no criteria were exceeded for 22 chemicals (Table 8). For 14 chemicals or chemical groups, only the SQS was exceeded. Both the SQS and CSL were exceeded for 6 of the 41 chemicals.

The chemical which exceeded its SQS most frequently (3 samples) was butylbenzylphthalate. All other chemicals or chemical groups for which the respective SQS were exceeded were in one or two samples each. Those chemicals were copper, mercury, bis(2-ethylhexyl)phthalate, hexachlorobenzene, total PCB Aroclors, and 14 individual or summed PAHs. However, where bis(2-ethylhexyl)phthalate exceeded the SQS, it also exceeded the CSL, whereas butylbenzyl phthalate did not exceed the CSL anywhere.

One or more SQS criteria were exceeded at eight of the 30 stations, for an incidence of contamination of 27% (Table 9, Figure 9). Those eight stations represented an estimated 3.7 km^2 or 15.5% of the study area. Six CSL criteria were exceeded at four stations (incidence of contamination 13%), representing 3.15 km^2 or 13.1% of the study area. No Washington State sediment quality standards were exceeded at 22 stations, representing a total of 20.3 km^2 or 84.5% of the study area.

Six samples exceeding SQS criteria did so for a single chemical or chemical group. Two samples, both from the Thea Foss Waterway, exceeded multiple SQS criteria: 11 in one sample (butylbenzylphthalate and 10 individual and summed PAHs) and 14 in the other (copper, butylbenzylphthalate, and 12 individual and summed PAHs).

Metals SQS and CSL (both) were exceeded at two stations, copper at one, mercury at the other, together representing 1.2 km^2 (8% of area). Organic compounds for which state sediment quality standards were exceeded included (Table 8):

- Numerous PAHs at two stations in the Thea Foss Waterway, representing 0.25 km^2, 1% of the total study area.
- Two phthalates across five stations (total 2.5 km^2 represented, 10.4% of area).
- Total PCB Aroclors (1 station, representing <1% of the study area).
- Hexachlorobenzene (1 station, <1% of area).

NOAA Sediment Quality Guidelines

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 290 to 2.78 at Station 294 (Table 9). Only Station 294, at the head of the Thea Foss Waterway, representing 0.126 km^2 (0.5% of total area), had a mean ERM quotient greater than 1, indicating that, on average, the concentrations of toxicants were greater than the median at which harmful effects to benthos were likely to occur. The next highest mean ERM quotient was 0.52 at Station 296, also in the Thea Foss Waterway; all others were 0.27 or below.

Based on analyses of matching estuarine chemistry and amphipod survival data compiled from studies conducted nationwide (n = 1513), Long et al. (2000) identified four ranges in mean ERM quotients that were associated with increasing percentages of toxicity. In the Commencement Bay 2008 survey, 19 samples had mean ERM quotient < 0.1, corresponding to <10% likelihood of samples being toxic. Nine samples had mean ERM quotient between 0.11 and 0.5, corresponding to 25-30% likelihood of toxicity. One sample each was in the third and fourth (highest) categories of toxicity likelihood, with mean ERM quotients in the ranges 0.51-1.5 and >1.5, corresponding to 50% and >75% likelihood of toxicity, respectively. Both of those two samples were from Thea Foss Waterway (Stations 296 and 294, respectively).

Spatial Patterns in Chemical Contamination

Metals concentrations in the Blair Waterway generally were similar to those in the bay. Concentrations of metals tended to be higher in the waterways than in the bay. Relatively high concentrations of arsenic (Figure 10) and selenium occurred in the Hylebos Waterway. The concentrations of cadmium, copper (Figure 11), lead, silver, tin, and zinc were highest in the Thea Foss Waterway. Both the SQS and CSL (same value as SQS) for copper were exceeded at Station 294 in the upper portion of that waterway.

Mercury concentrations were highest at one station (Station 286) on the southern shoreline of the bay, followed by the waterways except Blair, and lowest in the Blair Waterway and remainder of the study area (Figure 12). Both the SQS and CSL for mercury were exceeded at Station 286.

PAHs were generally highest in the waterways (Figures 13, 14). PAH contamination was an order of magnitude higher in the upper Thea Foss Waterway than in the other waterways. The lowest PAH concentrations were in the bay. Beyond that pattern, other spatial patterns were specific to individual PAHs: Some PAHs were higher in the Hylebos Waterway, with the levels in the Blair Waterway similar to, or lower than, those along the Tacoma waterfront. Generally (though not always), PAH concentrations were lowest in the outer bay.

The SQS and CSL for bis(2-ethylhexyl)phthalate were exceeded in two samples, the highest from Station 282 in the south-central portion of the bay and the other at Station 300 in the Blair Waterway (Figure 15).

Butylbenzylphthalate was found at all three stations in the Thea Foss Waterway one from immediately outside the Middle Waterway (Figure 16). The SQS was exceeded in three of those samples.

New sources of phthalate contamination and phthalate re-contamination of areas of Commencement Bay and adjoining waterways which have been cleaned up is a concern to citizens and environmental agencies. A multi-agency work group has been convened to study phthalate contamination and recommend courses of action (Singleton, 2008; Sediment Phthalates Work Group, 2007).

All PCB congeners detected (i.e., all but PCB 169) were found in the Thea Foss Waterway, and all but five congeners analyzed for were found in the Hylebos Waterway. Although no PCB congeners were detected in samples from Blair Waterway, PCB Aroclor 1254 was found in all three samples taken in the Blair Waterway. PCB Aroclor 1254 was detected in 20 of the 30 samples, including all taken in the waterways.

Sediment at one station in the Hylebos Waterway exceeded the SQS for total PCB Aroclors. The SQS for hexachlorobenzene was exceeded at a different station in the Hylebos.

DDT isomers were found in the Thea Foss and Hylebos Waterways.

PBDE congener 47 was found in samples from all stations, with the exception of two stations in the Thea Foss Waterway. PBDE concentrations were low or not detected in the central and outer portions of Commencement Bay and highest in the Hylebos and Thea Foss Waterways (Figure 17).

Three of the four samples in which hexachlorobutadiene was detected were in the Hylebos Waterway; the fourth was the outermost station sampled in the bay. Hexachlorobutadiene has been reported previously to occur in higher concentrations in the Hylebos Waterway, especially at the mouth of the waterway, than elsewhere in Commencement Bay or Puget Sound (Long, 1984; Norton, 1996).

Coprostanol was not found in the Thea Foss Waterway samples, though cholesterol was. Cholesterol and coprostanol are among several compounds which are used as markers of human waste.

Toxicity Tests (2008)

Samples were classified as highly toxic when mean sea urchin fertilization success in 100% porewater or mean percent survival among amphipods exposed to solid phase sediments was both significantly lower than in the control and less than 80% of the control response. These are the same criteria used previously nationwide in NOAA's sediment quality assessments (Long et al., 1996; Turgeon et al., 1998; Long and Sloane, 2005) and in all PSAMP sediment surveys (Long et al., 2003, 2005).

Mean amphipod survival ranged from 87% to 101% of the control response. There were five samples in which mean amphipod survival was significantly below control survival ($p<0.05$), but not less than 80% of control survival (Table 10). Two of those five samples were from the Blair Waterway, one each from outside the Blair and Middle Waterways, and one was from the outer bay, near Browns Point (Figure 18).

Mean sea urchin fertilization success in tests of 100% porewater ranged from 84% to more than 100% of control response in 25 of the samples (Table 11). There were two samples, one each in the Thea Foss and Hylebos Waterways in which mean sea urchin fertilization was significantly less than control, but not less than 80% of control fertilization (Table 11, Figure 19).

No samples were highly toxic in either of the two tests. Therefore, the incidence and spatial extent of toxicity were both 0% in each test and in both tests combined, and there were no geographic patterns in toxicity.

Benthic Community Analyses (2008)

For decades, benthic ecologists world-wide have been studying the ways that benthic communities respond to different levels of stress (e.g., Pearson and Rosenberg, 1978; Boesch and Rosenberg, 1981; Dauer and Ranasinghe, 1992; Nilsson and Rosenberg, 2000). Benthic invertebrate species have a wide range in sensitivity to various kinds of both natural and anthropogenic stresses such as low salinity, temperature, physical disturbance, chemical pollution, and hypoxia.

A number of publications include observations of the behavior of many species relative to these kinds of stresses. Benthic ecologists studying the effects of stress on benthic communities usually focus on indices of benthic community structure, including abundance, diversity, numbers of dominant species, species composition, presence of stress-tolerant species, and absence of stress-sensitive species.

Assemblage Characteristics

Numerical values of the calculated benthic condition indices are given for all stations in Tables 12 and 13. Graphical summaries are displayed in Appendix I, Figures I-1 through I-9.

Total Abundance and Taxa Richness

Among the 30 samples collected in 2008, 353 taxa of benthic invertebrates were identified, 256 to species level (Appendix J, Table J-1). Benthic invertebrates were found at all stations (i.e., there were no azoic samples). There were averages of 744 individuals (range 165-1771) and 63 taxa (range 28-115) per sample (Table 12).

Total invertebrate abundance was generally higher at the shallow stations along the shoreline of the bay and lower in the waterways and at deep stations in the central and outer portions of the bay (Figure 20). Taxa richness tended to be higher at shallower stations, lower at deeper stations, and intermediate in the waterways (Figure 21).

Evenness and Dominance

Pielou's Evenness Index, a measure of the equitability of species distribution, ranged from 0.46 to 0.80 (Table 12) and was 0.55 or greater for all but one station. Over the 30 stations, the mean evenness was 0.66. No geographical patterns were apparent (Figure 22).

Swartz' Dominance Index (SDI) is the minimum number of taxa accounting for 75% of the total invertebrate abundance in a sample. In the 30 samples in this study, SDI ranged from 3 to 24 taxa, averaging 9.7 (Table 12). SDI tended to be highest in the outer bay and along the southern shoreline of the bay into Thea Foss Waterway and lowest throughout the middle of the bay and along the northern shoreline into the Hylebos Waterway (Figure 23).

Major Taxa Abundance

Annelids accounted for 50.6% of the total abundance and included 165 taxa (47.1% of all taxa) from the 30 samples (Tables 13 and 14). Molluscs made up about 39.6% of the total abundance and were represented by 61 taxa (17.4% of all taxa). Ninety arthropod taxa (25.7% of all taxa) constituted 5.2% of the total abundance. Echinoderms in 12 taxa made up 3.7% of the total abundance, and 22 miscellaneous taxa made up 0.8% of the animals across all samples.

Overall, arthropod, echinoderm, and miscellaneous taxa abundances tended to be low. Arthropods were absent at one station (Station 302, at the head of Blair Waterway), echinoderms were absent at seven stations, and no miscellaneous taxa were found at three stations. Relatively low echinoderm and miscellaneous taxa abundances are not unusual for samples of benthos in Puget Sound.

Absolute abundance and relative abundance of the major taxa groups are displayed by station in Figures 24 and 25. Polychaetes and molluscs tended to be most abundant along the northeastern shoreline of the bay and at the mouth of Middle Waterway. Polychaetes were also abundant in the Hylebos. Arthropods were abundant at only a few scattered stations. The highest abundance of echinoderms and miscellaneous taxa occurred at the mouth of Middle Waterway.

For the most part, molluscs and polychaetes dominated the assemblages in the study area. Polychaetes tended to have the highest percent total abundance in the waterways, and molluscs tended to have highest percent total abundance in the bay itself. Assemblages with high arthropod percent total abundance were located at the mouth of the Commencement Bay, and at Station 290 in the center of the bay (Figure 25).

Dominant Fauna

The most abundant species in each sample ranged from 165 to 1398 individuals and accounted for 59% to 100% of the total abundance (Appendix J, Table J-2). Two species, the bivalve *Axinopsida serricata* and the polychaete *Cossura pygodactylata*, were found in 29 of the 30 samples—all but Station 294, in the upper Thea Foss Waterway.

The abundance of *Axinopsida serricata* ranged from 2 to 577 animals in the 29 samples where it was found, with a median abundance of 100 animals per sample. This accounted for 0.5% to 47.3% of the invertebrate abundance at any given station (excluding Station 294), with a median of 15.1%. *Axinopsida serricata* was among the most abundant taxa in almost all of the samples and was the single most abundant species in 11 of those samples.

Cossura pygodactylata ranged from 1 to 862 animals per sample, with a median abundance of 11. It was among the most abundant taxa in over half of the 30 samples, and was the most abundant species in 6 samples.

Polychaetes of the genus *Aphelochaeta* were found in 25 samples and were the most abundant species in 6 samples.

The polychaetes *Levinsenia gracilis* and *Scoletoma luti* were among the most abundant taxa in 21 and 17 samples, respectively. However, neither species was the most abundant species in any of the 30 samples.

Rochefortia tumida and oligochaetes were common in or near the Thea Foss and Middle Waterways and uncommon elsewhere.

The bivalve *Axinopsida serricata*, which was found at every station except Station 294 and was often the single most abundant species, is thought to be somewhat stress-tolerant. Stress-tolerant polychaete species, such as *Aphelochaeta glandaria*, *Scoletoma luti*, and *Prionospio steenstrupi*, were found in more than half the samples, but were often not among the most abundant species. Stress-sensitive echinoderms were uncommon throughout the study area, although a combination of natural factors such as sediment type and station depth, as well as anthropogenic factors, may account for this. Overall, there were more stress-sensitive than stress-tolerant species present in the samples; however, stress-tolerant species were far more abundant than the stress-sensitive species.

Benthic Invertebrate Assemblages

Four distinct assemblages of benthic invertebrates emerged from the data at 40% similarity (rare species excluded) (Figures 26-28). These assemblages are designated below by the most common and abundant taxa:

- Oligochaeta/*Rochefortia tumida*/*Alvania compacta* (1 station).

  This assemblage occurred at station 294, in the upper Thea Foss Waterway. Station 294 was characterized by a very shallow depth (4 m) and had sandy sediment with 12% gravel, the highest gravel content of all the samples. Oligochaetes comprised 20% of the animals at Station 294, followed by the bivalve *Rochefortia tumida* at 17% of the animals.

- *Cossura pygodactylata*/*Prionospio lighti*/*Trochochaeta multisetosa* (1 station).

  Found at station 290 in southeast Commencement Bay, this assemblage was dominated by the polychaete *Cossura pygodactylata*, which made up 39% of the total abundance. Station 290 was a relatively deep station (117 m) with sandy sediment, and supported the lowest total invertebrate abundance (165 animals) of any station in the study.

- *Cossura pygodactylata*/*Axinopsida serricata*/*Macoma carlottensis* (12 stations).

  Cossura pygodactylata and the bivalves *Axinopsida serricata* and *Macoma carlottensis* were highly abundant or very common at 12 deeper stations (>60 meters) located in central Commencement Bay. These three species made up 23%, 19%, and 12% of the benthos, respectively, at the 12 stations.

- *Axinopsida serricata*/*Aphelochaeta spp.*/*Parvilucina tenuisculpta* (16 stations).

  The bivalves *Axinopsida serricata* and *Parvilucina tenuisculpta*, along with *Aphelochaeta* polychaetes, were highly abundant or very common at 16 shallower (<35 meters) stations located along the shoreline of the bay and in the waterways. For the most part, these stations had silty sediments. Across the 16 samples, these three taxa made up 21%, 12%, and 12% of the benthic invertebrates, respectively.

Affected Benthos

The benthic assemblages at 12 of the 30 stations, representing an estimated 8.5 km^2 (35% of the area), were classified as adversely affected (Table 15). That is, the benthos were judged to be affected negatively by natural and/or anthropogenic stressors which caused reduced total abundance, species diversity, and abundance of stress-sensitive species, and increased abundance of stress-tolerant species. The remaining 18 stations were considered to have unaffected benthic assemblages. The classifications of benthos as adversely affected or unaffected are carried forward into the sediment quality triad analyses. Overall, there were no differences in habitat variables (depth, TOC, fines, salinity) or levels of contamination between adversely affected and unaffected stations.

Stations with adversely affected benthos were located in the Hylebos, Blair, and Thea Foss Waterways, in central to southeast Commencement Bay, and at the northern boundary of the bay (Figure 29). All three stations in the Hylebos Waterway, two of the three stations in Blair Waterway, and one of the three stations in Thea Foss Waterway had affected benthic assemblages. Adversely affected stations in the waterways generally had extremely low arthropod abundance (0-12 animals), low taxa richness, and were numerically dominated by stress-tolerant polychaetes such as *Aphelochaeta* spp., *Scoletoma luti*, and *Prionospio steenstrupi*.

Five of the six adversely affected stations located in Commencement Bay itself were deep stations with relatively low total abundance, taxa richness, and notably low arthropod abundance (16-30 animals). The benthic assemblages of these stations included *Cossura pygodactylata* and *Macoma carlottensis*, as well as stress-tolerant capitellid polychaetes. The final station in the bay that was classified as adversely affected, Station 293, had a high total abundance along with a somewhat higher taxa richness than the other stations; however, arthropod abundance was low, and large numbers of *Aphelochaeta* spp. accounted for most of the high total abundance.

Sediment Quality Triad Synthesis (2008): A Compilation of Chemistry, Toxicity, and Benthic 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 (Hyland et al., 1999, 2003; Long et al., 2000; Long and Sloane, 2005; Wenning et al., 2005; McCready et al., 2006). The data in these documents were compiled from studies performed in estuaries throughout the U.S. (including southeastern estuaries, California, Puget Sound, and Hawaii) and Sydney Harbor in 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; Chapman, 1996; Bay and Weisberg, 2008). 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 invertebrate communities, in fact, are adversely affected or not in association with chemically mediated toxicity.

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; Bay and Weisberg, 2008). 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). For example, some chemicals can occur in samples at elevated concentrations but may not be readily bioavailable and therefore not cause toxicity. Also, natural factors acting alone can cause what we view as adverse benthic effects. Sediments in which the data disagree often are classified as intermediate in quality (Long et al., 2003, 2005).

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 (Bay and Weisberg, 2008; California State Water Resources Control Board, 2009).

As described in the Methods, the Sediment Quality Triad Index (SQTI) developed for the PSAMP sediment monitoring program combines measures of exposure (sediment contamination), response (toxicity), and biological effects (benthic invertebrates) to classify sediment quality on a 4-level scale from high quality to degraded. These methods do not necessarily align with the state regulatory standards, but are based on our Sound-wide experience, Ecology's Sound-wide database, and peer-reviewed methods used in other regions and countries (e.g., Long and Sloane, 2005; Wenning et al., 2005). Equal weight is given to each element of the triad, and classifications of degraded conditions must include biological measures (Bay and Weisberg, 2008).

Fifteen stations, representing about 14.7 km^2 (60.9% of the study area), exhibited no chemical, toxic, or benthos impairment and therefore met the criteria for high sediment quality (Table 16, Figure 30). Ten stations, representing an estimated 6.6 km^2 (27.4% of area), met the criteria for intermediate-to-high sediment quality, with only one element of the SQTI indicating impairment. Another five stations, representing 2.8 km^2 (11.7% of area), had two triad elements indicating impairment and therefore met the criteria for intermediate-to-degraded sediment quality. No stations and none of the area met the criteria for degraded sediment quality, with all three triad elements indicating impairment.

There were eight stations, representing 3.74 km^2 (15.5% 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 12 stations, representing 8.48 km^2 (35.2% of area), the benthic assemblages were judged to have been adversely affected. Five of those stations also had chemical contamination; those five stations represented 2.81 km^2 (11.7% of the study area).

None of the 2008 samples were classified as highly toxic in the amphipod mortality or sea urchin fertilization tests. Therefore, the toxicity element of the triad showed no degradation of the area based on those two tests.

Most of the stations classified as intermediate in quality were in the waterways and in the deep central-southeast reaches of the bay (Figure 30). Many of the high-quality stations were located along the southern shoreline of the bay and in the bay entrance.

Comparisons with 1999 Data

In this section, we compare the results from the 2008 Commencement Bay Urban Waters Initiative survey to those from the 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 PSAMP/NOAA data* (Weakland et al., 2009); therefore, some of the results from 1999 in this report are different from the results in the original PSAMP/NOAA reports (Long et al., 2002, 2003). In particular:

- The results of only two of the original four toxicity studies from 1999 are included, for comparison with the same two toxicity tests performed on the 2008 samples.
- The condition of the benthos was reassessed, as part of the recent reassessment of all of the samples making up the PSAMP 1999-2003 baseline. The benthic experts have accumulated ten more years of experience in assessing benthic conditions in Puget Sound.
- Six of the chemicals for which there are Washington State Sediment Management Standards have not been included in SQTI assessments from both 1999 and 2008 due to long histories of unreliability of results when the reporting limits are frequently higher than the SQS.

In 1999, 25 stations were sampled in Commencement Bay as part of the PSAMP/NOAA survey. In 2008, those 25 stations were resampled, and an additional 5 stations were selected and sampled. In this Urban Waters study we made comparisons of data both from all 30 stations sampled in 2008, and from only the 25 resampled stations, to the 25 stations sampled in 1999. In almost all cases, the comparison results with both methods were the same (i.e., significant change or not). In a few cases, the conditions at the previously unsampled stations did affect the outcome of the 2008-vs-1999 comparisons; those cases are noted. A summary of statistical comparisons of the differences between years is provided in Table 17.

Graphical depictions of weighted and unweighted, and paired and unpaired, results for 1999 and 2008 are displayed for each parameter in Appendix D (grain size, TOC, chemistry) and Appendix I (benthos). For each parameter, the appendices include: (a) censored boxplots of the 1999 and 2008 data and a boxplot of the differences (2008 results minus 1999 results, by station); (b) cumulative distribution function (CDF) curves for the 1999 and 2008 data; (c) a bar chart displaying the 1999 and 2008 results side-by-side for each station; (d) a bar chart of the differences (2008 minus 1999). A map of stations is included for perspective. Below, we describe and discuss the results of the comparisons.

Sediment Characteristics and Chemistry

Grain Size

None of the comparisons (weighted or unweighted, paired or unpaired) indicated that the silt+clay content (percent fines) changed bay-wide from 1999 to 2008 (Table 17).

Total Organic Carbon (TOC)

All comparisons (weighted and unweighted, paired and unpaired) indicated that TOC concentrations decreased from 1999 to 2008 (Table 17). The concentrations of TOC and percent fines frequently are correlated with each other in estuarine sediments, including those throughout Puget Sound (Long et al., 2003), in Hood Canal (Long et al., 2007, 2010), and in the Whidbey Basin (Long, *in prep.*). However, in this area they appear to have not co-varied with each other.

Metals

Paired and unpaired, weighted and unweighted tests all indicated statistically significant decreases in the concentrations of arsenic, copper, lead, mercury, nickel, silver, tin, and zinc (Table 17). There was no change in the concentrations of cadmium, chromium, or selenium. Selenium was detected less often in 2008 than in 1999, but the reporting limit in 2008 was slightly higher than in 1999. The reporting limit for cadmium was lower in 2008 than in 1999, and cadmium was detected in all samples in 2008 (vs. 12 of 25 samples in 1999).

PAHs

All but one of the individual HPAHs and all but a few LPAHs decreased in concentration bay-wide from 1999 to 2008, according to all tests (Table 17). Those compounds that showed no change were acenaphthylene and 2,6-dimethylnaphthalene (LPAHs) and benzo(b)fluoranthene (HPAH). CDF comparisons did not show decreases bay-wide for dibenzothiophene (LPAH) or perylene (HPAH).

Because the Washington State Sediment Management Standards for PAHs are based on TOC-normalization (Ecology, 1995), data comparisons were conducted also for the TOC-normalized PAH concentrations. In contrast to the consistent changes in non-normalized PAH concentrations, indications of change for TOC-normalized concentrations were mixed.

The paired tests, both weighted and unweighted, consistently indicated bay-wide decreases in LPAHs 2-methylnaphthalene and fluorene, and all of the HPAHs, for the 25 resampled stations (Table 17). LPAHs acenaphthene and acenaphthylene showed no change, and indications were mixed for the other LPAHs. The unpaired tests, by contrast, showed decreases in TOC-normalized 2-methylnaphthalene (LPAH), fluorene (LPAH), and benzo(a)anthracene (HPAH) only, and no change for the other LPAHs. Indications of change in the TOC-normalized HPAHs were not significant at $\alpha=0.05$, but were significant at $\alpha=0.10$ (Table 17).

The contrast between non-normalized and TOC-normalized results may be an artifact of the significant decrease bay-wide in TOC concentrations.

It is important to note that PAHs often occur together as complex mixtures in nature. They rarely occur alone and they often occur in the same proportionate concentrations (i.e., the same ratios of one compound to another). A large body of both empirical data and physical chemistry models show the narcotic (i.e., toxic) effects of these compounds is predictable for total concentrations of all parent PAHs (Di Toro and McGrath, 2000; Swartz, 1999; Field et al., 1999). Therefore, data comparisons were conducted for the TOC-normalized summed totals of parent PAHs.

As for the TOC-normalized individual PAH concentrations, indications were mixed for TOC-normalized summed PAHs, likely no change in total LPAH and likely decrease in total HPAH (Table 17).

The Washington State Department of Fish and Wildlife reported that liver disease correlated with PAH exposure has dropped dramatically since the late 1990s in English sole caught in the

Thea Foss Waterway of Commencement Bay (PSAT, 2007). PAHs are narcotic to invertebrates and may be toxic to invertebrates, and some PAHs are carcinogenic or teratogenic to vertebrates (Burgess, 2009).

PCBs

With the exception of Aroclor 1254, PCBs were not detected in the central and outer bay or in Blair Waterway in the UWI samples taken in 2008. By contrast, PCBs were found at several stations scattered throughout the entire bay in 1999. However, our statistical tests indicated no changes occurred bay-wide in the concentrations of most congeners and Aroclor mixtures (Table 17).

Pesticides

Most of the chlorinated pesticides were undetected in both 1999 and 2008, or there were too few detected values, so that comparisons could not be made. The Paired Prentice-Wilcoxon test, a censored procedure, indicated decreases in a few of the DDT isomers (Table 17). Reporting limits were significantly lower in 2008 than in 1999 for most of the pesticides.

Base/Neutral/Acid (BNA) Organic Compounds

There were too few detected values to compare 1999 and 2008 concentrations of most BNA compounds. Comparison of hexachlorobenzene results is not warranted because the compound was analyzed by different methods in 1999 and 2008.

The comparison tests (weighted and unweighted, paired and unpaired) indicated that concentrations of bis(2-ethylhexyl)phthalate increased (Table 17). The concentrations of other forms of phthalates did not change between the two sampling periods.

Changes Relative to Sediment Chemical Criteria

Comparisons between 1999 and 2008 results in this discussion are based on the same chemical lists for both years. As mentioned in the Methods section, the 1999 and 2008 results of sample concentrations in relation to the SQS criteria for several BNA compounds (Long et al., 2002) are not included here, due to the unreliability of chemical analytical results for those compounds.

The numbers of chemicals and stations exceeding the SQS values remained almost unchanged between 1999 and 2008 (Table 17). In 2008 one or more SQS values were exceeded at eight of 30 stations (27%), representing an estimated 3.7 km^2 or 15.5% of the area. In 1999 there were seven stations out of the 25 (28%) where one or more SQS values were exceeded, representing 1.1 km^2 and 4.4% of the area. Therefore, the incidence of chemical contamination changed very little, but the spatial extent of the contamination increased between 1999 and 2008 fourfold.

CSL criteria were exceeded for six contaminants combined over four of 30 stations in 2008, compared with four contaminants across two of 25 stations in 1999. Although the incidence was similar (13% of stations in 2008 vs. 8% of stations in 1999), the spatial extent was far greater in

2008 than in 1999. The two stations in 1999 represented 0.14 km^2, less than 1% of the area, whereas the four stations in 2008 represented 3.15 km^2, or 13% of the area. Two of the stations exceeding CSL criteria in 2008 were in the central and south portions of the bay, and two were in the waterways; whereas in 1999, both stations were in the waterways.

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). Since then, 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 2008 survey, two types of toxicity tests were performed, sea urchin fertilization success and amphipod survival. The sea urchin test has been performed in all of the PSAMP and UWI surveys, and the amphipod mortality test has been performed in most of them.

The lab for the urchin fertilization test was the same USGS lab that tested the 1999 samples. There was a minor methods change, described below, but it did not affect the comparability of the results. Both sets of data met or exceeded Ecology's performance criteria and were acceptable. The tests in both years were performed with the Pacific purple urchin, *Strongylocentrotus purpuratus*.

The sea urchin fertilization test has been performed throughout Puget Sound and nationwide for NOAA by the same lab with very low within-sample variability for many years (Long and Sloane, 2005). 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 1999 and 2008 are comparable.

Both a different lab and a different test species were used for the amphipod mortality tests in 1999 and 2008. The amphipod test species used in the PSAMP/NOAA survey was *Ampelisca abdita*, the same species used nationwide by both NOAA and U.S. EPA in numerous other estuarine sediment quality surveys (Long et al., 1996; Long and Sloane, 2005; U.S. EPA, 2003). *Ampelisca abdita* is a native species in the estuaries of the Atlantic coast and is an invasive species in San Francisco Bay (ASTM, 1993; Long et al., 1990). *A. abdita* has been a reliable and sensitive test species in thousands of samples tested throughout the Atlantic and Gulf of Mexico coasts. It rarely indicated toxicity in uncontaminated samples, and the incidence and degree of response always increased incrementally with increasing contamination of sediments (Long et al., 2000; Field et al., 1999). However, it proved to be relatively insensitive to contaminated sediments in Puget Sound, indicating a significant response in only 1 of 300 samples (Long et al., 2003). Therefore, Ecology switched to using *Eohaustorius estuarius*, a native of Pacific Northwest estuaries, as a test organism for the PSAMP and Urban Waters surveys.

Because the comparisons of sediment toxicity in this 2008 study are based on only the sea urchin fertilization test and the amphipod mortality test, the bay-wide toxicity results for 1999 discussed here differ somewhat from those in Long et al. (2003) which were based on results of four kinds of tests.

In 1999, one station (Station 294) was highly toxic in the urchin fertilization test of 100% porewater; whereas in 2008, none were. Because the number of stations (1 of 25, 4%) and percent of area (0.5%) in 1999 were so small, that decrease to zero in 2008 was not statistically significant at $\alpha = 0.05$.

The amphipod mortality test with *Ampelisca abdita* in 1999 indicated that no stations in Commencement Bay or waterways were highly toxic. Hence, both the incidence and spatial extent of toxicity to amphipods was 0%. In 2008, amphipod mortality tests using *Eohaustorius estuarius* as a test organism indicated that no stations in the same study area were highly toxic. Therefore, both the incidence and spatial extent of toxicity in 2008 also were 0%.

It is noteworthy that two other kinds of tests performed in 1999 showed either significant or highly significant responses in Commencement Bay sediments (Long et al., 2003). Both of these tests were performed on organic solvent extracts of the sediments, were viewed as tests of potential for toxicity, passed or exceeded NOAA's criteria for acceptability, and had been performed nationwide as a part of the NS&T Program (Long et al., 1996). Neither of the tests was run in 2008.

Community Composition and Benthic Indices

Tests of differences in benthic indices between 1999 and 2008 indicated a variety of outcomes for the nine indices (Table 18). Some indices increased overall, some decreased, and others were equivocal. The multiple lines of evidence all gave consistent indications of decreases in arthropod abundance and no change in SDI.

The paired comparison tests on the resampled stations indicated significant changes bay-wide in several benthic measures: decreases in annelid, arthropod, and total abundance, and increases in Pielou's Evenness (Table 18).

CDF comparisons for the resampled stations indicated changes in total abundance, taxa richness, arthropod abundance, and abundance of miscellaneous taxa (Table 18). However, comparisons of CDFs for all stations indicated decreases in taxa richness, arthropod abundance, and mollusc abundance, with suggestions ($0.05 < \text{p-value} \leq 0.10$) of possible decrease in annelid abundance and possible increase in echinoderm abundance.

In a hierarchical cluster analysis of the 1999 and 2008 benthic data together (excluding rare taxa), five assemblages of benthos were apparent at the 40% similarity level (Figures 31, 32). These groupings are named below by the most common and most abundant taxa:

- Oligochaeta/*Rochefortia tumida*/*Alvania compacta* (both years).

  This assemblage occurred at station 294 in the upper Thea Foss Waterway in both 1999 and 2008. In both years, the assemblage at this station was unique in that the species present were different from those at the other stations. From 1999 to 2008, the species remained the same for the most part, but the relative abundances changed. Total abundance nearly tripled and taxa richness increased by about one-third. TOC decreased remarkably from 7.9 to 4.7, and the sediment became sandier, with a marked increase in gravel. It is probable that this station was capped between the sampling in 1999 and that in 2008.

- *Axinopsida serricata*/*Aphelochaeta* spp./*Parvilucina tenuisculpta* (both years).

  This group was characteristic of shallow stations along the shoreline of the bay and in the waterways in both years. At most of the stations with this assemblage, benthic indices and sediment type remained about the same, with a slight decrease in TOC at most stations. Five stations in this group, located in the waterways, had notable shifts in the relative abundance of the species present. Total abundance decreased, driven primarily by decreases in the abundance of stress-tolerant *Aphelochaeta* spp. At four of the five stations, this was accompanied by increases in abundance of the echinoderm *Amphiodia* spp.

- *Cossura pygodactylata*/*Ampharete* cf. *crassiseta*/*Trochochaeta multisetosa* (1999).

  In 1999, Stations 288, 289, and 290 supported an abundant and diverse benthos, characterized by high numbers of *Cossura*, *Ampharete*, and *Trochochaeta*. These stations were located in southeast Commencement Bay near the base of a steep underwater slope and within the Puyallup River plume.

- *Cossura pygodactylata*/*Prionospio lighti*/*Trochochaeta multisetosa* (2008).

  In 2008, Station 290 showed extreme reduction in total abundance, taxa richness, and annelid, arthropod, and mollusc abundance. Ampharetid polychaetes, abundant in 1999, were rare in 2008, along with most other species found in 1999. A shift from silty to sandy sediment appears to be the most likely factor in the change in the assemblage.

- *Axinopsida serricata*/*Cossura pygodactylata*/*Macoma carlottensis* (both years).

  This assemblage characterized all of the deep stations in central Commencement Bay in both years except for Stations 288, 289 in 1999 and 290 in 1999 and 2008.

Between 1999 and 2008, most environmental variables showed little difference between affected and unaffected stations. However, Stations 282, 288, 289, and 290 in south-central to southeast Commencement Bay showed large decreases in the fines and TOC from 1999 to 2008 that accompanied the change in characterization of the benthos from unaffected to adversely affected.

Possible mechanisms which could explain the changes in sediment, and therefore the animals living in or on the sediment, include:

- TOC reduction resulting from source control.
- Reductions in both percent fines and TOC resulting from cleanup by dredging and/or capping.
- The 10 years between sampling events were marked by the growth of a new delta at the mouth of the Puyallup River. The extended mouth may now jet larger grained sediments farther into the bay (Brenner, *pers. comm.*).
- Scouring of fines or deposition of sand by extra-heavy Puyallup River flow resulting from the storms and flooding of late 2007.
- Slumping of underwater slopes, resulting from the 2001 Nisqually earthquake (Gardner et al., 2001).

The degradation of condition of the benthos at those four stations may be temporary. Depending on the mechanism(s) which caused the change in the assemblage species compositions and abundances, regaining unaffected status may be a function of time and biological succession.

In addition, the best professional judgment assessments of the health of the benthos at several stations in the waterways which had been classified as adversely affected in 1999 noted improvements in the benthos, even though those improvements had not been sufficient to classify the same stations as unaffected in 2008.

Sediment Quality Triad Index

Chemistry Element

The number of stations with a triad chemistry "hit" (one or more chemicals exceeding the SQS) increased from seven to eight, but the estimated proportion of area affected increased from 4.4 to 15.5% (from 1.06 to 3.74 km^2) (Table 19). Neither change was statistically significant at $\alpha = 0.05$. One station at the mouth of the Middle Waterway, Station 299, improved from 16 chemicals exceeding the SQS in 1999 to none in 2008. By contrast, Station 296, near the mouth of the Thea Foss Waterway, had 11 chemical concentrations exceeding the SQS in 2008, compared to two in 1999.

Toxicity Element

In 1999, one station in 25 (incidence of 4%) was highly toxic and in 2008, no stations were highly toxic (Table 19). Because the number of stations (1) and percent of area (0.5%) in 1999 were so small, the decrease to zero in 2008 was not statistically significant $\alpha = 0.05$.

Benthos Element

Prior to comparison of benthic community health in 1999 vs. 2008 for this report, the 1999 benthos were reexamined using the same methods as used in 2008. That reassessment resulted in different classification of the benthic assemblage at one station from that published in Long et al. (2002, 2003). The benthos at Station 298, at the mouth of the Middle Waterway, previously categorized as unaffected, was reclassified as affected.

The benthos at six stations in the waterways which had been adversely affected in 1999 were not affected in 2008, and the benthos at an additional four stations showed signs of improvement from 1999 to 2008 (Table 15). But four stations in south-central to southeast Commencement Bay where the benthos was previously unaffected had adversely affected benthic assemblages in 2008 (Tables 15, 18).

The number of stations with affected benthos remained almost unchanged from 1999 (13 stations, incidence of 13/25 = 52%) to 2008 (12 stations, incidence of 12/30 = 40%). Although the amount of area with affected benthic assemblages increased from 3.36 to 8.48 km^2 (from 14% to 35.2% of area), the change was not statistically significant different at $\alpha = 0.05$.

There were several reasons for the seemingly different trends in incidence and spatial extent. Primarily, the stations in the south-central to southeastern portion of the bay where benthic health deteriorated represented a larger fraction of the total area than those in the waterways where benthic community health improved.

Triad

Due to the above-mentioned alterations in the set and treatment of 1999 results for comparison to the 2008 UWI results, the 1999 Sediment Quality Triad Index results differ somewhat from those described in the initial evaluations (Long et al., 2003). The comparisons presented here of the triad results from 2008 to the reassessed 1999 triad results were made on the same basis.

Sediment quality, as measured by the SQTI, improved 6 of the 25 stations sampled in 1999 (24% of stations), remained the same for 13 of 25 stations (52%), and declined for 6 of 25 stations (24%) (Table 19, Figure 33). Most of the improvements were in the waterways.

Sediment quality in the outer and northeastern portions of the bay and along the Tacoma waterfront, already high, remained high.

Sediment quality declined at five stations in the south-central to southeastern portion of the bay due primarily to adversely affected invertebrates. Sediment quality at several other south-central stations declined as a result of increased concentrations of bis(2-ethylhexyl)phthalate. Sediment quality improved at one station as a result of a change in the tests of toxicity.

Overall, 50% of the stations and 61% of the area had high sediment quality in 2008, in contrast to 48% of stations and 86% of area, respectively, in 1999 (Table 20, Figure 34). Although the incidence was essentially the same, the spatial extent of high sediment quality decreased due to the relative weights of the waterway stations which improved and the bay stations which deteriorated.

The incidences of intermediate/high and intermediate/degraded sediment quality were not significantly different in 1999 and 2008 (Table 20). The spatial extent of intermediate/high sediment quality in 2008 was somewhat larger than in 1999, and the spatial extent of intermediate/degraded slightly larger in 2008 than in 1999 (Table 20, Figure 34). Neither difference was statistically significant.

None of the sampling stations was classified as degraded in 2008. In 1999, a single station in the Thea Foss Waterway, representing 0.5% of the study area, had degraded sediment. In 2008, sediment quality at that station was classified as intermediate/high. The decrease from one station representing 0.5% of the study area in 1999 to none (0% of the area) in 2008 was insubstantial and not statistically significant.

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 from the PSAMP Central Sound region and for all of Puget Sound.

Results from the PSAMP/NOAA surveys of 1997-1999 (Long et al., 2003) were combined with results from the surveys of the San Juan Islands, eastern Strait of Juan de Fuca, and Admiralty Inlet in 2002-2003 (Long et al., 2008) for these comparisons. The results of these surveys have been updated for consistency with the methods in this UWI study (Weakland, 2009). 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 toxicity tests.
- Combine expert best professional judgment and the quantitative comparisons of nine benthic measures to the 80% confidence intervals for the Puget Sound 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., 2009) to reflect revised estimates of the area of the target population based on success in the field, according to the methods specified in Stevens and Olsen (2004).

Therefore, the results for the PSAMP sediment monitoring Central Sound region and entire Puget Sound described here differ somewhat from those published from previous evaluations of the data (Long et al., 2002, 2003).

The Central Sound region was sampled a second time in 2008-2009 and by 2012 the second PSAMP rotation through all eight Puget Sound regions will be complete, so these comparisons will be updated in the future.

The incidence (% stations) of the four classifications of sediment quality was very similar in Commencement Bay in 1999 and 2008 and in the Central Region (1998-1999) and in the Sound-wide baseline (1997-2003) (Table 21, Figure 34). In all four data sets, approximately half (48-54%) of samples were classified as high quality, 42-50% were classified as intermediate, and 0-7% were degraded.

The spatial extent (% area) for the four sediment quality categories was similar for Commencement Bay in 2008 and the entire Puget Sound (1997-2003), with 61-62% high, 37-39% intermediate, and 0-1% degraded (Table 21, Figure 34). The proportion of area in the bay with high sediment quality in 2008 (61%) was considerably lower than in 1999 (86%) or in the Central Region (91%), and the proportion classified as intermediate was much higher (27% in 2008 vs. 10% in 1999 and 9% for the region).

Comparison with PSAMP Puget Sound Ambient Values

Puget Sound sediment chemistry average ambient values were calculated as the means of all PSAMP sediment data from basin, passage, or rural strata (290 stations from surveys in 1997-2003, all results including nondetects). Because the purpose was to approximate naturally-existing, non-anthropogenic conditions, data from industrialized harbor and urban bay strata were not included. Nondetects were represented by the reporting limits. Figures 35-38 illustrate the comparisons of the 2008 UWI results to the PSAMP Puget Sound mean ambient results as boxplots of ratios. Values above 1 indicate contaminant levels in Commencement Bay (which are in harbor and urban strata) in 2008 that are above the 1997-2003 PSAMP ambient means.

Cadmium, chromium, silver, and zinc levels in Commencement Bay in 2008 were below Puget Sound ambient levels, with a few exceptions (outliers), usually Station 294 (Figure 35). Median concentrations of arsenic, lead, and mercury were very close to ambient levels, with maximum values—outliers all—four times (As) to 10-11 times (Hg, Pb) the ambient mean (Figure 35).

Copper levels in Commencement Bay in 2008 were higher than the mean ambient concentration in almost 75% of samples (Figure 35). With the exception of a very high outlier from the head of the Thea Foss Waterway which was more than 20 times the ambient mean, all copper levels were within five times the ambient mean.

The bulk of the LPAH concentrations in the study area were above Puget Sound ambient levels, but within an order of magnitude (Figure 36). In the Thea Foss Waterway, however, LPAHs were up to two orders of magnitude greater than ambient and almost 400 times ambient for some LPAH compounds. A similar pattern held true for HPAHs, with most HPAH levels being within 20 times ambient, but those in the Thea Foss Waterway being up to 400 times ambient (Figure 37).

PCB Aroclor 1260 was mostly undetected, though when it was measurable, the concentrations were often higher than the ambient mean concentration. The median concentration of PCB Aroclor 1254 in Commencement Bay in 2008 was at the Puget Sound ambient mean. Most measured concentrations were less than 5 times ambient, though concentrations in the Thea Foss and Hylebos Waterways ranged up to 40 times ambient (Figure 38).

Dibenzofuran levels were all higher than ambient, most within one order of magnitude higher, but up to two orders of magnitude higher in the Thea Foss Waterway (Figure 38). The bulk of bis(2-ethylhexyl)phthalate levels across the study area were above the mean ambient concentration, most within ten times the ambient level (Figure 38). The highest bis(2-ethylhexyl)phthalate concentration was at a station in the inner bay (Station 88), not far from the Sitcum and Blair Waterways, where the bis(2-ethylhexyl)phthalate level was about 20 times the mean ambient concentration.

Comparison with Other Commencement Bay Studies

Chemical Contamination

The spatial patterns of chemical contamination in the 2008 UWI survey were similar to those found in 80 surveys from 1990-2007, 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 1999 in this 2008 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, up to 27 samples were taken by NOAA at 22 stations throughout Commencement Bay and the waterways in 1978-1981 (Malins et al., 1982). Ecology and NOAA sampled the same region again as part of the PSAMP/NOAA survey in 1999, and Ecology sampled it once again as a part of this 2008 UWI survey. The sampling and analytical methods were sufficiently similar in all three surveys to warrant comparisons of percent incidence of contamination relative to the state criteria and spatial patterns, though not estimates of spatial extent of contamination, 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 arsenic, cadmium, lead, and silver concentrations from 1979 to 1999 and 2008 (Appendix A Figures A-10, -11, -12, and -14).

Mean mercury concentrations declined from 1979 to 1999 and 2008 (Appendix A Figure A-13), though the maximum concentrations in 2008 and 1999 were still higher than the 1979 mean. The maximum value observed for mercury in the 2008 survey was just over half the mercury maximum in 1979.

The mean summed PAH concentrations in 1999 and 2008 were less than 5% of those reported in the 1979 MESA results (Appendix A Table A-6, Figure A-15). The maximum PAH sums in 2008 and 1999 were about twice the 1979 mean, but about one-third of the 1979 maximum.

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 survey found that concentrations of PAHs, PCBs, chlorinated butadienes, and most trace metals often (but not always) were highest in various reaches of the Tacoma waterways, especially the City and Hylebos Waterways (Dexter et al., 1981). In 2008, the same pattern held for metals, PAHs, and hexachlorobutadiene. PCBs were not often measurable in samples taken in 2008.

The incidence of contamination by one or more chemicals or chemical classes relative to the NOAA ERM values was 12/27 or 44% of stations in the MESA data from the early 1980s (Malins et al., 1982). In 1999, the incidence of contamination relative to ERMs was 6/25 or 24%, and in 2008 it was 4/30 or 13%, a downward trend.

The Hylebos Waterway and City Waterway (now, Thea Foss) often had the highest levels of contaminants in the MESA survey. These two areas often ranked highest in sediment contamination among all industrialized bay stations sampled during the 1980s. While some contamination was still present in the Hylebos Waterway in 2008, the location of greatest contamination in the Urban Waters survey was the Thea Foss Waterway.

In the MESA study, the concentrations of some metals were high near the former ASARCO mill at Ruston. The PSAMP/NOAA and 2008 Urban Waters studies did not sample that area.

Polybrominated diphenyl ethers (PBDE) have been in use since the 1970s but were not target analytes in either the MESA or PSAMP/NOAA surveys, so temporal comparisons are not possible. PSAMP sediment surveys since 2004 have included PBDEs and have found PBDE congeners 47, 99, and 209 to be the most commonly detected PBDEs throughout Puget Sound (Dutch and Weakland, 2009).

Decreasing trends in sediment chemical concentrations have been seen at monitoring stations surrounding the Commencement Bay Dredged Material Management Program open-water disposal site west of Browns Point (SAIC, 2009).

Toxicity

U.S. EPA amphipod survival toxicity tests in 1981 with the estuarine amphipod *Rhepoxynius abronius* indicated that 58% of the 175 samples taken throughout the bay and waterways were highly toxic (Swartz et al., 1982). By contrast, the amphipod mortality tests conducted with *Eogammarus confervicolus* as part of the NOAA MESA surveys found very little acute mortality

(Chapman et al., 1982). Chapman et al. (1982) indicated general agreement with the Swartz et al. (1982) results in heavily contaminated areas such as the Hylebos Waterway and noted the difference in sensitivity of the two species. Toxicity tests were a new science at that time.

The PSAMP/NOAA and UWI studies used yet other species in the amphipod mortality tests, *Ampelisca abdita* and *Eohaustorius estuarius*, respectively. As indicated earlier in this report, because of the relative insensitivity of *A. abdita* in Puget Sound sediments, *E. estuarius* was chosen for the UWI survey. In 1999, only one of 25 samples was toxic, and in 2008, none was. The comparisons are imperfect, however, because different laboratories and different species of test animals were used in the PSAMP/NOAA and UWI studies than in the U.S. EPA and NOAA MESA studies. Still, they strongly suggest positive results due to the cleanups which have taken place in the interim.

Other kinds of tests with sublethal and metabolic endpoints indicated significant results in the MESA studies (Chapman et al., 1982, 1983, 1984a,b). Because of the differences in the kinds of tests performed in the MESA studies, comparisons with the PSAMP and UWI results are not warranted.

Health of Benthic Communities

The intent of sediment quality evaluations, such as this survey of Commencement Bay, is to use the information from the triad approach to help protect the benthos (Long and Chapman, 1985). The benthos is an important component of diverse and productive estuarine ecosystems (Sverdrup et al., 1963). In addition to their importance in a healthy ecosystem on their own right, benthic assemblages are important as sources of prey for demersal fishes, marine birds, and invertebrates than can, in turn, be important prey for top predators such as humans, salmon, seals, and orcas in Puget Sound (Simenstad et al., 1979).

The benthos in Puget Sound is at risk of losses as a result of the toxic effects of anthropogenic chemicals, hypoxia, physical disturbance and changes in habitat type. Any one of these sources of stress or combinations of them can have lasting adverse effects on the benthic resources of the Sound. There is ample evidence that chemically mediated toxicity in Puget Sound sediments can and has caused impacts to the benthos (Long and Chapman, 1985). The spatial scales and temporal trends of such impacts have been documented in the PSAMP sediment quality monitoring (Long et al., 2003; Partridge et al., 2005). However, it is important to consider that in some areas of Puget Sound, such as Hood Canal, the adverse effects to the benthos may be attributable to hypoxia (Long et al., 2007).

Establishing and proving cause-effect relationships in the oceans and estuaries is very difficult because of the wide variety of anthropogenic and natural factors that can be important sources of stress (Sindermann, 1997; Norton et al., 2002; Engle and Summers, 1998). Our recent experience indicates that the patterns in response of benthic assemblages to stress caused by hypoxia and by toxic chemicals in the sediments are indistinguishable (Hyland et al., 2003; Long et al., 2003, 2007) and follow the classic patterns previously identified in Scandinavian fjords (Pearson and Rosenberg, 1978).

Therefore, although the triad approach relies upon sediment chemistry to evaluate the risks of chemically caused toxicity, other confounding or exacerbating factors may have equally important roles. Cause-effect relationships are undoubtedly site-specific. The sediment quality triad is not a tool to determine causality; rather, it is a method to evaluate the potential for risks of impacts.

The SQTI currently relies on assessment of benthic assemblages by professional benthic ecologists to determine whether benthic communities are "adversely affected" or "unaffected". The binary designation of "affected" or "unaffected" does not allow for intermediate results. Although environmental characteristics and presence or absence of stress-tolerant species are factored into the assessment, the "affected/unaffected" designation does not provide information on types of effects on the benthos.

Quantitative, multivariate indices of the health of benthic communities are currently available for many estuaries and marine bays across the U.S. and in other countries. However, none of them can be applied successfully to the distinct resident benthic communities of Puget Sound. The development of such an index or indices specifically for Puget Sound would be a vital tool for further understanding the benthic assemblages unique to this region.

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:
    - Current conditions of, and changes to, the ecosystem.
    - Impacts to important ecosystem goods and services.
    - 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, stakeholders, 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 sediment conditions 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 with the South Central and North Central PSP Action Areas (Figure 39). 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 the 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 1997-1999 PSAMP/NOAA survey. In 2008 and 2009, the PSAMP sediment monitoring program will complete sampling throughout the PSAMP Central Sound region and thus will complete the second round of sampling and provide updated information on that 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. The SQTI is inherently a multi-parameter index of degradation.

- *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 provide information to environmental managers concerned 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 health 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 assess sediment quality among different geographic scales (bay-, region-, and/or sound-wide). For example, ecosystem managers for Commencement Bay can see the 2008 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 use of the PSAMP strata in this study was the comparison of Commencement Bay 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 of degradation, (2) statistical analysis of chemical contamination data containing nondetects, (3) statistical comparison among benthic assemblages, and (4) relation of benthic assemblages to environmental conditions. Other technical developments are added as the program matures. Such methods are important for interpreting 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 technical reports, Ecology "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). Ecology scientists have regularly presented the data in regional scientific conferences and inter-agency meetings.

Summary and Conclusions

As part of the Urban Waters Initiative, Ecology's Environmental Assessment Program conducted a sediment quality survey throughout Commencement Bay in 2008. 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 degradation.
2. Determine whether there had been changes in sediment quality over time and, if so, describe the nature and degree of those changes.
3. Compare the extent of sediment-quality degradation in Commencement Bay with estimates for other regions and throughout Puget Sound.

A weight-of-evidence approach was used to compare the results of a previous study in 1999 with those from the 2008 Urban Waters study to determine what changes had taken place in the interim.

Current Conditions in Commencement Bay

Sediment Contamination

- There were 8 stations that were chemically contaminated. Therefore, an estimated 3.7 km^2 or 15.5% of the total study area was chemically contaminated with one or more chemicals exceeding Washington State SQS sediment management criteria. The SQS values were exceeded for 19 of 41 chemicals or chemical groups for which there are State criteria.
- CSL criteria were exceeded at four stations (13%), representing 13.1% of the study area. These are the stations where ecological risks were highest.
- Six samples exceeding SQS criteria did so for a single chemical or chemical group. Two samples, both from the Thea Foss Waterway, exceeded multiple SQS criteria: 11 in one sample (butylbenzylphthalate and 10 individual and summed PAHs) and 14 in the other (copper, butylbenzylphthalate, and 12 individual and summed PAHs).
- Most chemicals or chemical groups exceeded their respective SQS values in only one or two samples each. Mixtures of copper, mercury, bis(2-ethylhexyl)phthalate, hexachlorobenzene, total PCB Aroclors, and 14 individual or summed PAHs exceeded their respective criteria. The chemical that exceeded its SQS most frequently was butylbenzylphthalate.
- No individual Washington State sediment quality standards were exceeded at 22 of the 30 stations (73%), representing almost 85% of the study area. Therefore, chemical contamination did not represent a high toxicological threat to the local benthos in the majority of the bay.
- The toxicological risks of the presence of mixtures of chemicals also were very low in 19 stations, slightly elevated in 9 stations, moderate in 1 station, and high in 1 station. The latter

two stations were in Thea Foss Waterway. In general, contaminant concentrations were highest in the Thea Foss and Hylebos Waterways and lowest in the outer bay.

Sediment Toxicity

- None of the stations in this area had highly toxic sediments, based on the lethal (amphipod mortality) and sublethal (sea urchin fertilization) toxicity tests conducted in 2008. Therefore, both the incidence and spatial extent of toxicity were zero in each test and both tests combined.

Invertebrate Communities

- There were wide ranges in total abundance and taxa richness among stations. Most stations had relatively high numbers of dominant taxa.
- The annelids and molluscs were the most abundant groups, followed by the arthropods, echinoderms, and miscellaneous taxa. Arthropod abundance was relatively low at most stations. Echinoderms were absent from seven stations, miscellaneous taxa were absent from three stations, and arthropods were absent from one station.
- There were four distinct assemblages of benthic species among the 30 stations. Species composition of the assemblages was primarily related to differences in water depth and to a lesser degree TOC and percent fines concentrations. One station in Thea Foss Waterway had a unique assemblage dominated by oligochaetes.
- The benthic invertebrate assemblages were considered to be adversely affected at 12 stations, representing 8.5 km^2 and about 35% of the study area.
- Adversely affected benthic invertebrate communities often had low taxa richness and supported large numbers of pollution-tolerant species.

Sediment Quality Triad Index

- Fifteen of the 30 stations sampled, representing almost 14.7 km^2 (60.9% of the study area) had high sediment quality, as gauged by the Sediment Quality Triad Index.
- Ten stations, representing 6.6 km^2 (27.4% of area), met the criteria for intermediate/high sediment quality (degradation in only one of the triad elements). Three of those ten stations, representing 0.93 km^2 (3.87% of area), were contaminated; the remainder had adversely affected benthic communities. No samples met the criteria for toxic sediment.
- Another five stations, representing 2.8 km^2 (11.7% of area), met the criteria for intermediate/ degraded sediment quality (degradation in two triad elements). Those samples had both chemical contamination and adversely affected benthos.
- None of the stations or area had degraded sediment quality, with degradation in all triad elements.

Comparison to 1999 Conditions

There was a mixture of temporal trends between 1999 and 2008. Many *individual* parameters indicated improvements in sediment quality on a bay-wide scale. Concentrations of most metals and most PAHs decreased. Sediment toxicity decreased, though the change was too small to be statistically significant. There were improvements in benthic community health in all of the waterways, but they represented small fractions of the total study area.

Although there were no changes in percent fines overall, there were large changes at several stations in the central-southeast part of bay.

There was a bay-wide decrease in sediment TOC concentration. Therefore, some TOC-normalized PAHs did not show decreases that non-normalized PAHs did.

Sediment quality, as measured by the SQTI, declined from 1999 to 2008. The largest component of the decline was adversely affected benthos at several stations in the south-central to southeastern portion of Commencement Bay. Another contributory factor was the increased concentrations of butylbenzylphthalate or bis(2-ethylhexyl)phthalate at several stations, which exceeded the SQS.

Some of the decrease in sediment quality is an artifact of the sample design. The decision was made to increase the sample size from 25 stations to 30. Most of the randomly-placed additional stations landed in the outer bay, diluting the per-station weight of the stations in that area, which had high sediment quality. However, the decreased weighting of the stations in the main portion of the bay also had the effect of reducing the magnitude of the shift from high to intermediate sediment quality at the stations in the southeastern bay.

Sediment Contamination

- *Metals:* The concentrations of arsenic, copper, lead, mercury, nickel, silver, tin, and zinc decreased significantly. There were no statistically significant changes in the levels of cadmium or chromium.
- *PAHs:* The concentrations of most PAHs decreased. There were no changes in the levels of acenaphthylene or benzo(b)perylene.
- *PCBs:* There were too few detected results in either 1999 or 2008 to conduct a statistical comparison.
- *Phthalates:* Bis(2-ethylhexyl)phthalate concentrations increased.
- *Chlorinated pesticides, other organic compounds (BNAs):* There were too few detected results in either 1999 or 2008 to conduct a statistical comparison.
- *Comparison to sediment-quality standards:* There were no statistically significant changes in numbers of stations, proportion of area, and number of chemicals exceeding their respective SQS, with the exception of an increase in the proportion of area for which the SQS for bis(2-ethylhexyl)phthalate was exceeded.

Sediment Toxicity

- Sediment toxicity decreased from one station, representing 0.5% of the study area, in 1999 to none in 2008.

Invertebrate Communities

- Some measures of benthic invertebrate community health improved from 1999 to 2008.
- Although the number of stations with healthy (unaffected) benthos increased, the amount of area with unaffected benthos decreased. The primary reason was different station weights (amount of area represented) for the areas where benthic community health improved, compared to those where health of the benthos deteriorated.

Sediment Quality Triad Index

- Sediment quality, as measured by the SQTI, improved for 6 of the 25 stations sampled in 1999 (24% of stations), remained the same for 13 of 25 stations (52%), and declined for 6 of 25 stations (24%). Most of the improvements were in the waterways.
- The area affected throughout the bay by both high quality and degraded conditions decreased between 1999 and 2008, while the area affected with intermediate conditions increased. So, the conditions at some clean stations got worse and the conditions at some degraded stations got better.
- Sediment quality in the outer and northern portions of the bay and along the Tacoma waterfront, already high, remained high.
- Sediment quality declined at five stations in the southeastern portion of the bay due primarily to adversely affected invertebrates.
- Increased levels of bis(2-ethylhexyl)phthalate resulted in declining sediment quality at several stations.
- No sediment was classified as degraded in 2008. In 1999, a single station in the Thea Foss Waterway, representing 0.5% of the study area, had degraded sediment. In 2008, sediment quality at that station was intermediate/high.

Sediment Quality at Different Spatial Scales

The 2008 UWI Commencement Bay 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.[8]

[8] Such nested sampling frames for environmental assessment have been used extensively by the U.S. EPA's Environmental Monitoring and Assessment Program (EMAP) and National Coastal Assessments (NCA),

- The SQTI results for Commencement Bay in 2008, both incidence (% of stations) and spatial extent (% of area), were almost identical to those for the entire Puget Sound baseline 1997-2003 (Table 21). By contrast, the SQTI incidence and spatial extent for Commencement Bay in 1999 closely resembled that of the Central Region 1997-1999.
- The proportion of area with intermediate sediment quality was much higher in the study area in 2008 than in the Central Region (1997-1999) or in the entire Puget Sound (1997-2003). 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.

Comparisons to Other Studies

- The chemical concentration levels in this 2008 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 1999 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 and PAHs 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 1999 and since the historical 1978-1981 NOAA surveys.

Meeting the Needs of the Puget Sound Partnership

The Urban Waters Initiative sediment monitoring program is a new bay-level 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. The triad approach provides

culminating in the National Coastal Condition Reports (U.S. EPA, 2008; www.epa.gov/nccr). Those surveys were designed so that assessments could be made at the level of states, geographic regions of the country, and the country as a whole.

information on not only the chemistry, but also on the toxicological significance and biological relevance of the chemistry. These assessments provide information that can assist environmental managers concerned 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. The SQTI has evolved over the years and will continue to do so. For example, 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. To keep track of the state of science, it is also necessary to interact with colleagues in other state agencies, academia, and federal agencies.

- *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.

Recommendations

The results of the 2008 Urban Water Initiative study point to the following recommendations for improvement of sediment monitoring at all scales, including individual stations, individual waterways, reaches of the bay, bay-wide and Puget Sound-wide. A considerable amount of monitoring of chemical contamination and its effects has been conducted in the bay during the past 30 years. There are numerous indications that conditions in the bay have improved over that span. However, it is important to not suspend monitoring, but, rather, to continue to monitor to track the degree of future improvements.

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

- Maintain the existing PSAMP Spatial and Temporal monitoring programs. Ongoing monitoring of the 10 sentinel long-term PSAMP stations, the eight regions of Puget Sound, and the five geomorphological/anthropogenic-use strata is essential. The 20+ year time series of the ten PSAMP sentinel stations is an important and unique program. The sampling design of the PSAMP Spatial program takes approximately 10 years to cycle through all 8 regions and 5 strata. The baseline was completed in 2003 and the first all-Puget Sound update is near completion. The UWI sample design is nested within the PSAMP Spatial program, which enables us to put the urban waters into perspective within the regions.

- Expand the UWI bay-scale sediment monitoring to other urban bays or urbanized regions. Proceeding beyond the urban bays specified in the UWI legislation (Elliott Bay/Lower Duwamish and Commencement Bay), Ecology has begun sampling other large urban areas in Puget Sound. These surveys began with Sinclair and Dyes Inlets and the Bainbridge Basin in 2009 and will continue with Bellingham Bay in 2010. These urban bays studies should be followed with Budd Inlet in 2011 and Everett Harbor/Port Gardner in 2012.

- Resample the six large urban bays on a rotating annual basis. Ongoing monitoring of urban bays is essential to determining progress in the Puget Sound Partnership's mandate to clean up Puget Sound by 2020. The generalized average sedimentation rate throughout most of Puget Sound is about 1 cm per year, though that amount is affected by such factors as bioturbation and physical disturbance. By waiting six years or so between sampling events, it is reasonable to expect the top 2-3 cm to contain newly deposited materials carrying newly released toxicants.

- Expand the UWI bay-scale sediment monitoring to smaller urbanized regions. There are numerous small urban bays (e.g., Oakland Harbor, Gig Harbor, Quartermaster Harbor, Eagle Harbor, Dyes Inlet, Oak Harbor, Port Ludlow, Friday Harbor, Semiahmoo Bay) adjoining Puget Sound for which there is no regular monitoring program.

- 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 sizes 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 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 Commencement Bay.

  One approach that could be explored for sediment chemistry 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. It has been developed with the use of national guidelines, but not with the Washington criteria. A similar approach could be taken for the chemistry element of the SQTI in Puget Sound.

  The relationships between mean SQG quotients and both the incidence and degree of toxicity were published recently with data from many estuarine case studies performed nationwide (Long et al., 1998, 2000; Wenning et al., 2005). Similarly, the increasing incidence and degree of adverse benthic effects with increasing mean SQG quotients has been explored, mostly with data from the southeastern US estuaries (Hyland et al., 1999, 2003). 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, 2009; Bay and Weisberg, 2008). California is pursuing a mean SQG quotient approach for the chemistry.

- Develop a multi-chemical index of ecotoxicological risk 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 based on a scale of increasing ecotoxicological risk in sediments.

- 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 that should be measured include pharmaceuticals and personal care products and perfluorinated compounds. Some of these groups are endocrine disruptors, mutagens, carcinogens, or teratogens, and not acute toxins. Toxicity tests that respond to them have yet to be developed, and it is not known how the benthic assemblages would respond. While researchers are working to address these challenges, it is important to determine what the concentrations of these chemicals in the environment.

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 in Elliott Bay, the results of only a single toxicity test were available and reliable. Restoration of funds for toxicity testing is necessary to answer "So what?" questions and to maintain continuity so that temporal comparisons (e.g., "Has sediment quality improved?") can be made.

Benthic Invertebrates

- Develop a multi-metric benthic index or indices for Puget Sound and refine the interpretation of benthic community health and the relationships between sediment characteristics, toxicity and benthos data. The SQTI currently relies on the best professional judgment of benthic ecologists to determine the condition of Puget Sound benthic invertebrate communities. While this approach is a valid method of assessing ecological condition (Bay et al., 2008; Teixeira et al., in press), an objective, quantitative index attuned to habitat types within Puget Sound would provide another tool for use in monitoring programs and classifications of sediment quality.
- Change the binary designation of "affected" or "unaffected" to accommodate intermediate or uncertain results and develop a more responsive scale. The intent and approach used to develop a benthic index would be similar to those of similar 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.
- Develop a sediment/benthic health index with the information from sediment imaging cameras. Such cameras are now readily available and have been used worldwide. Typically, the data are interpreted in narrative reports based on the images captured by the camera. Thus far, there are no quantitative indices that can be used in classifying sediment/benthic quality. Such images and indices would be extremely useful in Hood Canal, Saratoga Passage and other regions of the Sound that experience hypoxia.

Sediment Quality Triad Index

- Remain current with state-of-the-science developments in other multi-metric or weight-of-evidence approaches to assessments of environmental or ecological condition and, if appropriate, test and incorporate them for use for Puget Sound. For example, new graphical methods for displaying triad data (individual components and combined) could enhance the SQTI's value as a communication tool.

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. Discharged pharmaceuticals and personal care products may not accumulate in sediments, but, rather in fish and other animals. Therefore, it might be best to determine the presence and concentrations of these compounds in mussel and fish tissues. Work has begun to explore those patterns.

- Integrate PSAMP marine sediment monitoring with emerging ecosystem monitoring, such as the nearshore component of stormwater monitoring being developed by the Puget Sound Stormwater Work Group (Puget Sound Stormwater Work Group, 2009).

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Figures

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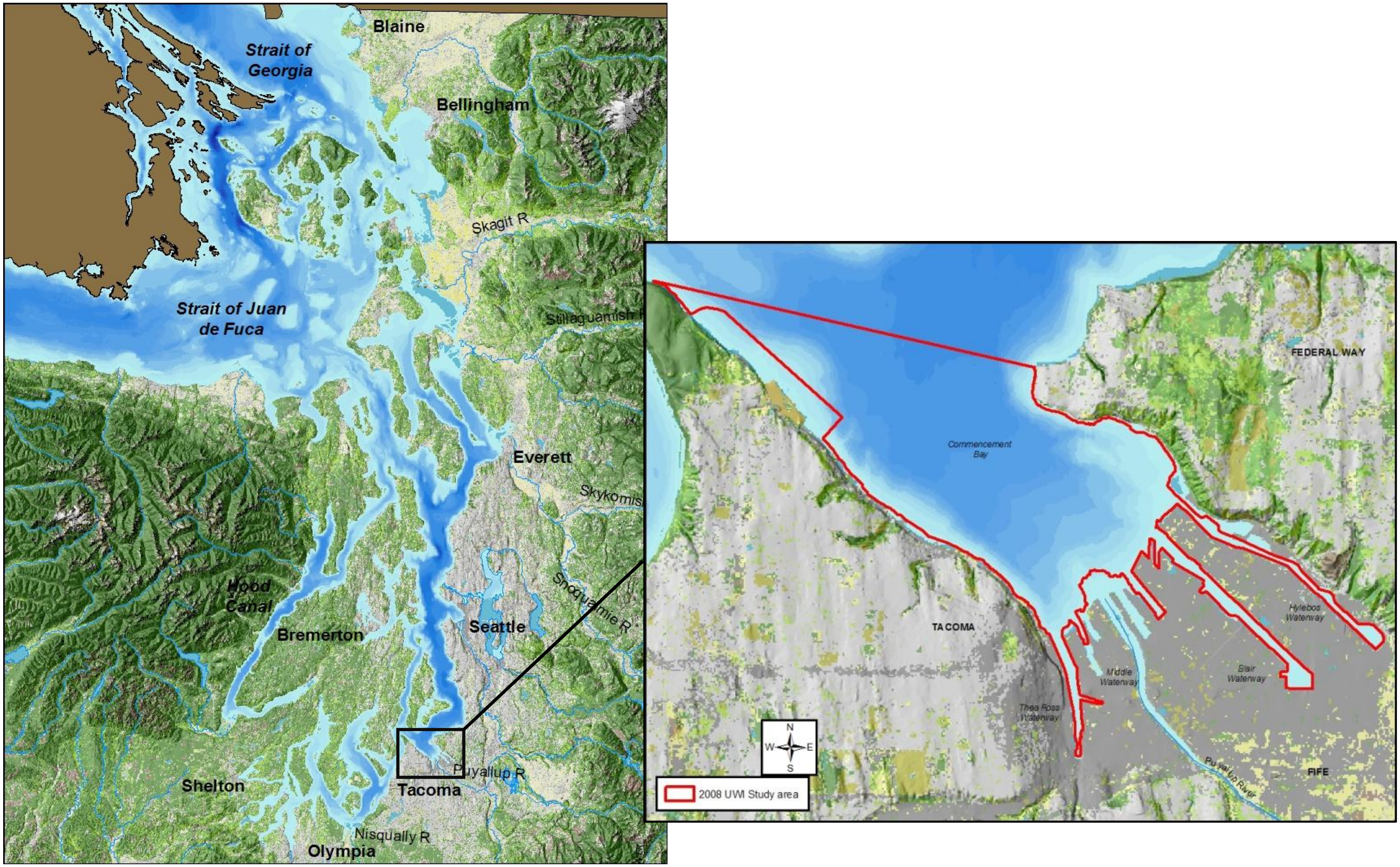


Figure 1. Urban Waters Initiative 2008 study area (Commencement Bay, inset) in context of Puget Sound.

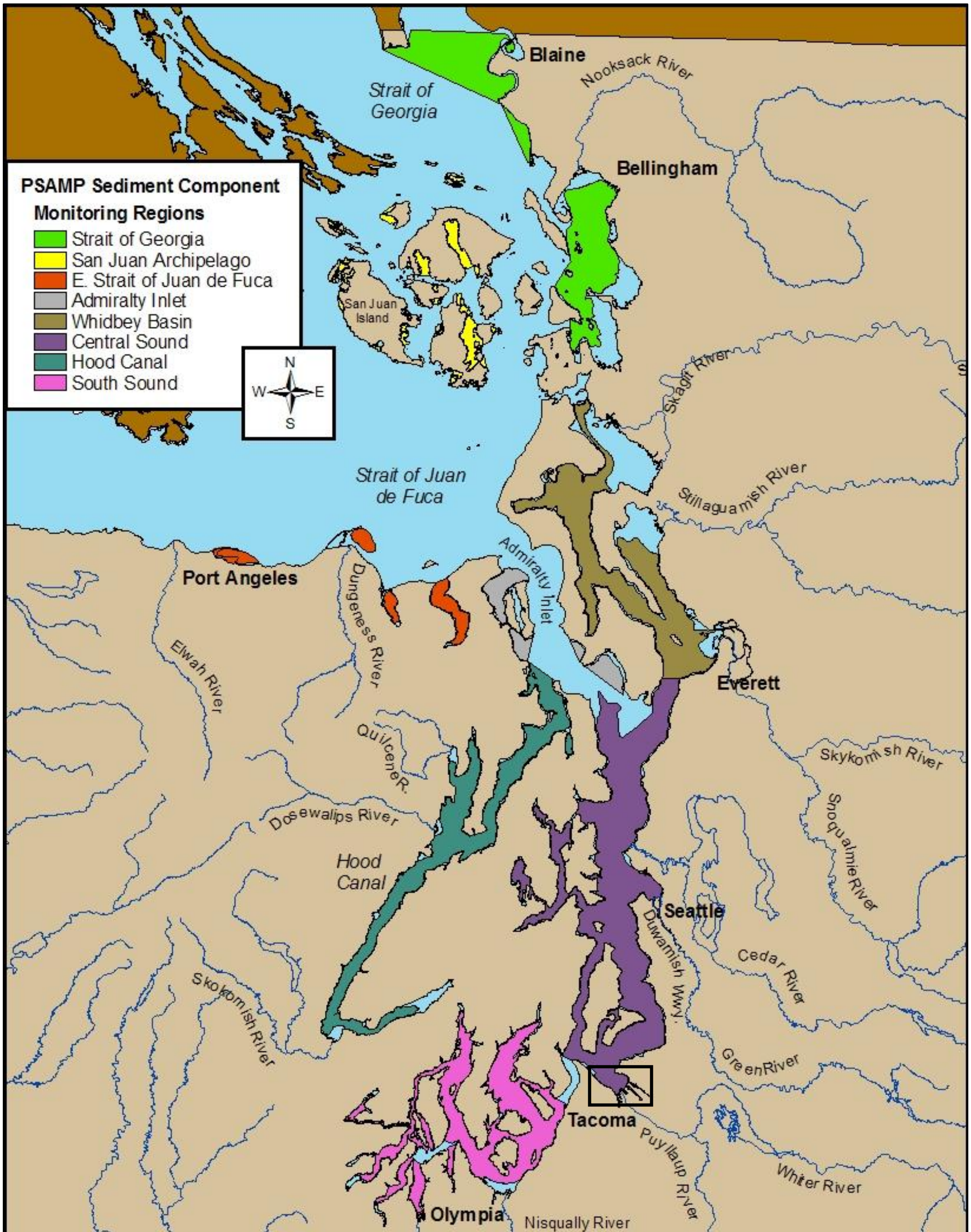


Figure 2. Eight sediment monitoring regions defined for the PSAMP sediment component. *The study area (outlined) is in the Central Sound region.*

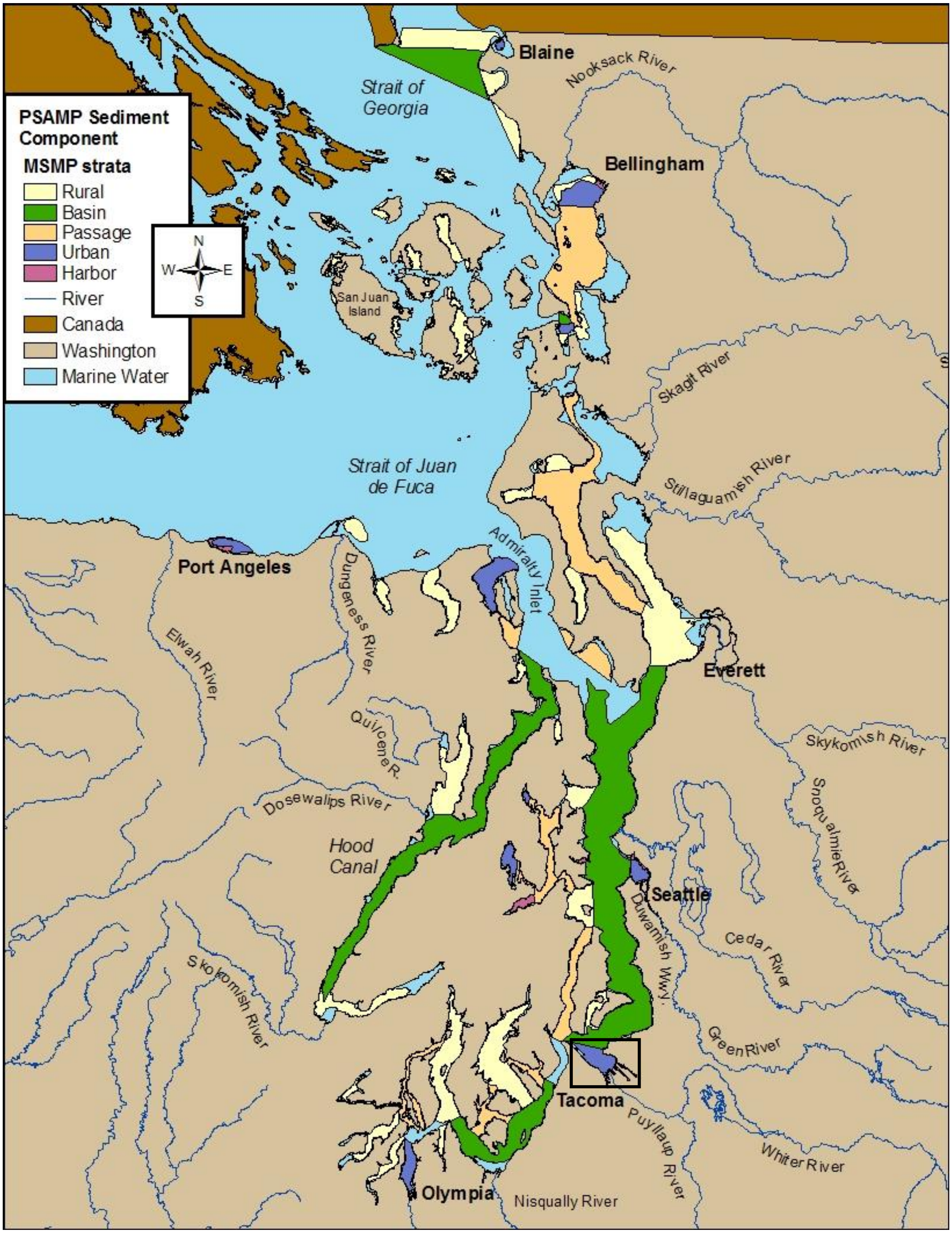
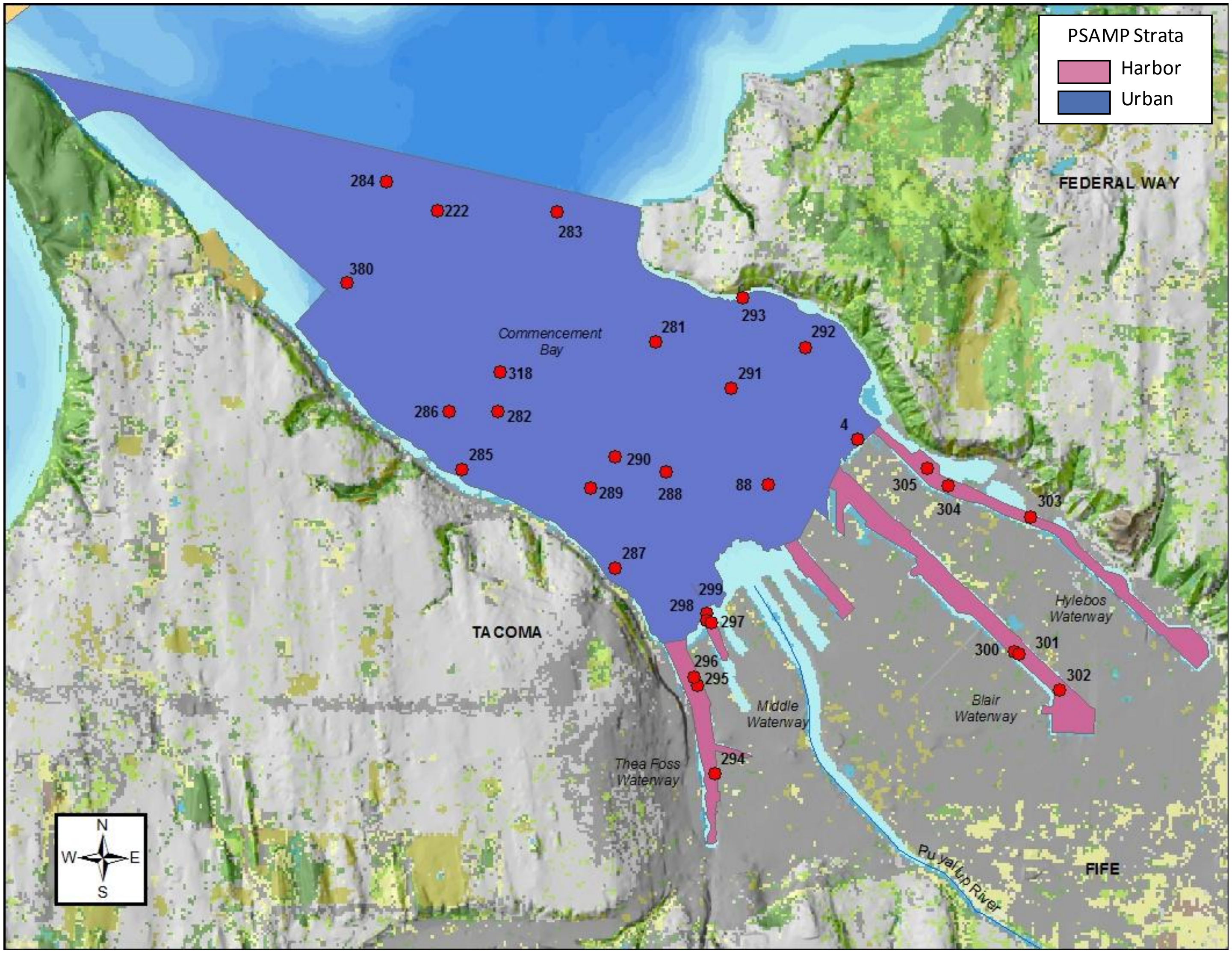


Figure 3. Five sediment monitoring strata defined for the PSAMP sediment component.
The study area (outlined) includes harbor and urban stratum types (detailed view in Figure 4).



Outer Bay
222
283
284
380
Central Bay
281
282
318
Southeast Bay
288
289
290
South Shoreline
285
286
287
East Bay
88
Northeast Bay
4
291
292
293
Thea Foss Waterway
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295
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Middle Waterway
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Blair Waterway
300
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Hylebos Waterway
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Figure 4. Station locations for the 2008 Urban Waters Initiative sediment study.
Stations 4, 88, 222, 318, and 380 were sampled in 2008 only; all of the other stations were sampled in both 2008 (UWI) and 1999 (PSAMP/NOAA).

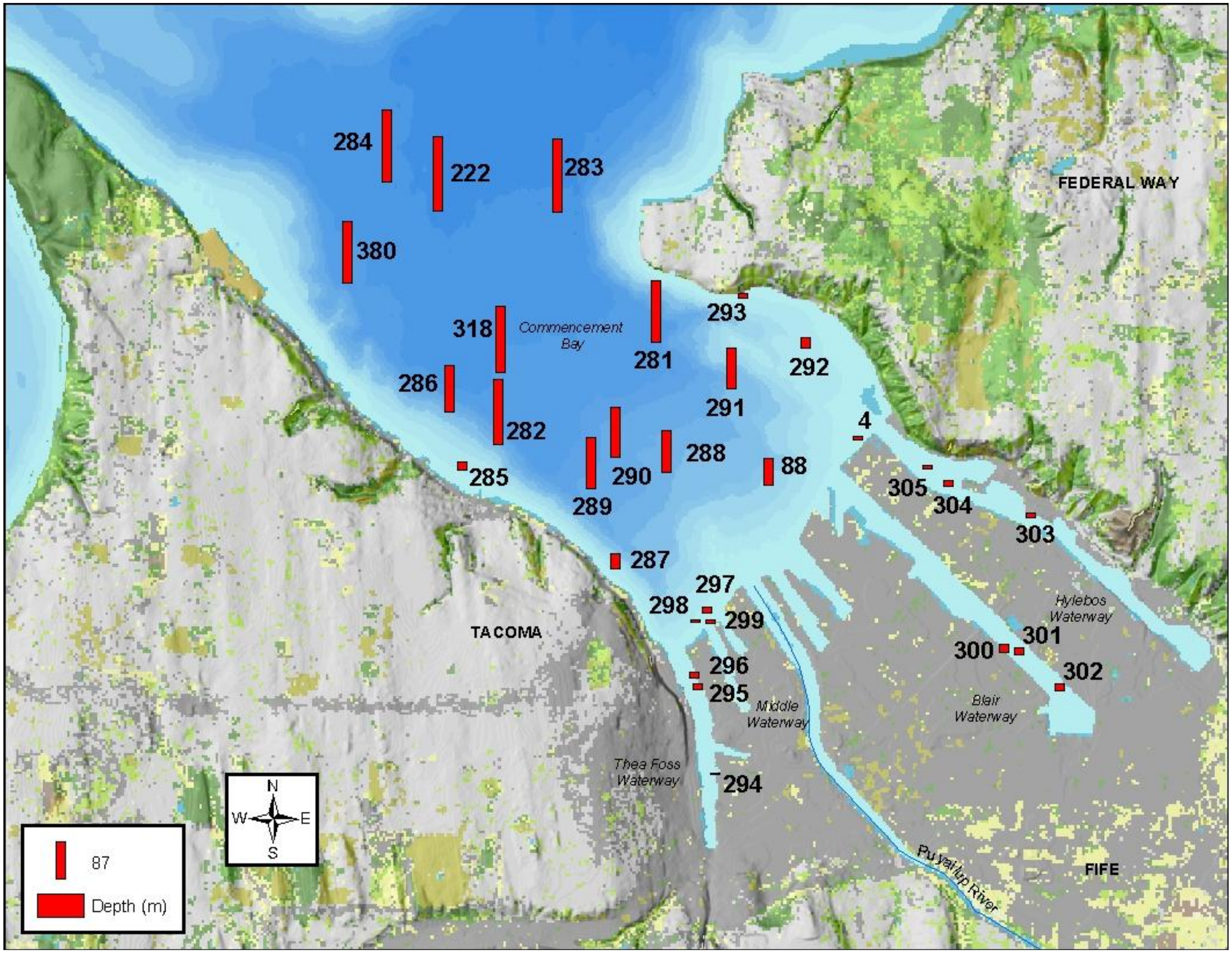

Figure 5. Water depths (meters) at the 30 stations sampled for the 2008 Urban Waters Initiative study.
The numbers on the map are the station identifications.

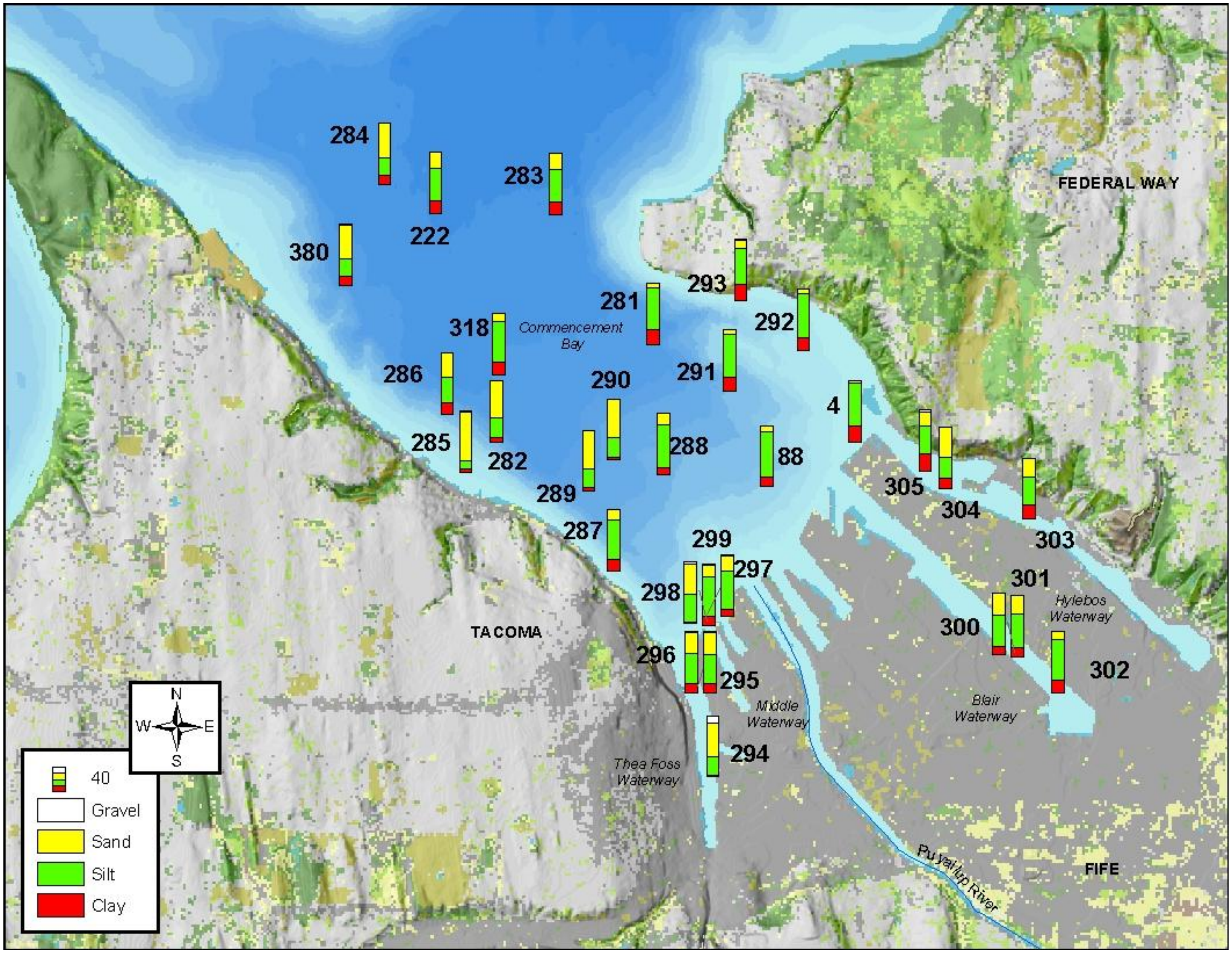

Figure 6. Spatial patterns in particle size classes (percent gravel, sand, silt, and clay) at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.

The numbers on the map are the station identifications.

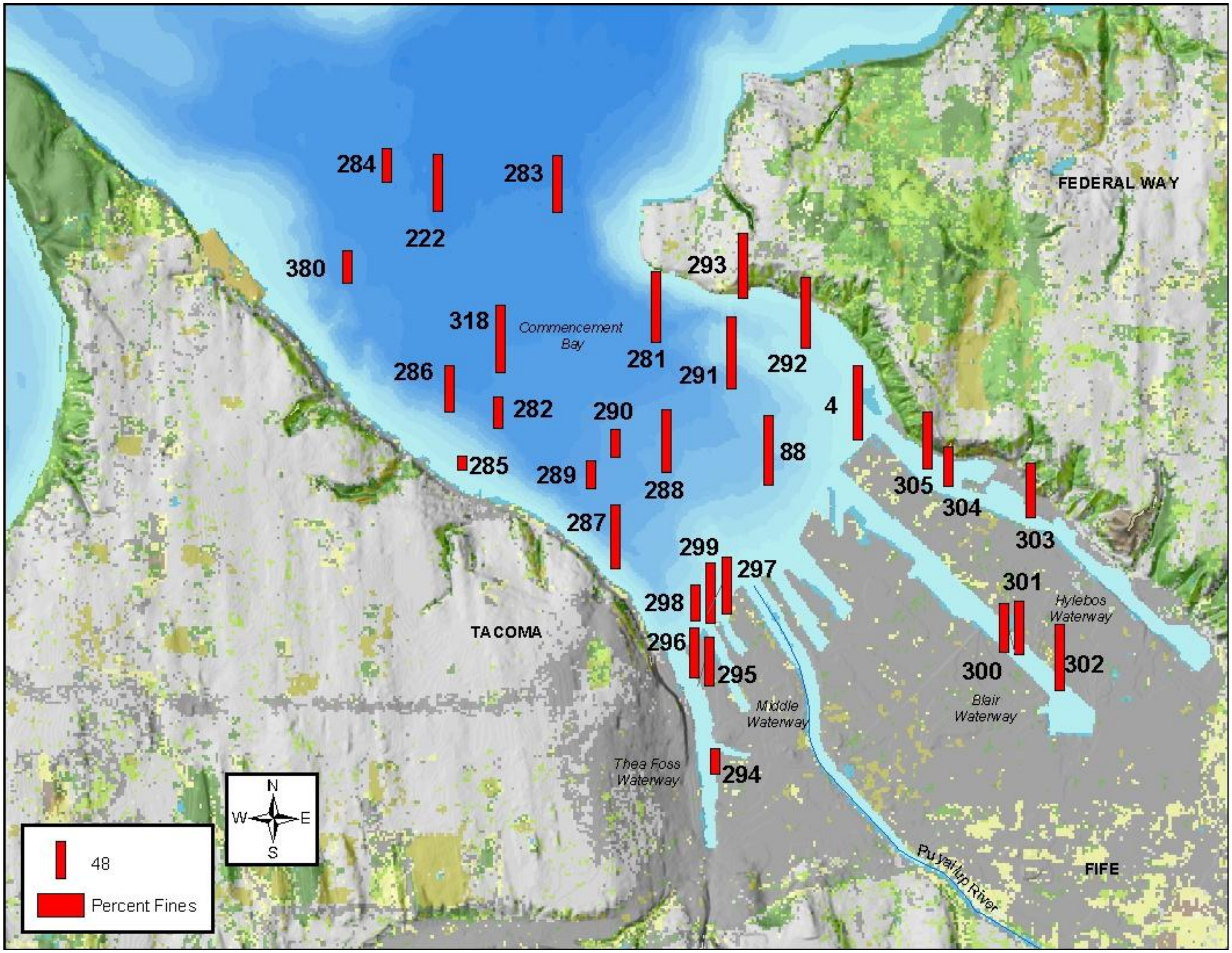

Figure 7. Spatial patterns in percent fines (silt + clay) at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study. *The numbers on the map are the station identifications.*

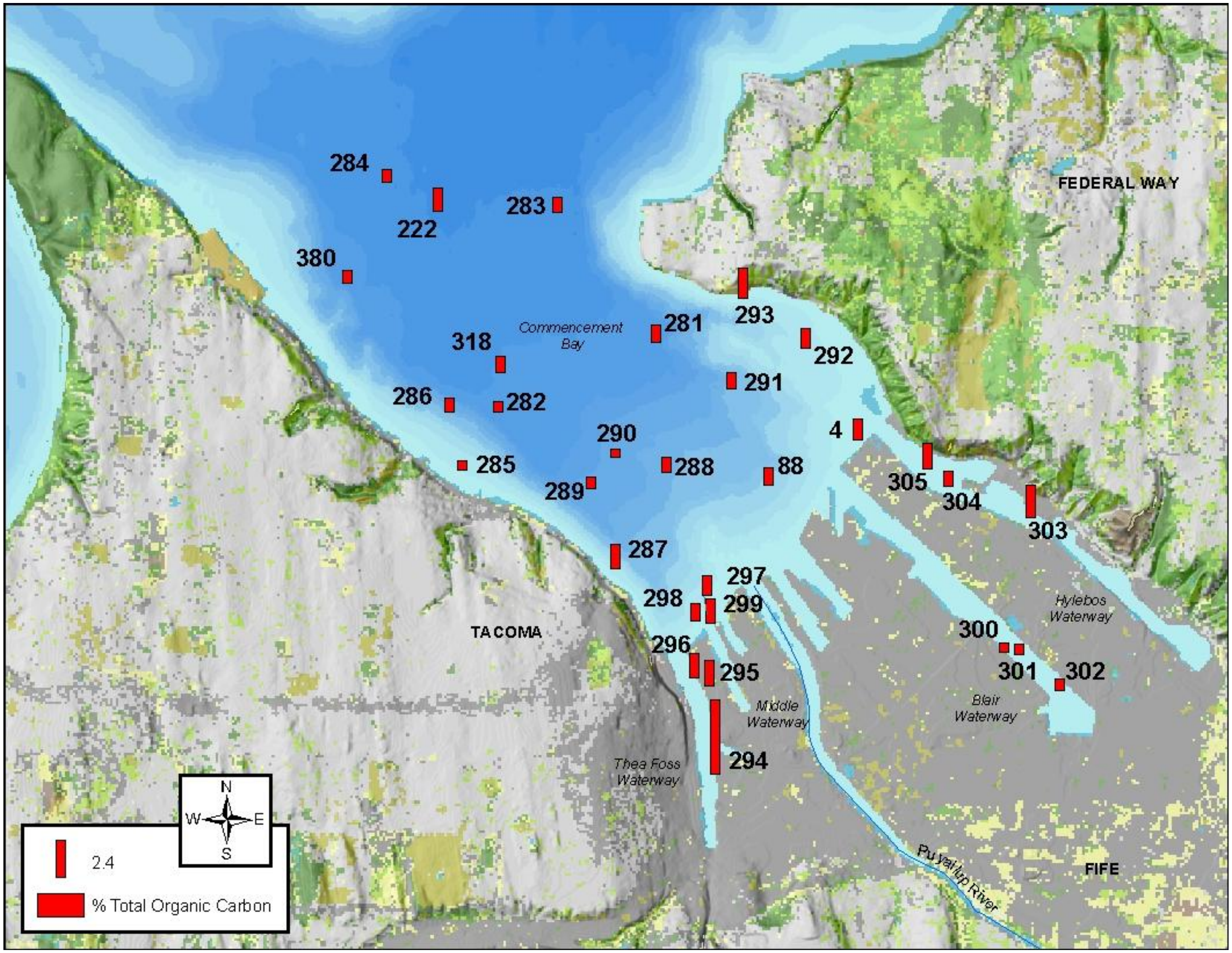

Figure 8. Spatial patterns in total organic carbon concentrations (%) at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.

The numbers on the map are the station identifications.

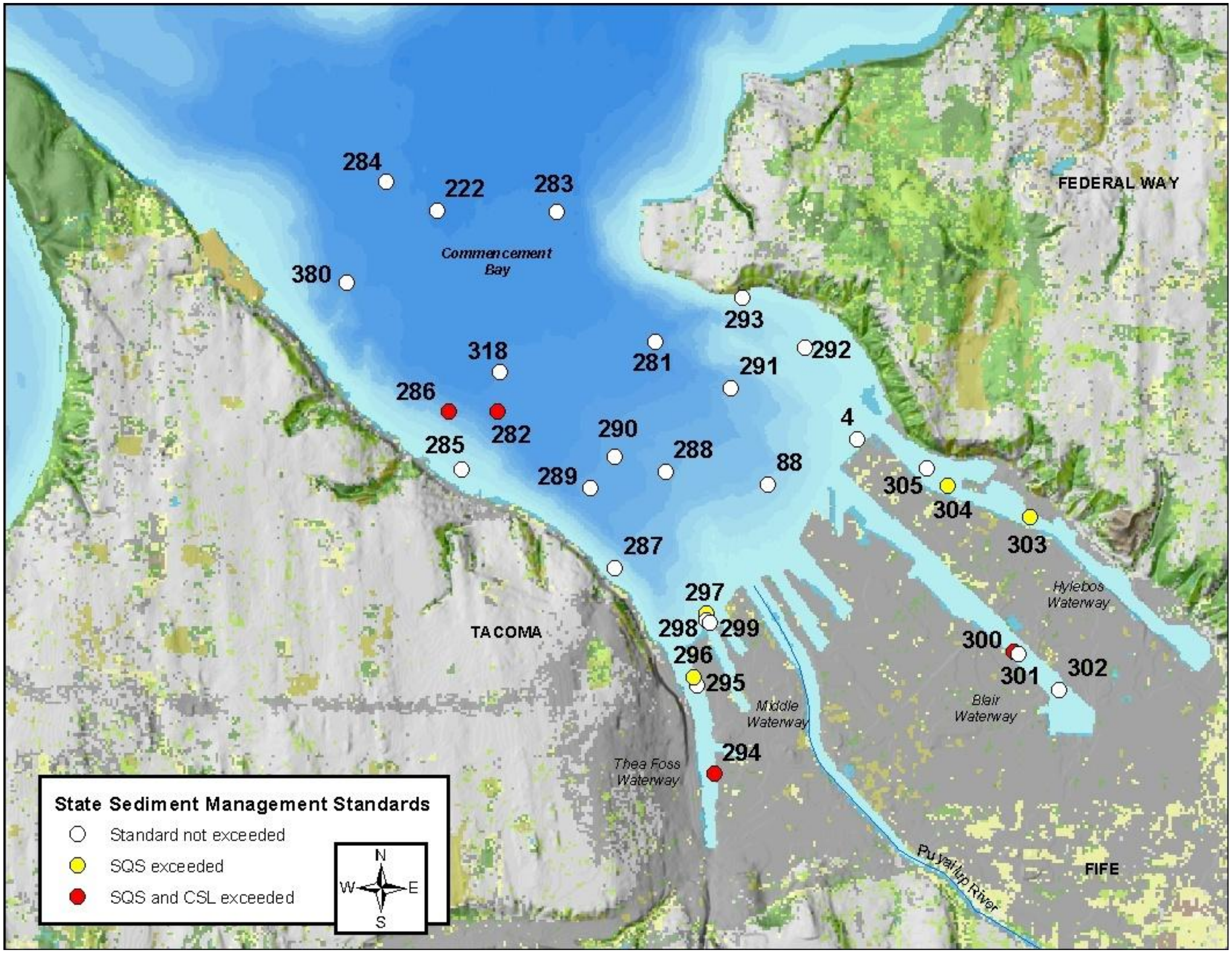

Figure 9. Sampling stations at which Washington State Sediment Management Standards were exceeded in the 2008 Urban Waters Initiative sediment study.

SQS = Sediment Quality Standard; CSL = Cleanup Screening Level.

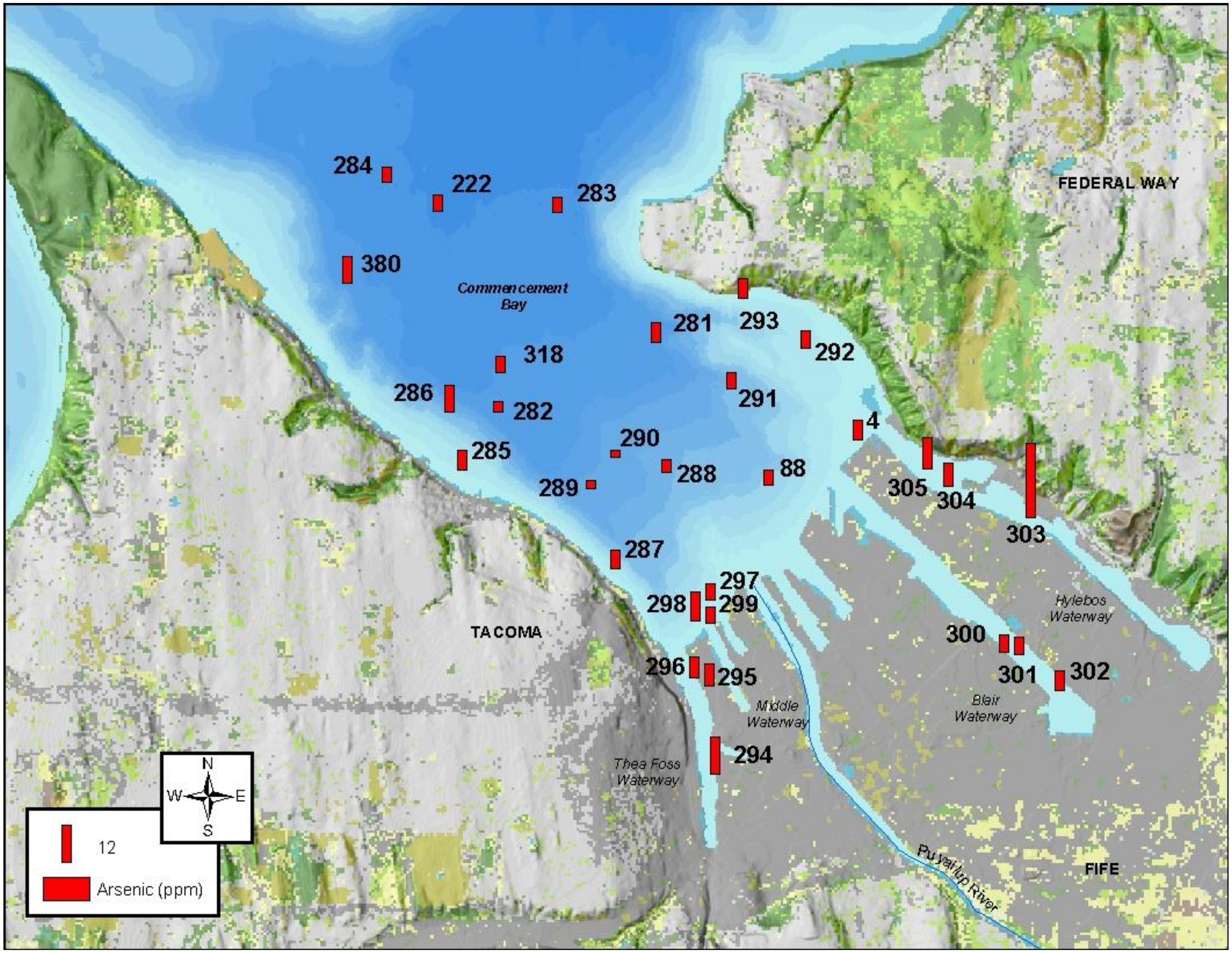

Figure 10. Spatial patterns in arsenic concentrations (μg/g dry weight) at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.

The Sediment Quality Standard for arsenic is 57 ppm. The numbers on the map are the station identifications.

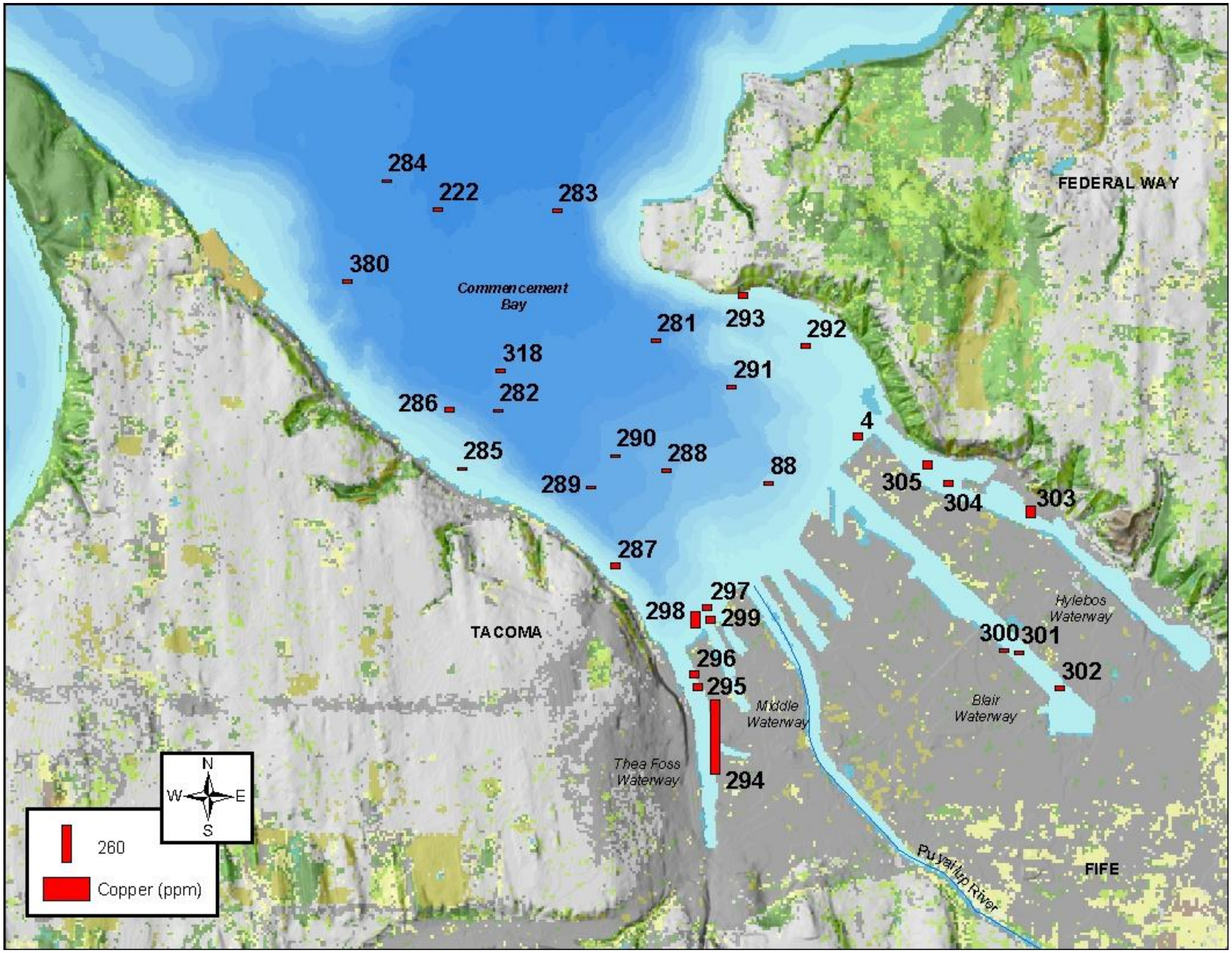

Figure 11. Spatial patterns in copper concentrations (µg/g dry weight) at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.

The Sediment Quality Standard for copper is 390 ppm. The numbers on the map are the station identifications.

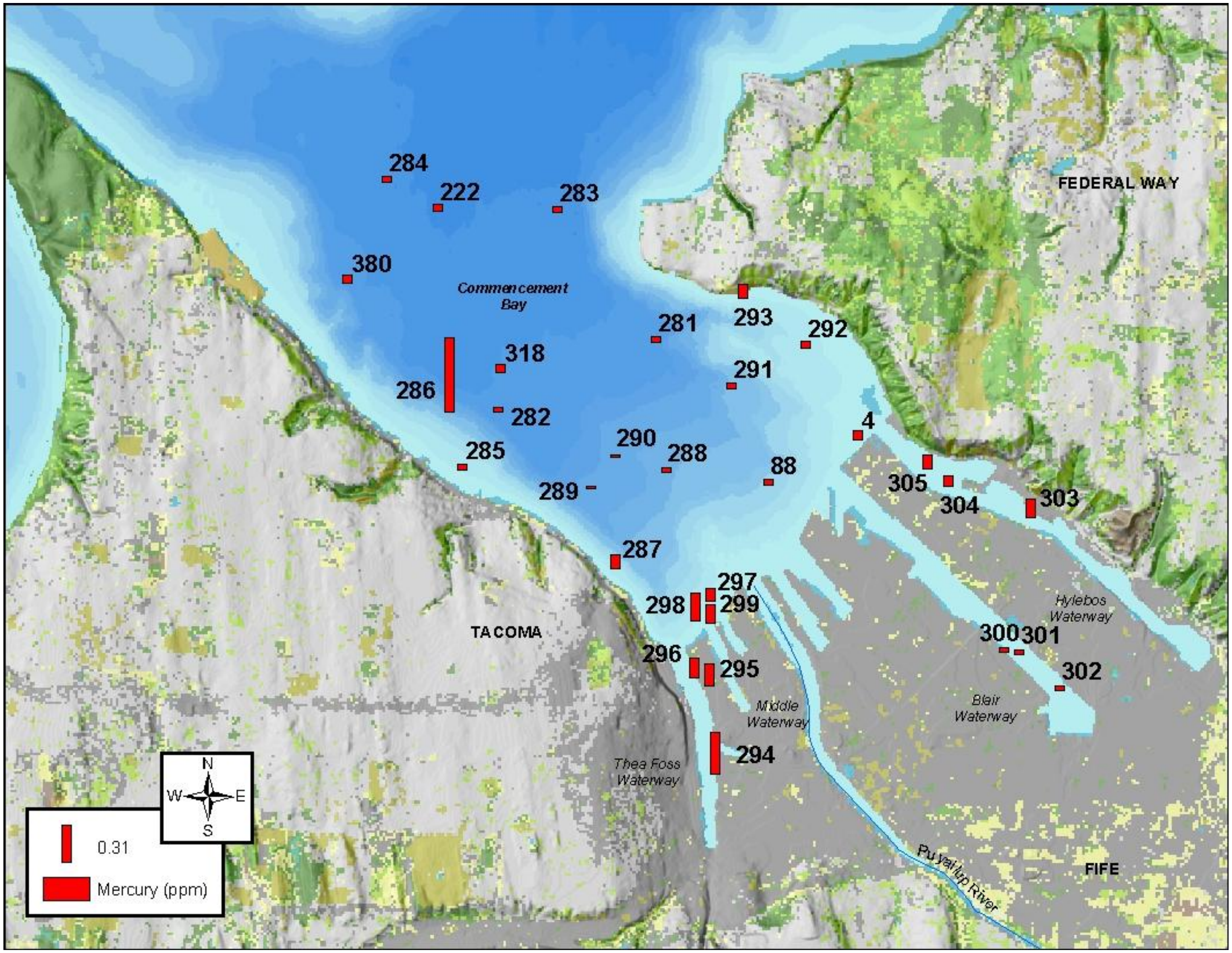

Figure 12. Spatial patterns in mercury concentrations (µg/g dry weight) at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.

The Sediment Quality Standard for mercury is 0.41 ppm. The numbers on the map are the station identifications.

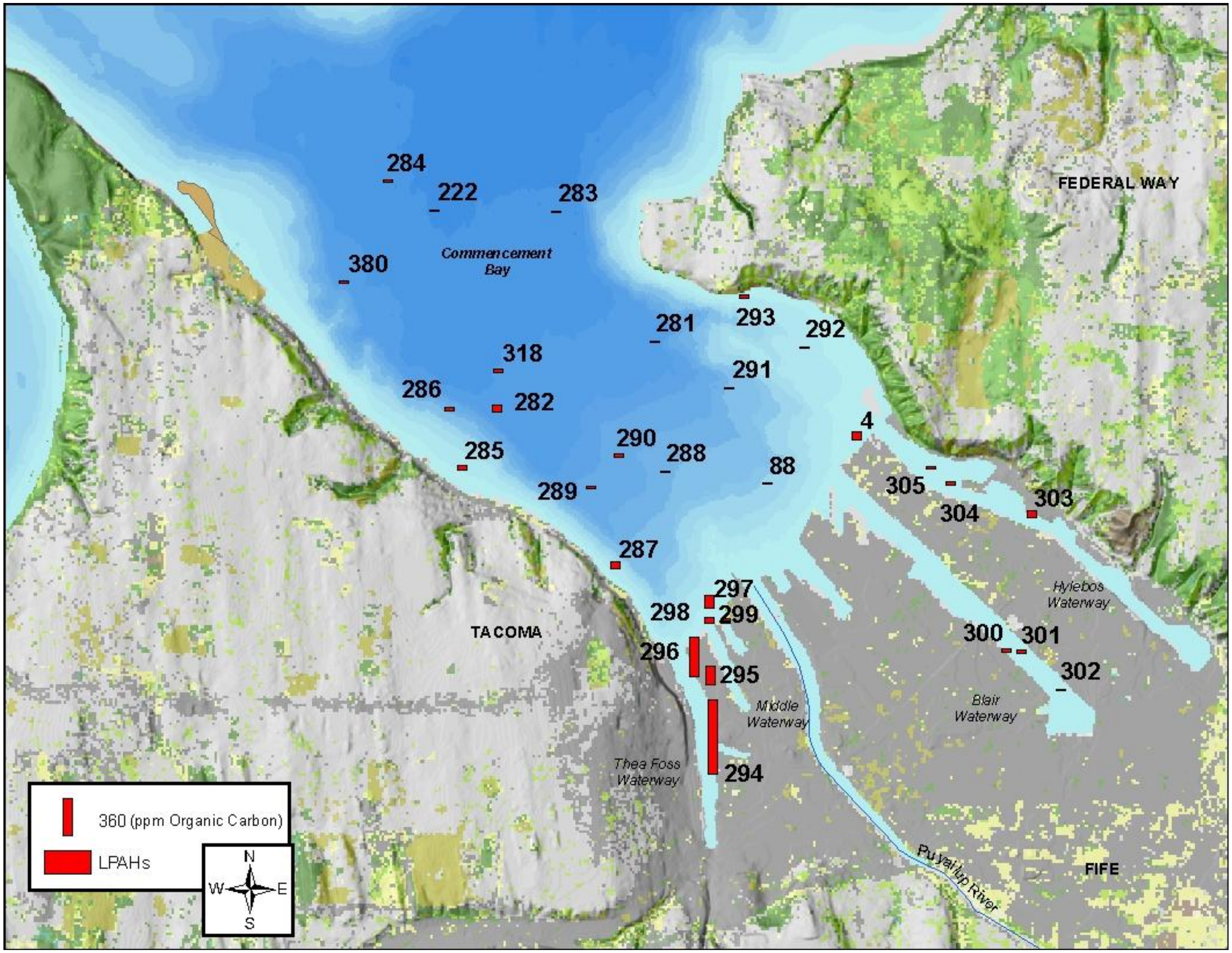

Figure 13. Spatial patterns in TOC-normalized total LPAH (sum of 6 LPAH compounds) at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.
The Sediment Quality Standard for total LPAH is 370 ppm organic carbon. The numbers on the map are the station identifications.

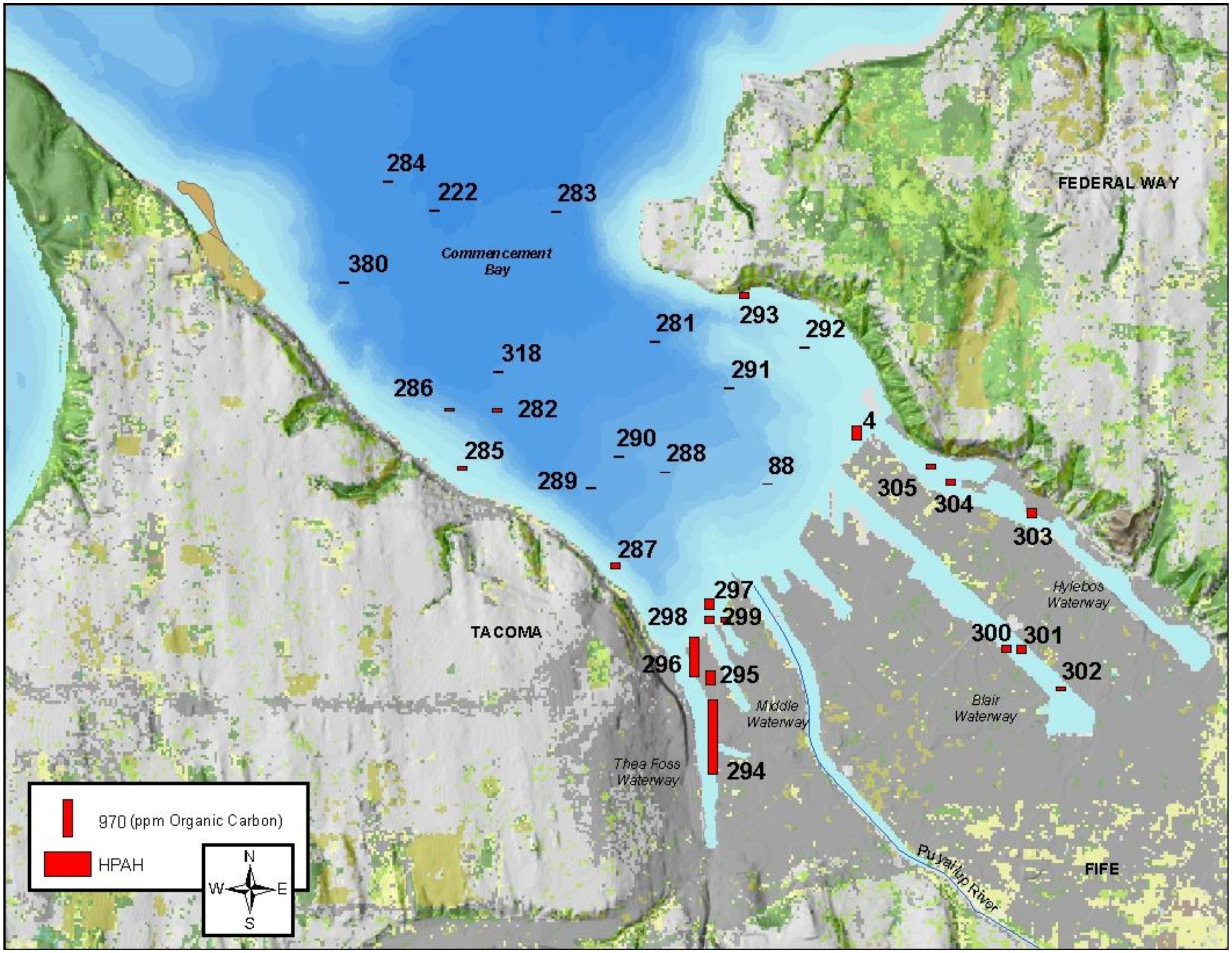

Figure 14. Spatial patterns in TOC-normalized total HPAH (sum of 9 HPAH compounds) at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.

The Sediment Quality Standard for total HPAH is 960 ppm organic carbon. The numbers on the map are the station identifications.

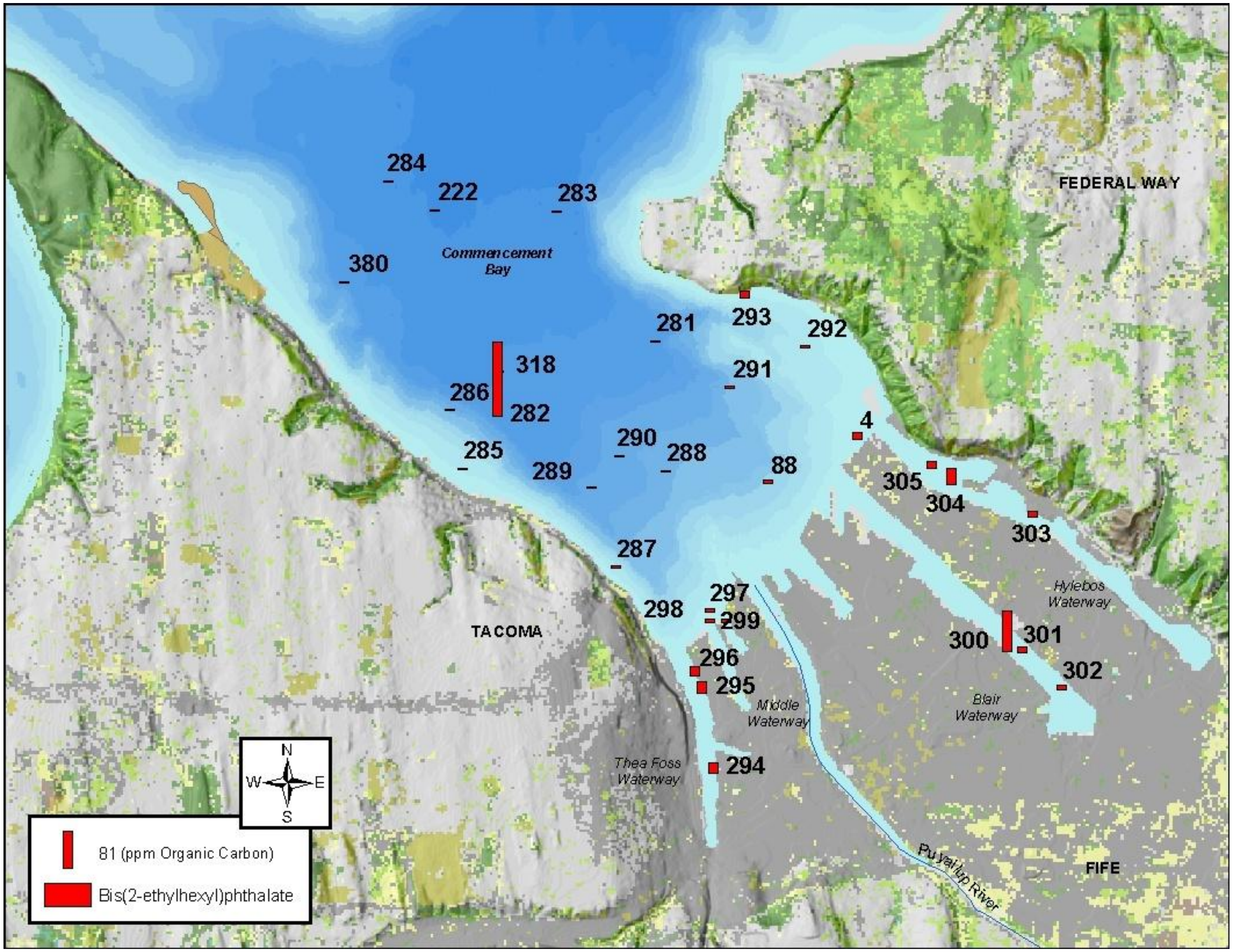

Figure 15. Spatial patterns in TOC-normalized bis(2-ethylhexyl)phthalate at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.

The Sediment Quality Standard for bis(2-ethylhexyl)phthalate is 47 ppm organic carbon. The numbers on the map are the station identifications.

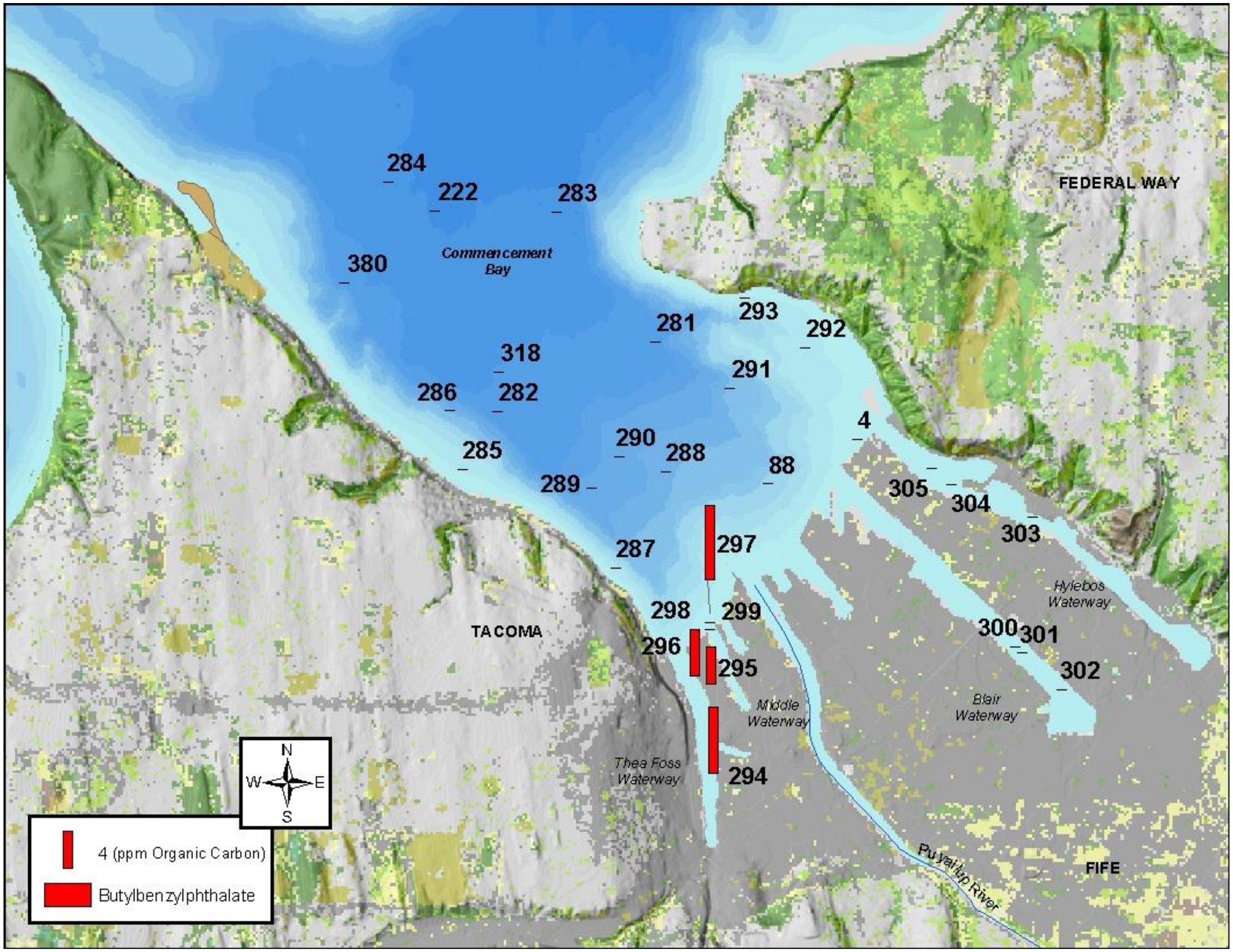

Figure 16. Spatial patterns in TOC-normalized butylbenzylphthalate at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.
The Sediment Quality Standard for butylbenzylphthalate is 4.9 ppm organic carbon. The numbers on the map are the station identifications.

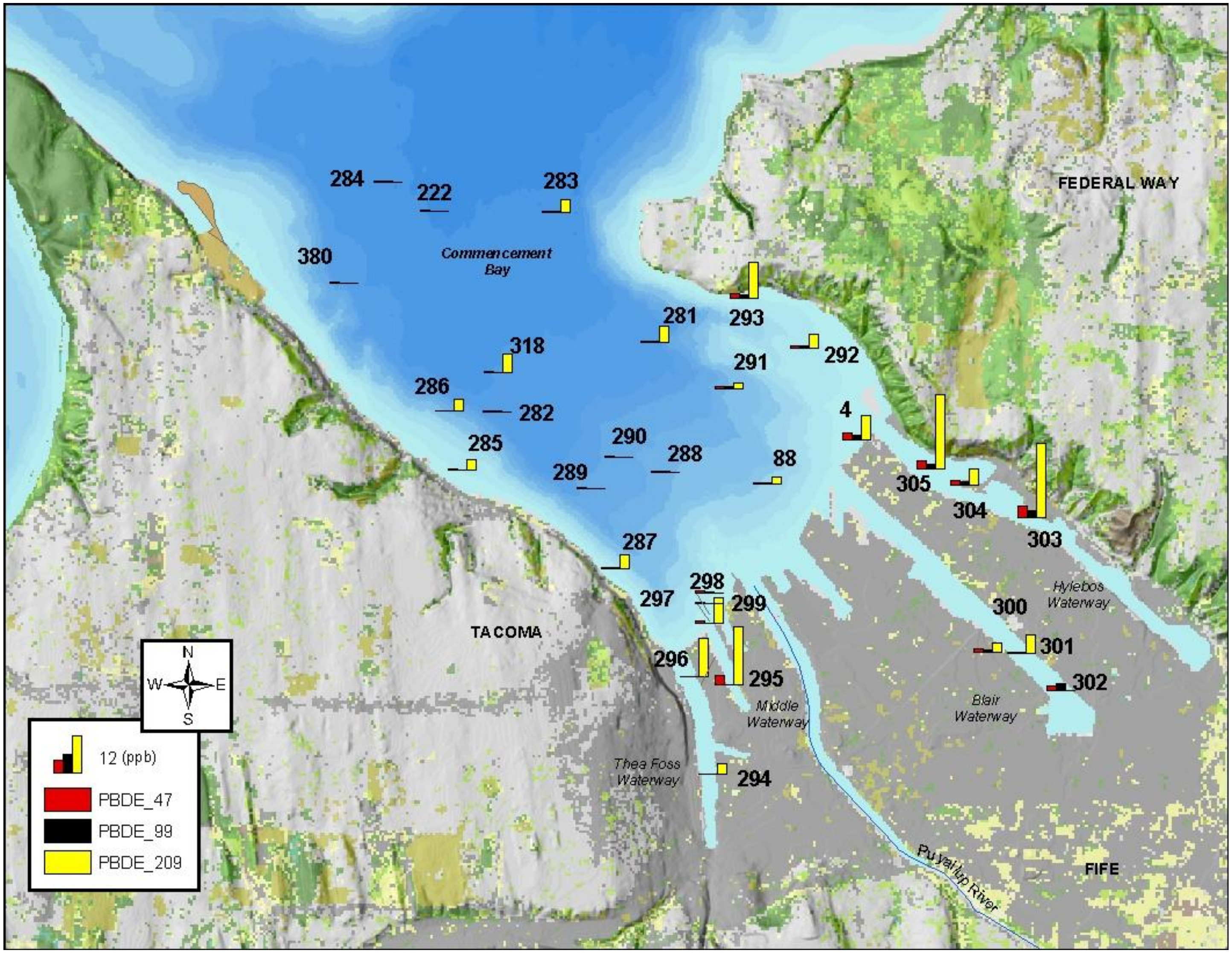

Figure 17. Spatial patterns in concentrations of PBDE congeners 47, 99, and 209 (ng/g dry weight) at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.
The numbers on the map are the station identifications.

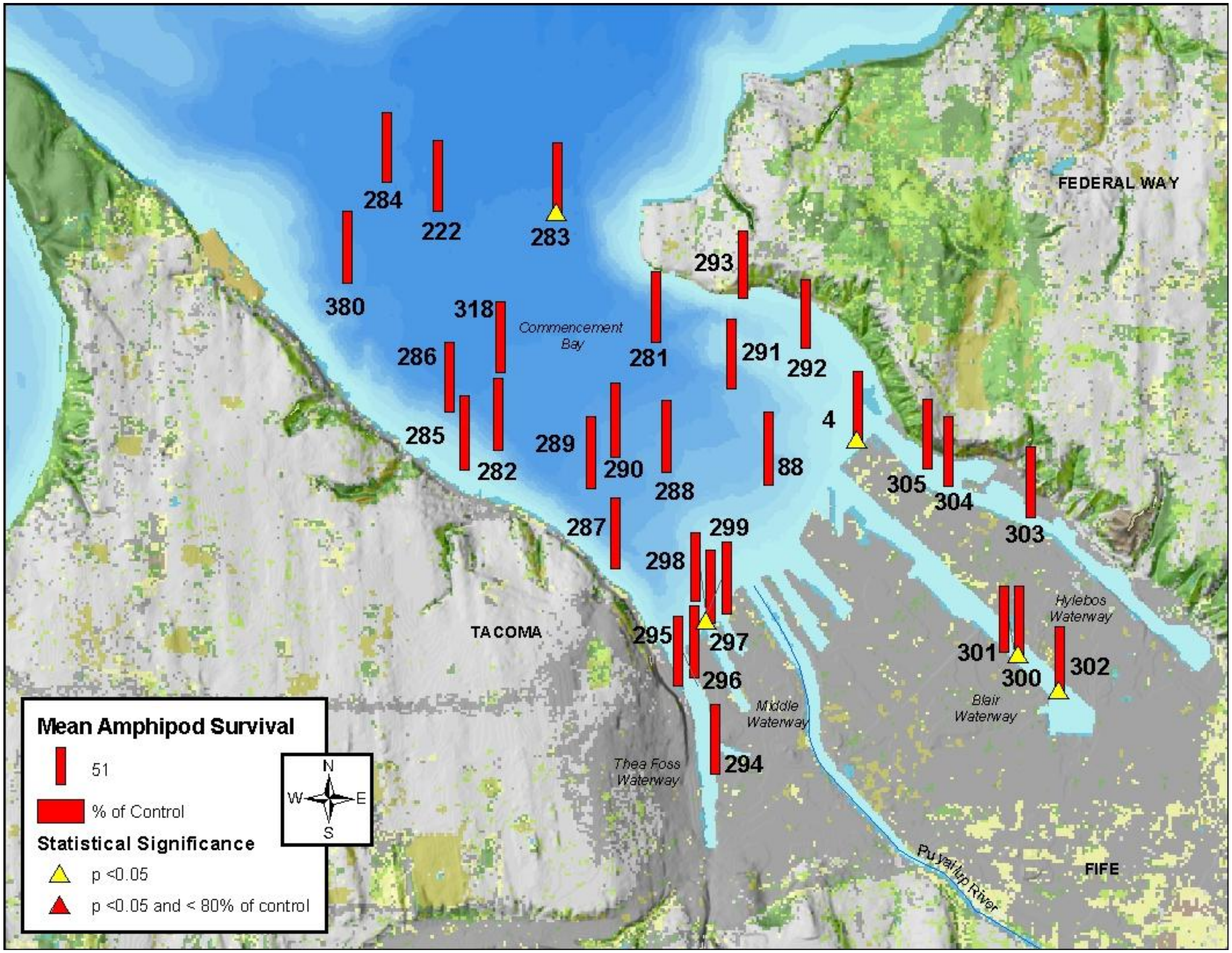

Figure 18. Spatial patterns in toxicity as determined with the amphipod *Eohaustorius estuarius* in tests of solid phase sediments. (control-corrected percent survival) at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.
The numbers on the map are the station identifications.

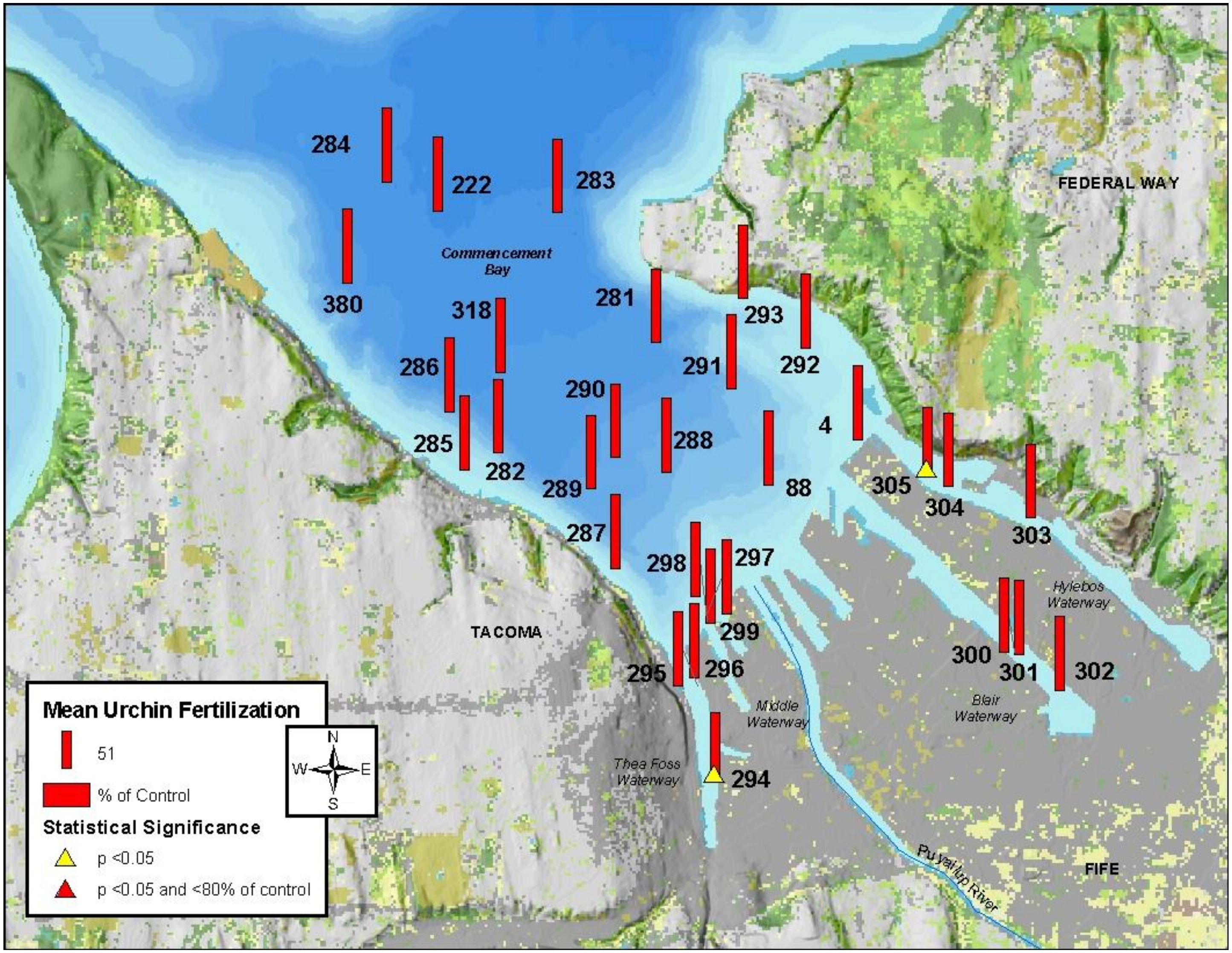

Figure 19. Spatial patterns in toxicity as determined with the sea urchin *Strongylocentrotus purpuratus* in porewater from sediments (control-corrected percent fertilization) at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.
The numbers on the map are the station identifications.

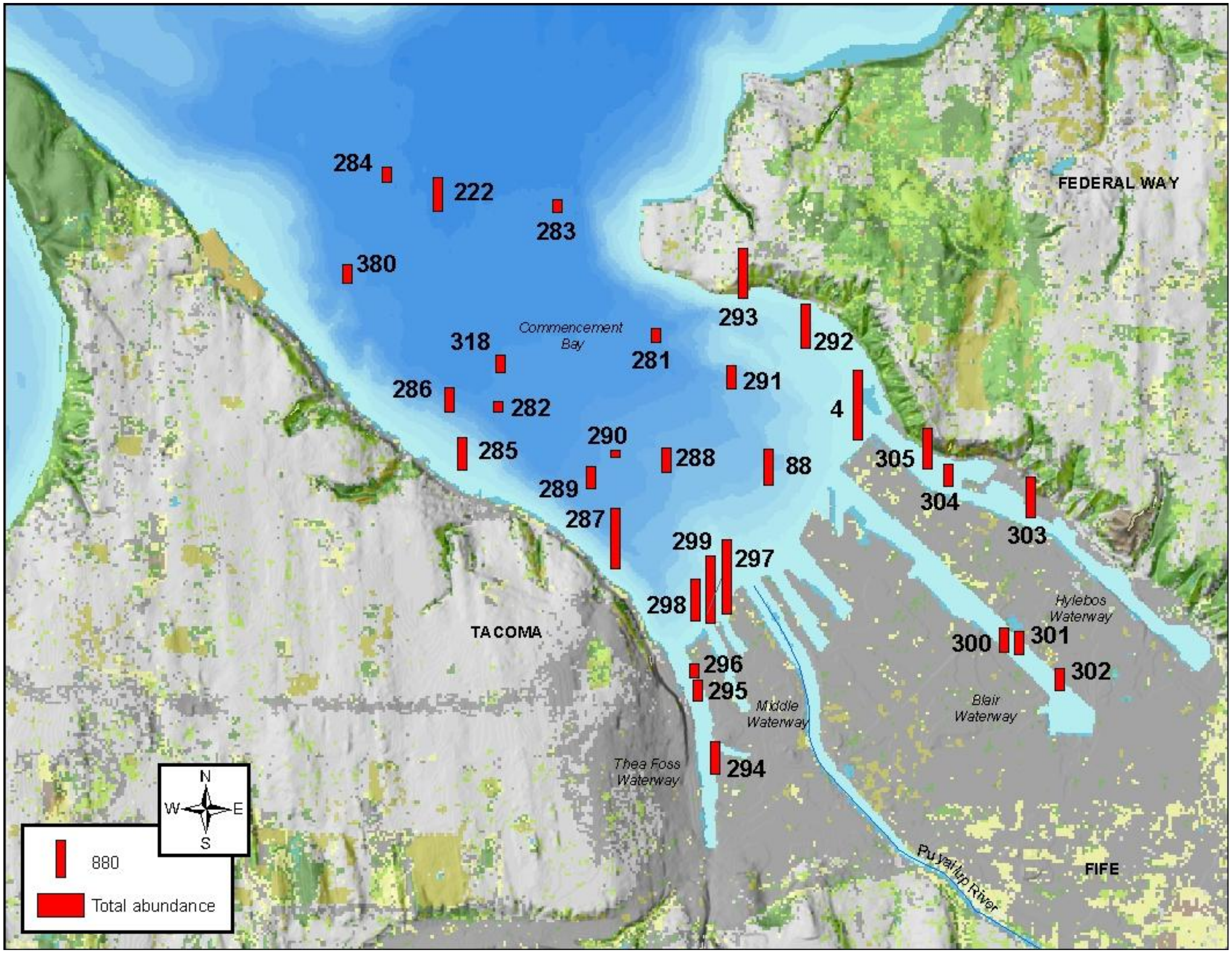

Figure 20. Total abundance of all benthic organisms (number of individuals per 0.1 m^2) at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.
The numbers on the map are the station identifications.

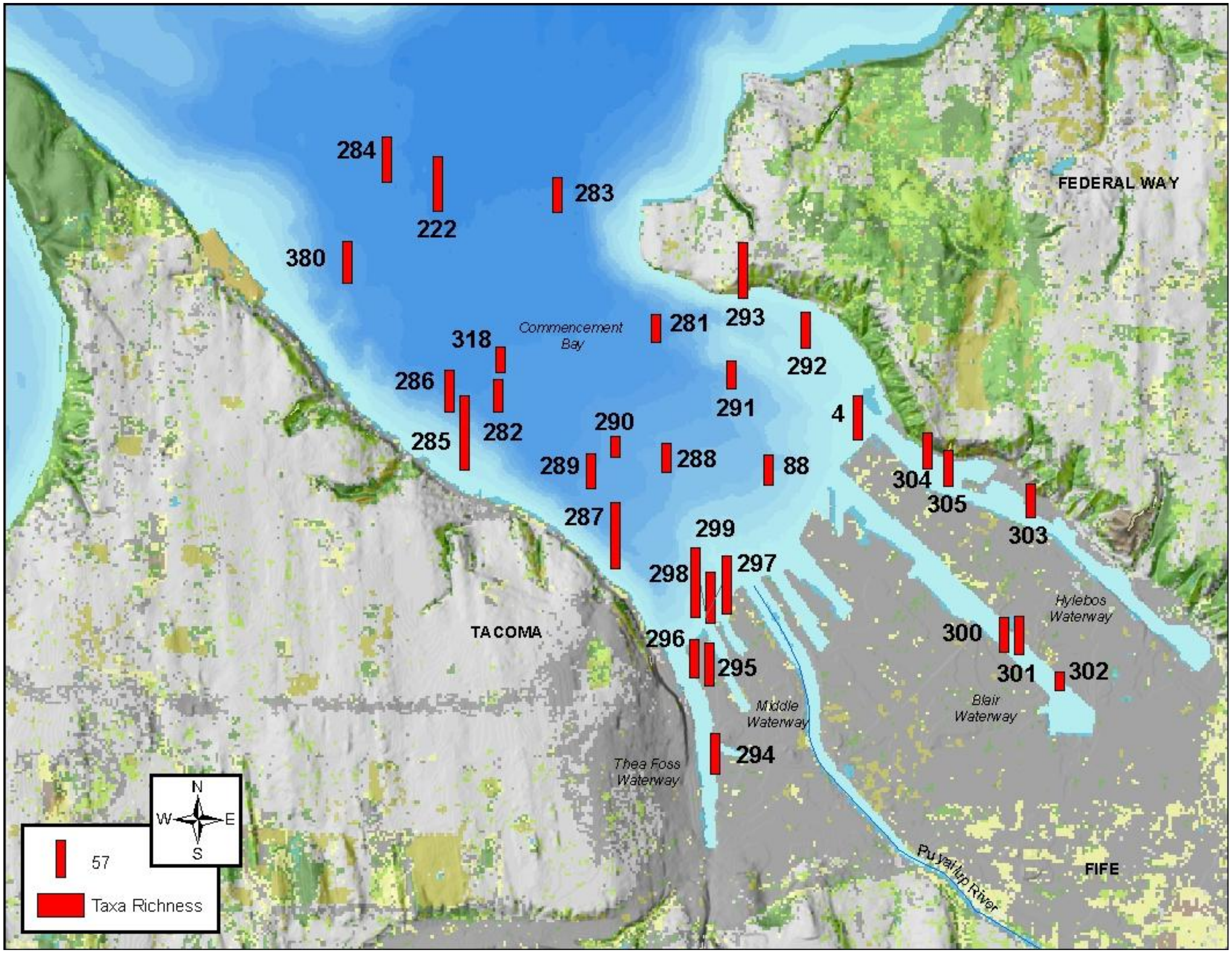

Figure 21. Taxa richness (number of taxa per 0.1 m^2) at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study. *The numbers on the map are the station identifications.*

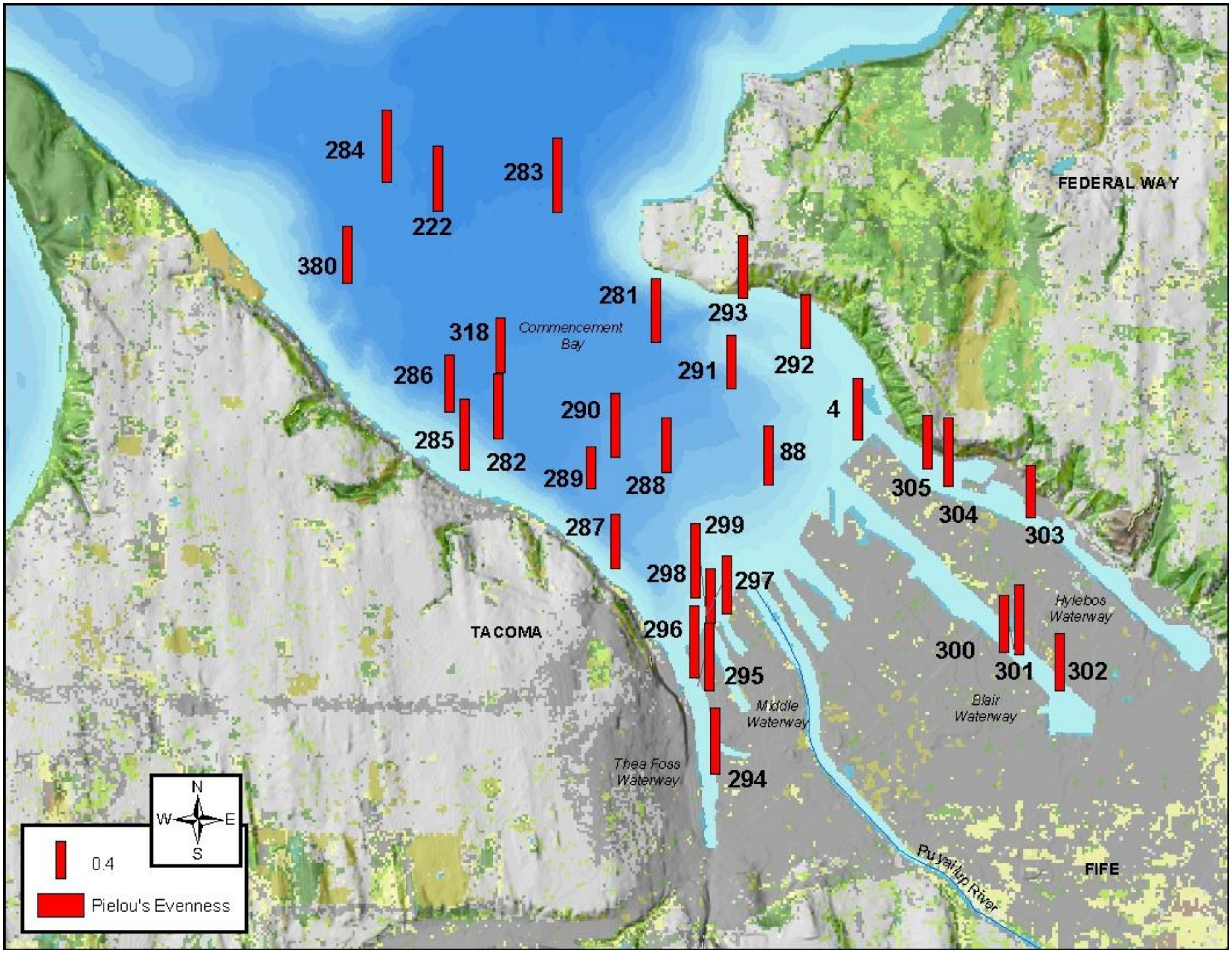

Figure 22. Pielou's Evenness index values for the benthos at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.

The numbers on the map are the station identifications.

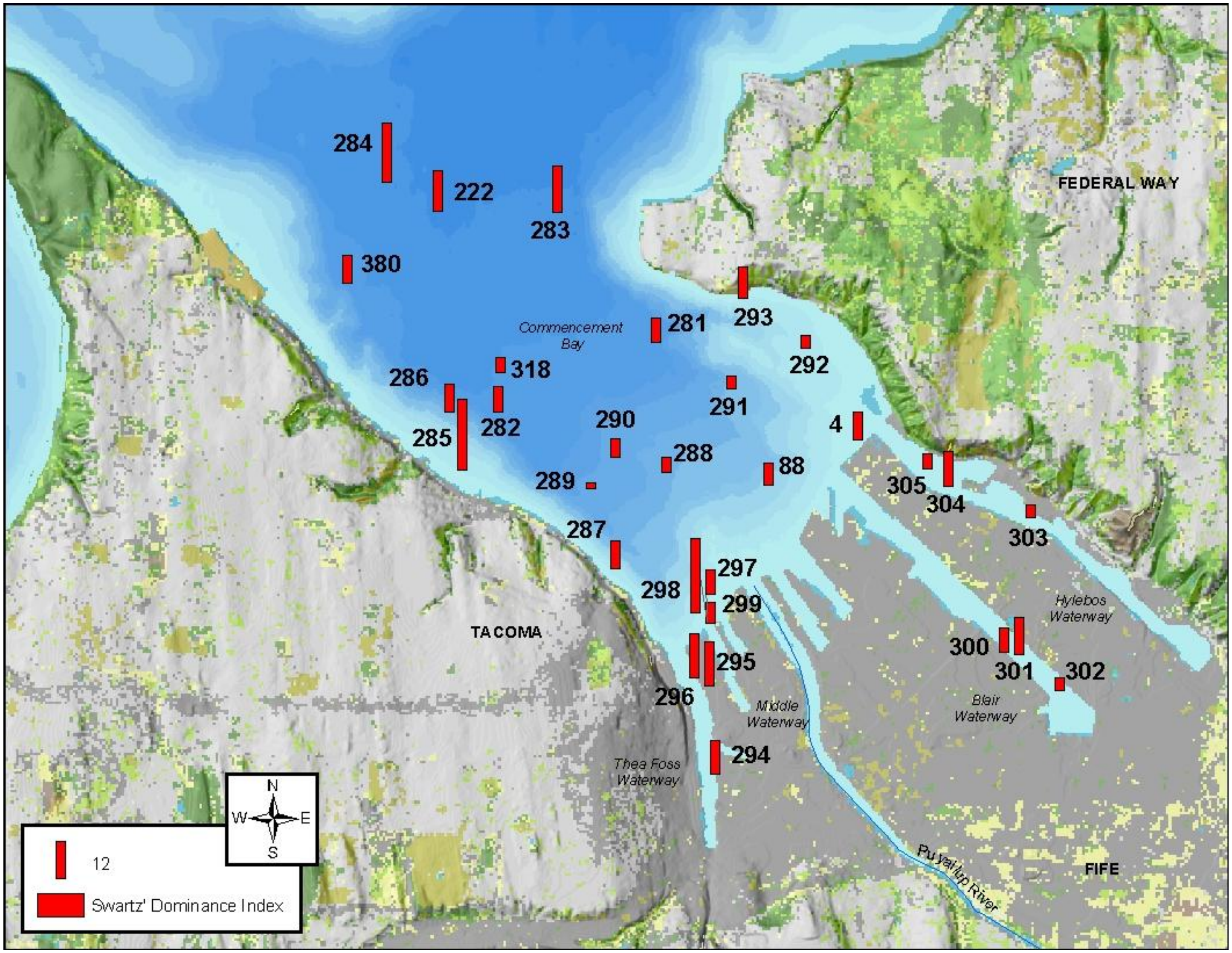

Figure 23. Swartz' Dominance Index values (number of taxa) for the benthos at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.
The numbers on the map are the station identifications.

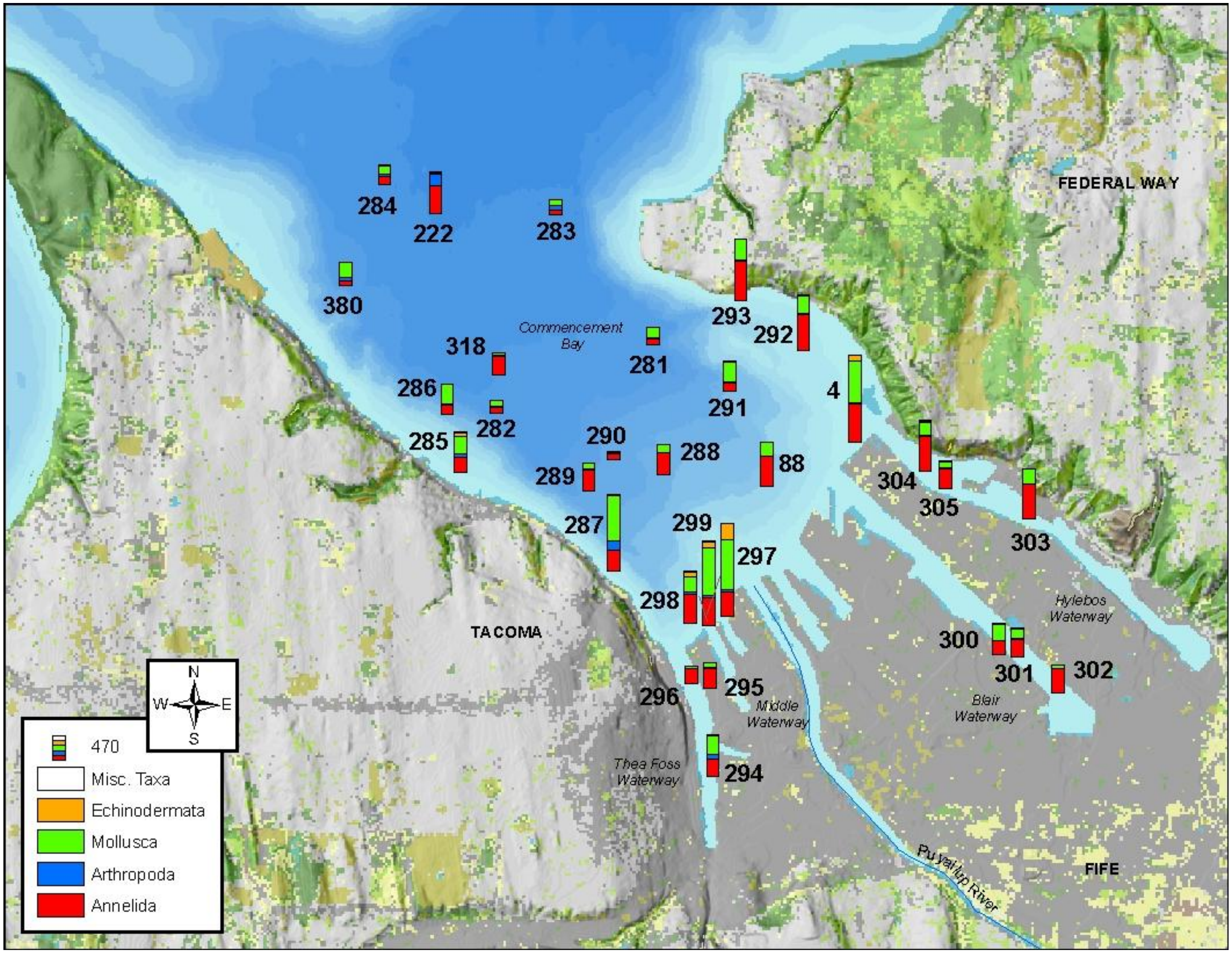

Figure 24. Abundance of each major benthic taxonomic group (number of individuals per 0.1 m^2) at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.
The numbers on the map are the station identifications.

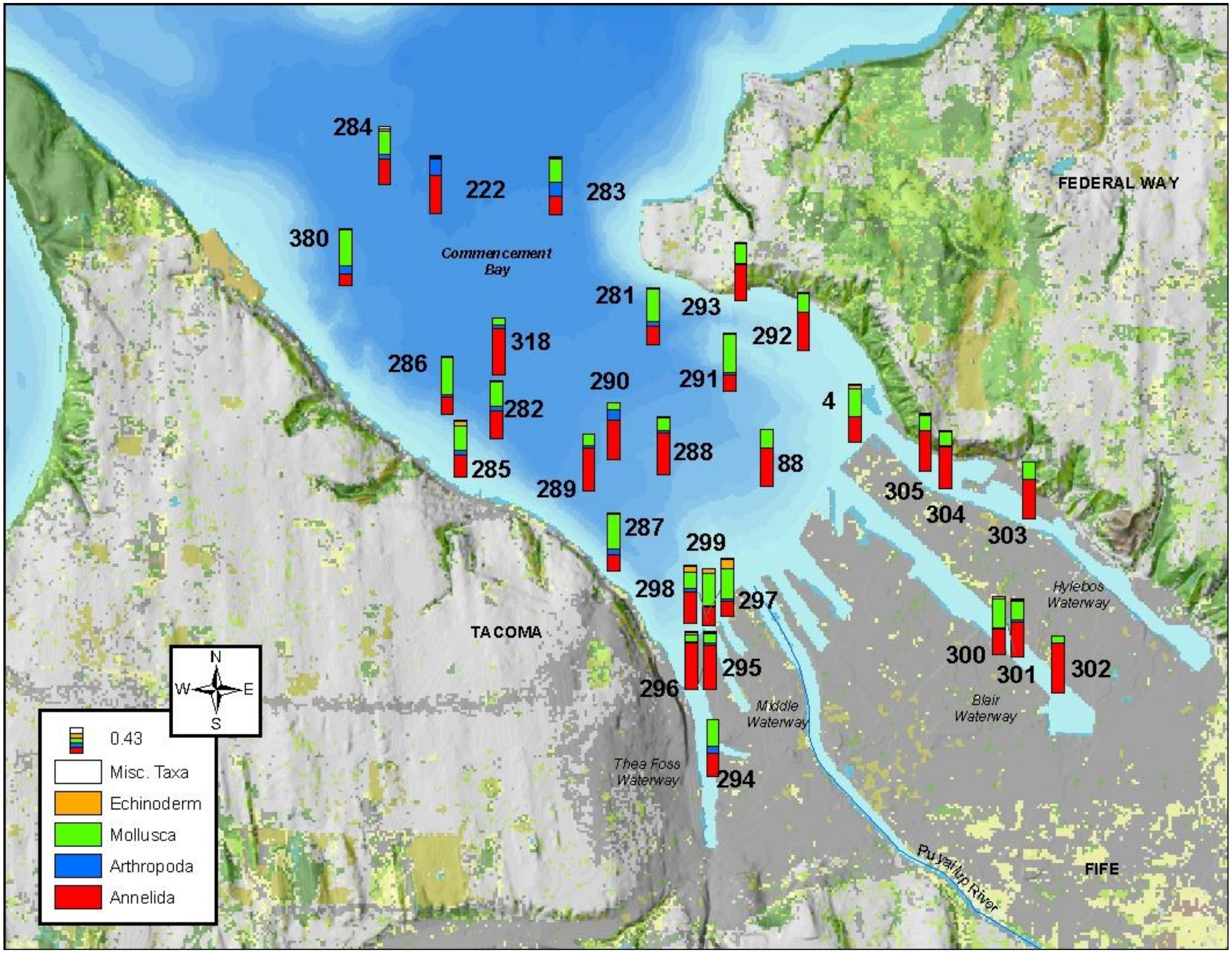

Figure 25. Relative abundance of each major benthic taxonomic group (percent of total abundance) at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.

The proportions sum to 100% in each bar. The numbers on the map are the station identifications.

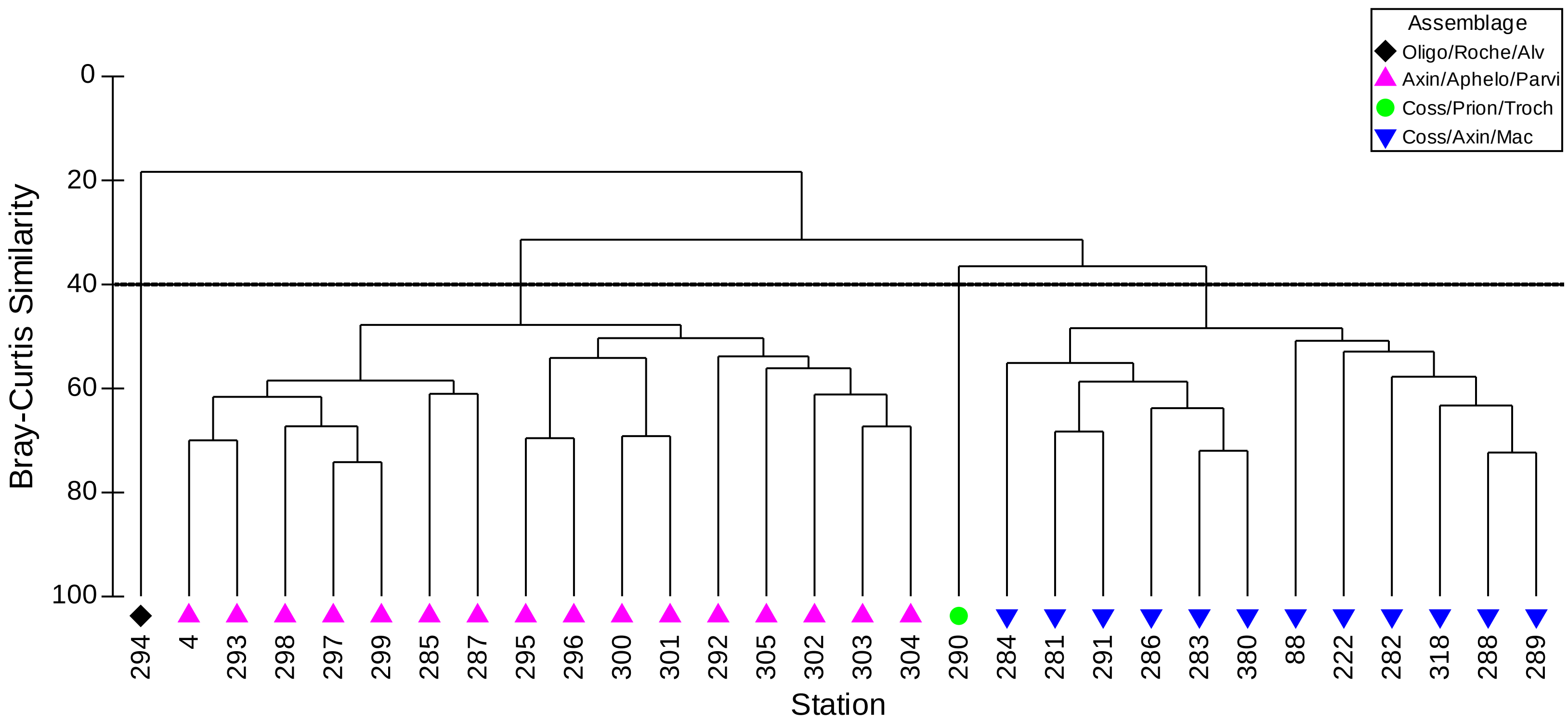

Figure 26. Cluster dendrogram of benthic invertebrate assemblages at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.

The clusters are based on Bray-Curtis similarities of 4th-root-transformed species abundances ("rare" species excluded), using group-average linkage. A line indicating 40% similarity level is drawn across the dendrogram. The clusters at 40% similarity are identified by the most common and most abundant taxa. The same clusters are depicted in two dimensions, from a multidimensional scaling analysis, in Figure 27. These clusters are:

- Oligochaeta/*Rochefortia*/*Alvania*
- *Axinopsida*/*Aphelochaeta*/*Parvilucina*
- *Cossura*/*Prionospio*/*Trochochaeta*
- *Cossura*/*Axinopsida*/*Macoma*

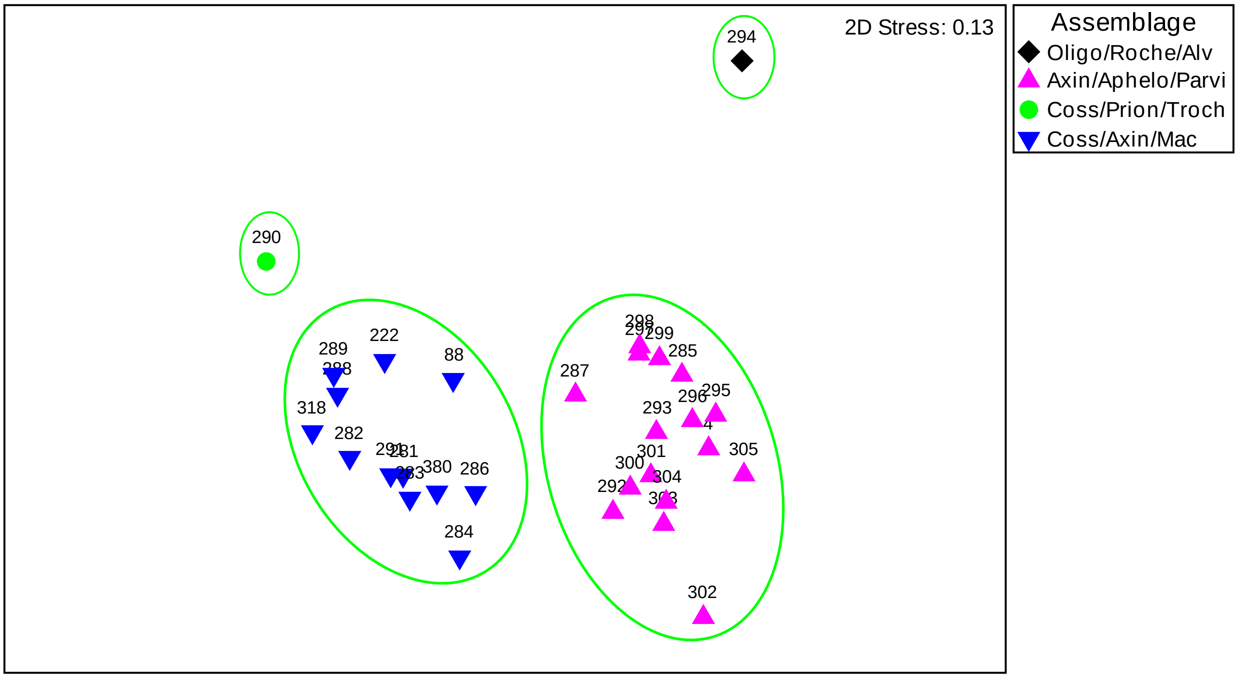

Figure 27. Multidimensional scaling (MDS) map of benthic invertebrate assemblages at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.

Degree of similarity between assemblages is depicted by relative distance in this two-dimensional map. The similarity measure used was Bray-Curtis similarity, calculated on 4th-root-transformed species abundances ("rare" species excluded). Overlaid on the MDS map are clusters at 40% similarity (see cluster dendrogram in Figure 26). The clusters are identified by the most common and most abundant taxa:

- Oligochaeta/*Rochefortia*/*Alvania*
- *Axinopsida*/*Aphelochaeta*/*Parvilucina*
- *Cossura*/*Prionospio*/*Trochochaeta*
- *Cossura*/*Axinopsida*/*Macoma*

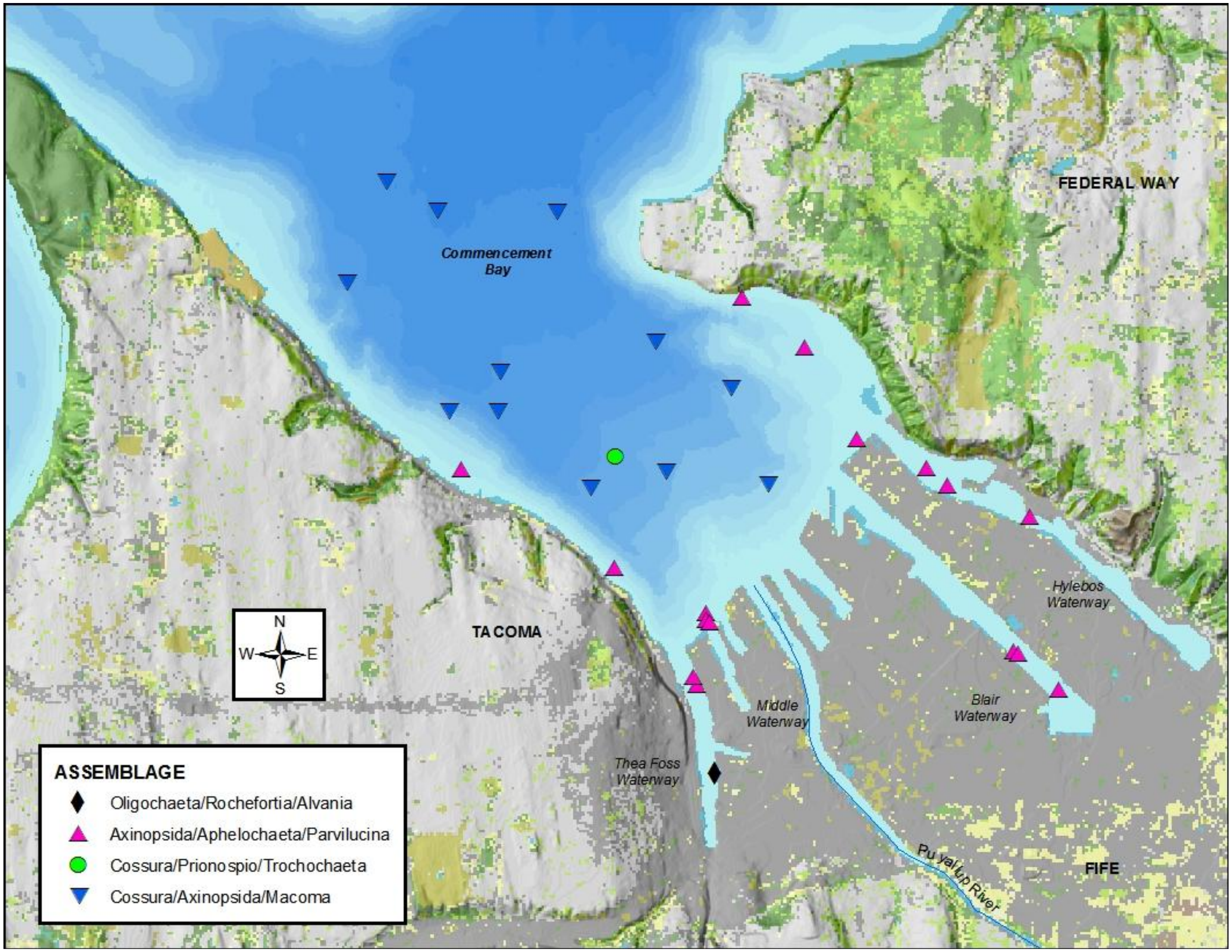

Figure 28. Map of benthic invertebrate assemblages at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study. *The clusters are identified by the most common and most abundant taxa (see cluster dendrogram in Figure 26).*

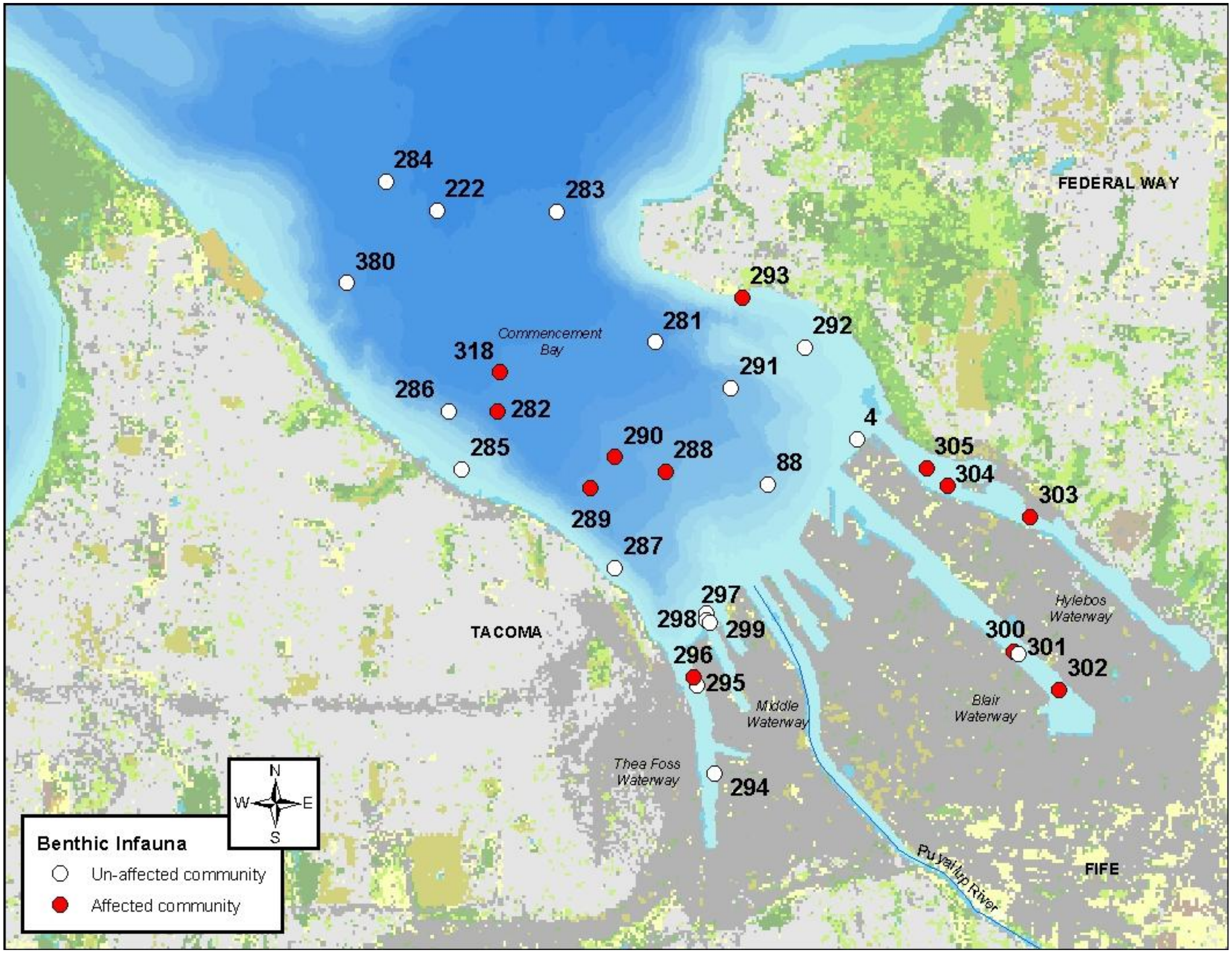

Figure 29. Spatial distribution of stations at which the benthos were classified as unaffected or adversely affected (2008 Urban Waters Initiative sediment study).

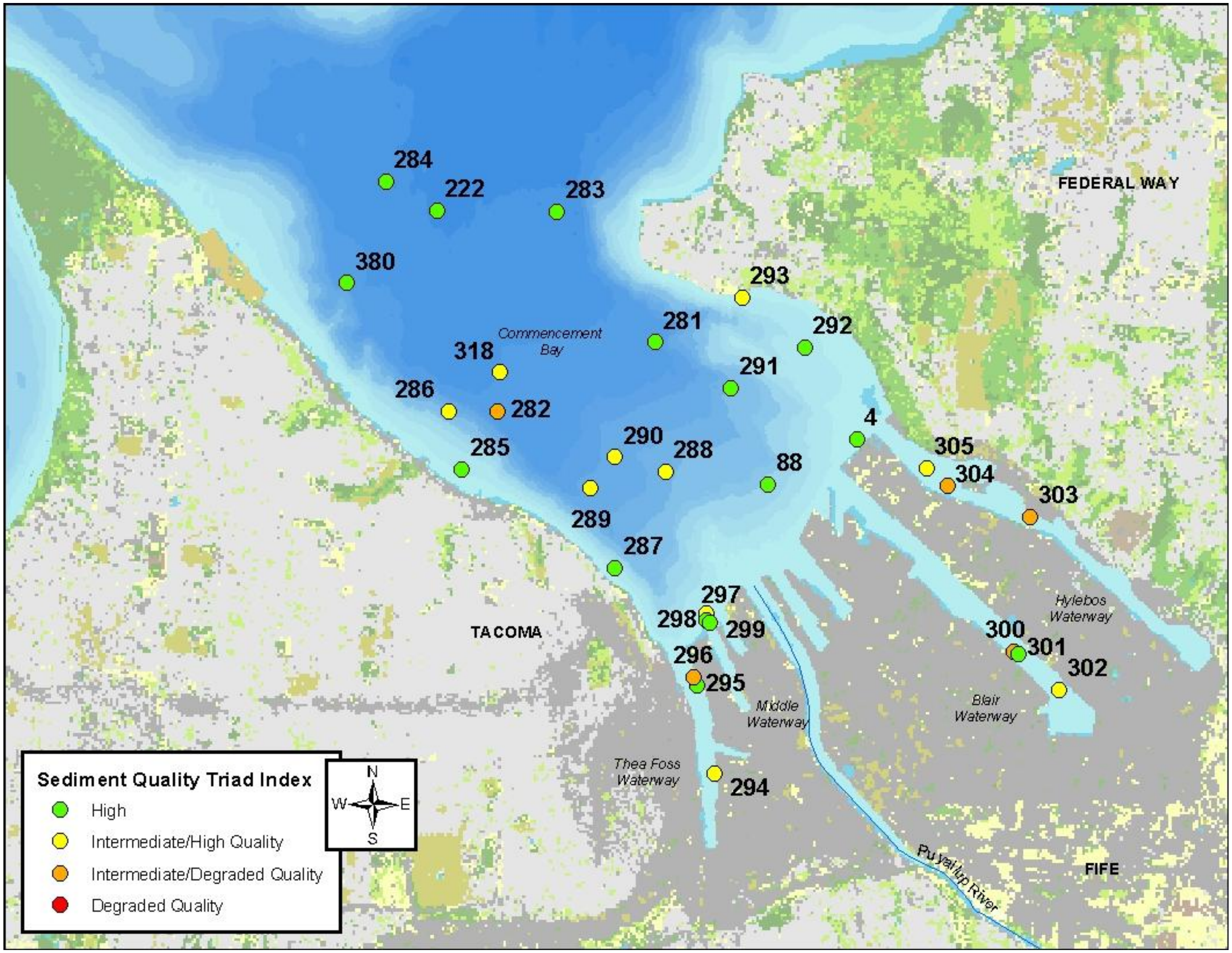

Figure 30. Spatial distribution of stations classified as one of four possible categories with the Sediment Quality Triad Index (2008 Urban Waters Initiative sediment study).

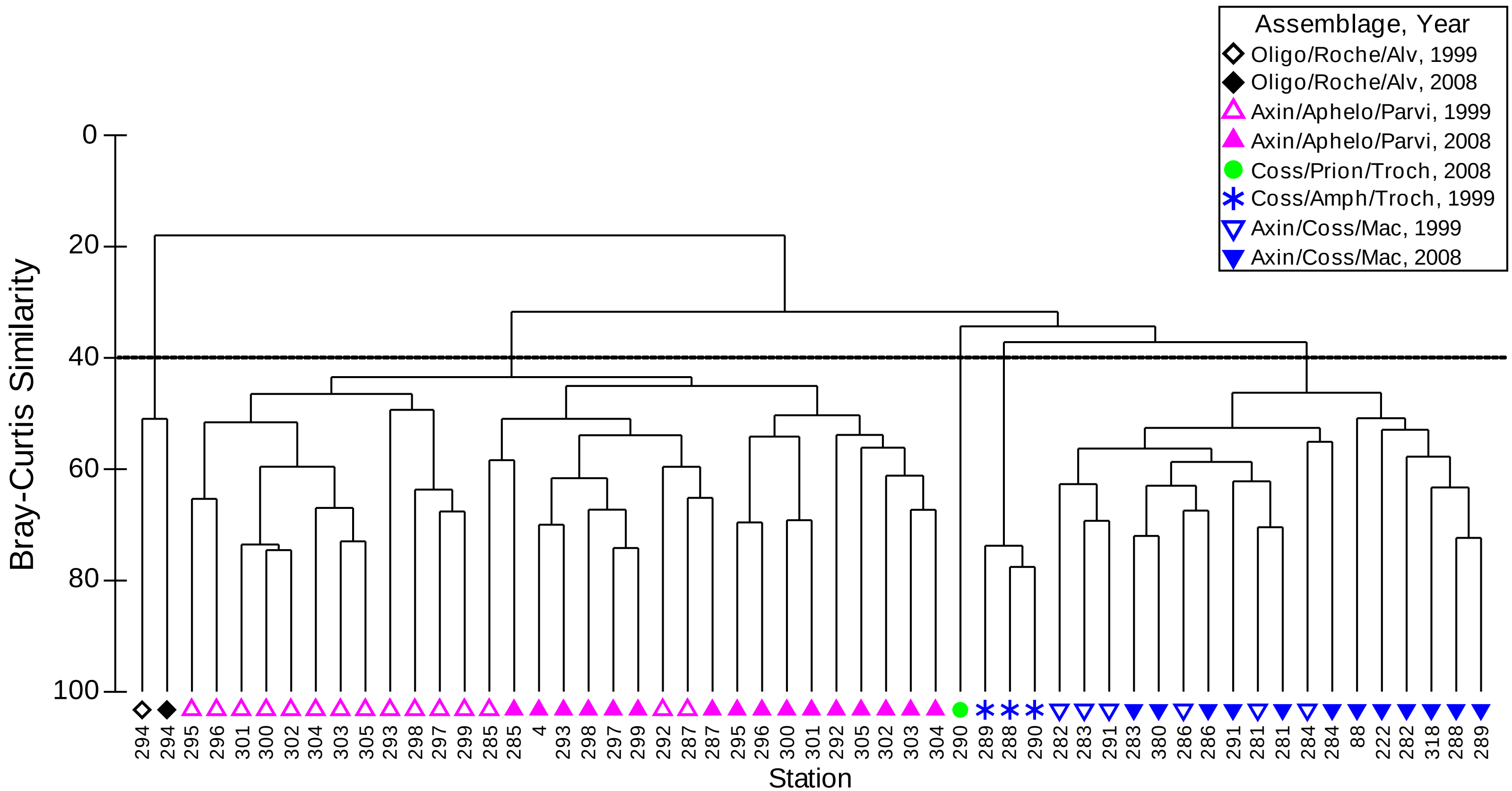

Figure 31. Cluster dendrogram of benthic invertebrate assemblages at 30 stations sampled for the 2008 Urban Waters Initiative sediment study and 25 stations sampled in 1999.

The clusters are based on Bray-Curtis similarities of 4th-root-transformed species abundances ("rare" species excluded), using group-average linkage. A line indicating 40% similarity level is drawn across the dendrogram. The clusters at 40% similarity are identified by the most common and most abundant taxa. The same clusters are depicted in two dimensions, from a multidimensional scaling analysis, in Figure 32. These clusters are:

- Oligochaeta/*Rochefortia*/*Alvania* (both years)
- *Axinopsida*/*Aphelochaeta*/*Parvilucina* (both years)
- *Cossura*/*Prionospio*/*Trochochaeta* (2008)
- *Cossura*/*Ampharete*/*Trochochaeta* (1999)
- *Axinopsida*/*Cossura*/*Macoma* (both years)

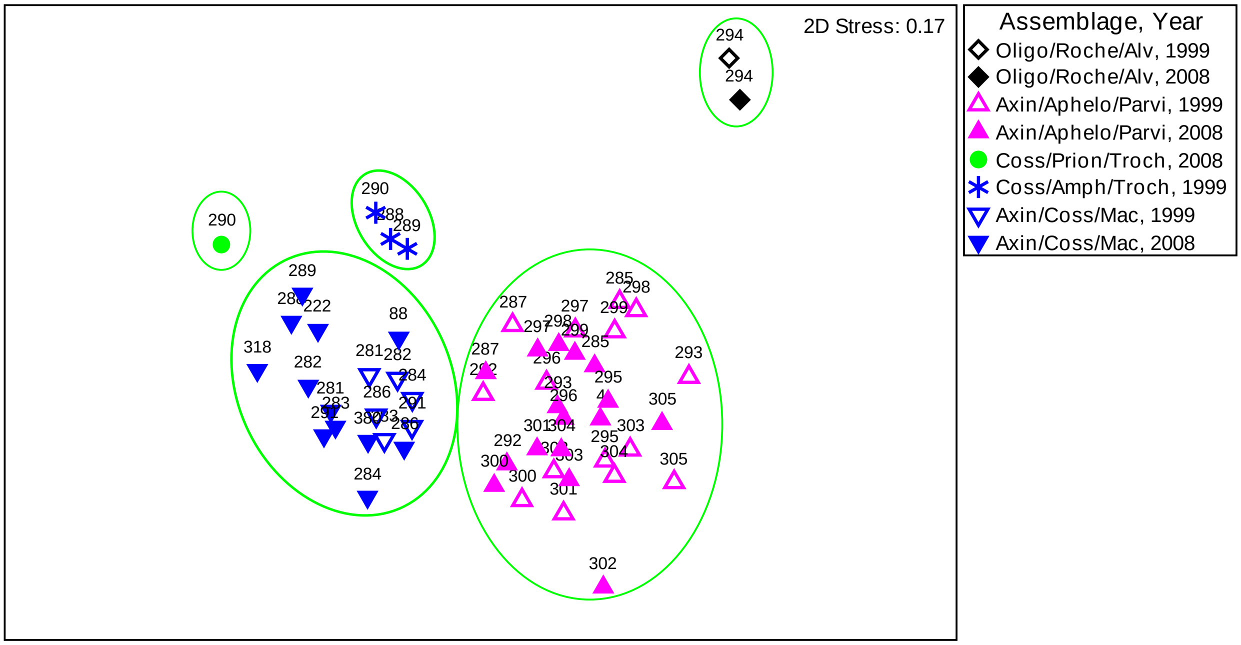

Figure 32. Multidimensional scaling (MDS) map of benthic invertebrate assemblages at 30 stations sampled for the 2008 Urban Waters Initiative sediment study and 25 stations sampled in 1999.

Degree of similarity between assemblages is depicted by relative distance in this two-dimensional map. The similarity measure used was Bray-Curtis similarity, calculated on 4th-root-transformed species abundances ("rare" species excluded). Overlaid on the MDS map are clusters at 40% similarity (see cluster dendrogram in Figure 31). The clusters are identified by the most common and most abundant taxa:

- Oligochaeta/*Rochefortia*/*Alvania* (both years)
- *Axinopsida/Aphelochaeta*/*Parvilucina* (both years)
- *Cossura*/*Prionospio*/*Trochochaeta* (2008)
- *Cossura*/*Ampharete*/*Trochochaeta* (1999)
- *Axinopsida*/*Cossura*/*Macoma* (both years)

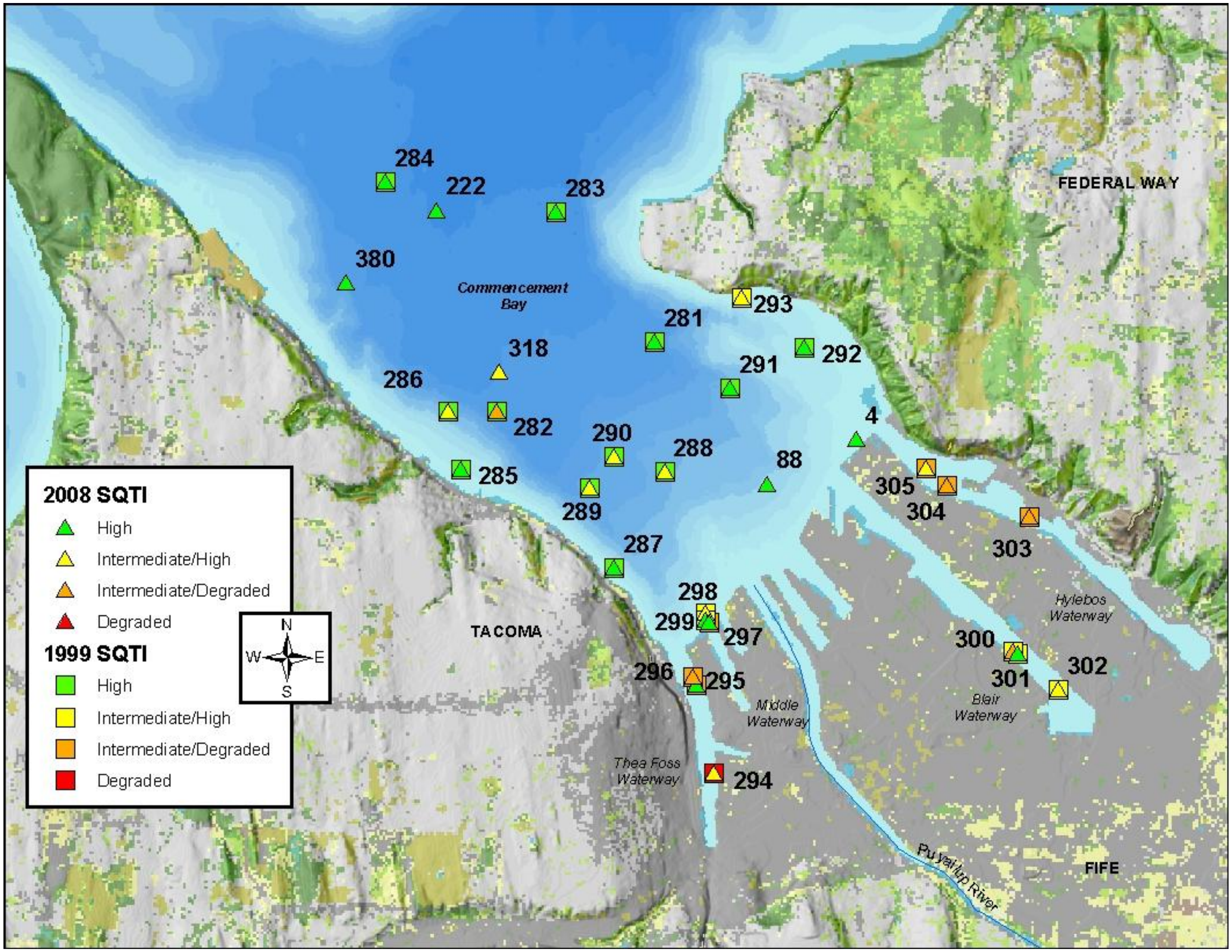

Figure 33. Classification of sediment quality at sampling stations in 2008 compared to 1999, according to the Sediment Quality Triad Index (SQTI).
Stations 4, 88, 222, 318, and 380 were sampled in 2008 only.

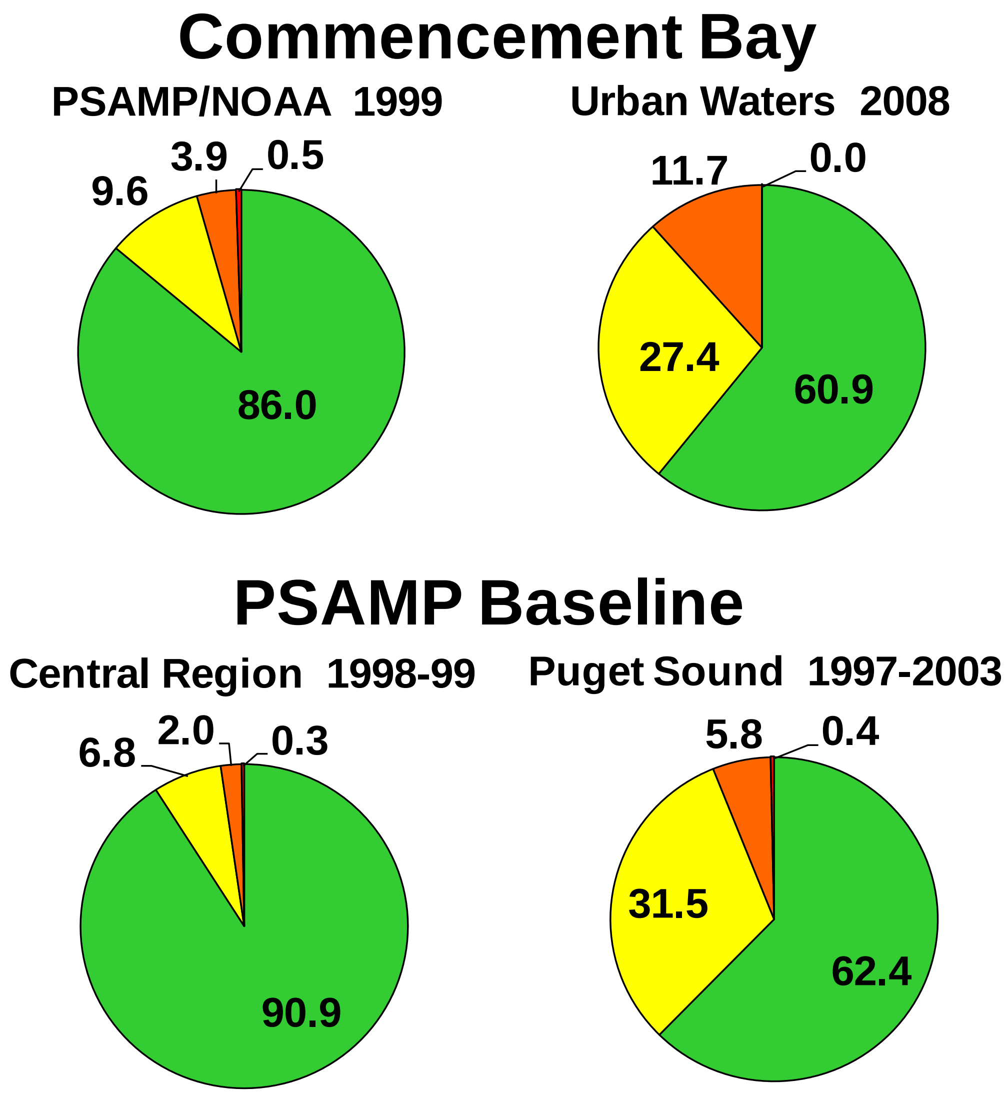

Figure 34. Spatial extent (% of area) of sediment quality by Sediment Quality Triad Index categories for Commencement Bay in 1999 and 2008, PSAMP Central Sound region (1998-1999), and all of Puget Sound (1997-2003).

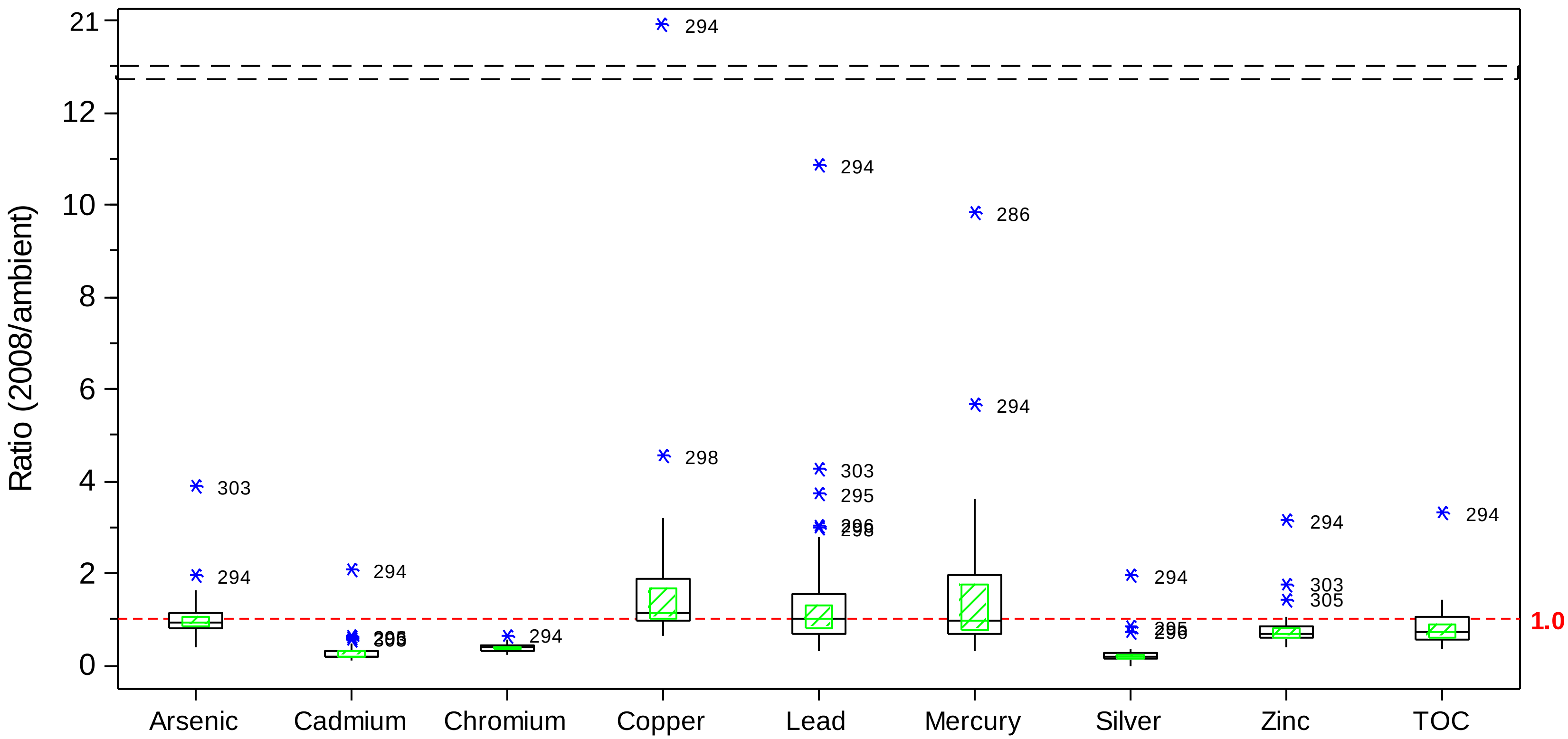

Figure 35. Comparison of 2008 Urban Waters Initiative sediment metals concentrations to 1997-2003 PSAMP ambient means. *Outliers are labeled with station numbers.*

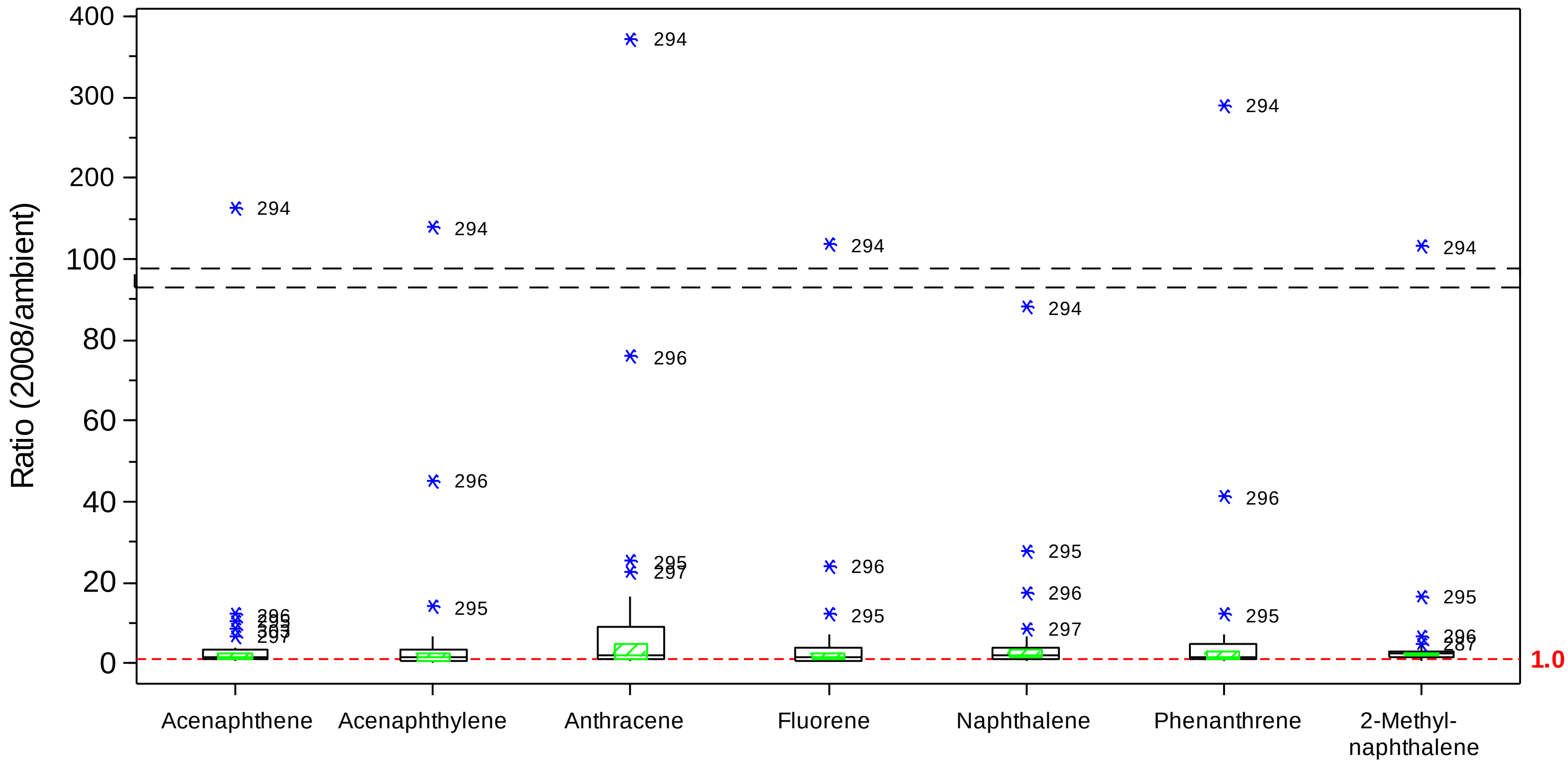

Figure 36. Comparison of 2008 Urban Waters Initiative sediment LPAH concentrations to 1997-2003 PSAMP ambient means. *Outliers are labeled with station numbers.*

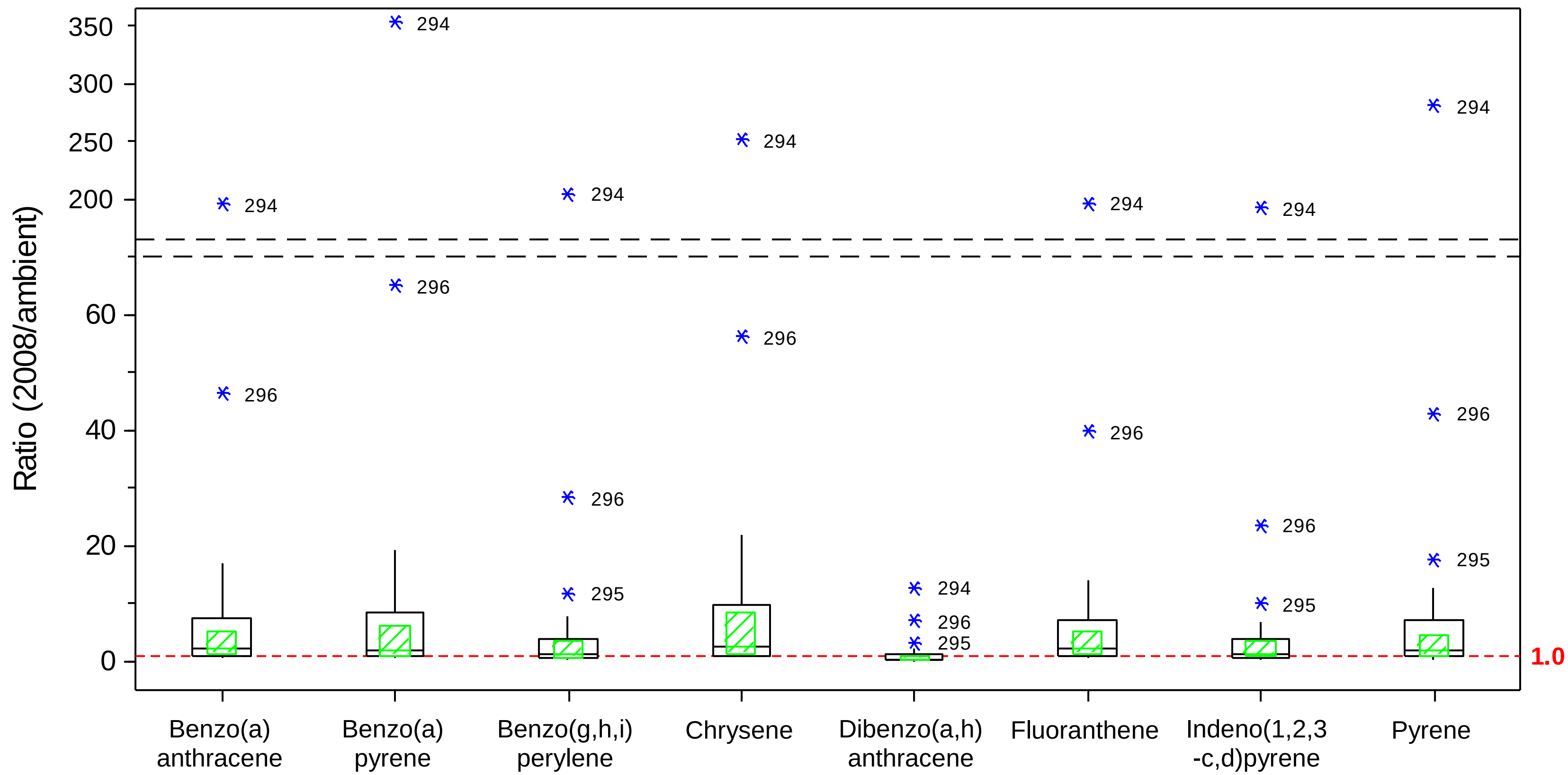

Figure 37. Comparison of 2008 Urban Waters Initiative sediment HPAH concentrations to 1997-2003 PSAMP ambient means. *Outliers are labeled with station numbers.*

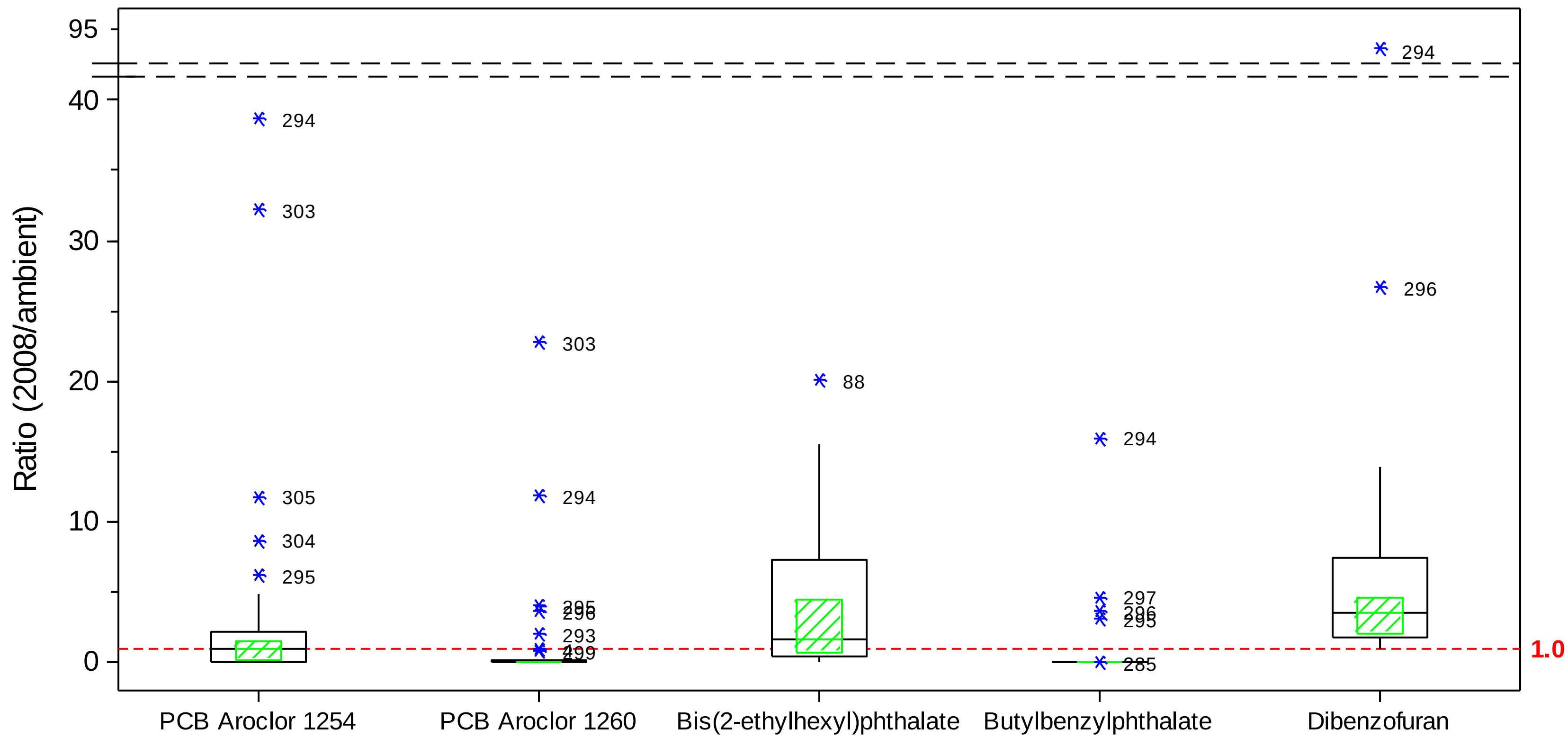

Figure 38. Comparison of 2008 Urban Waters Initiative sediment contaminant concentrations to 1997-2003 PSAMP ambient means. *Outliers are labeled with station numbers.*

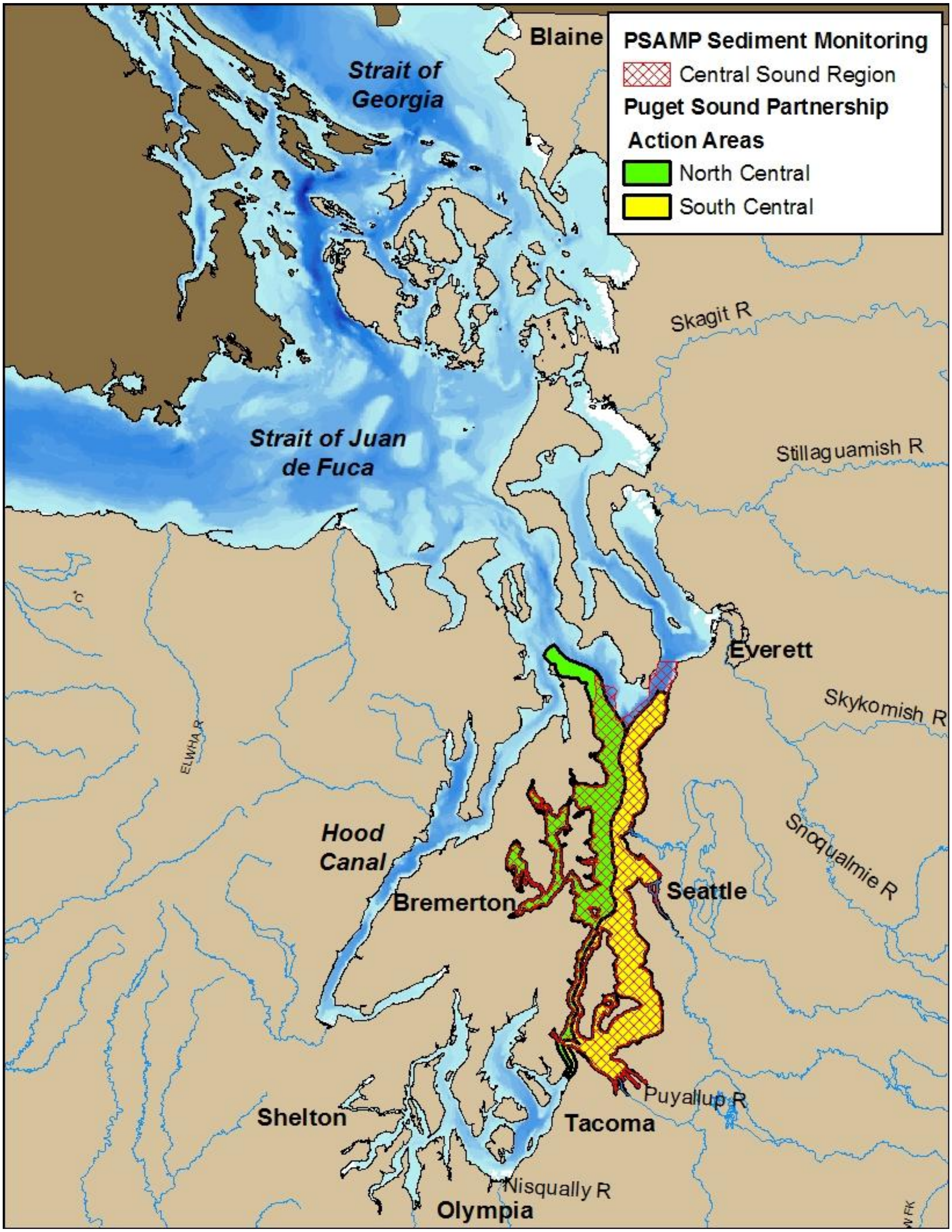

Figure 39. Overlap of PSAMP sediment monitoring Central Sound region and Puget Sound Partnership South Central and North Central Action Areas.

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Tables

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Table 1. Station numbers, names, stratum types, and sample weights at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.

Station Number	Location	Stratum Type (Multidensity Category)	Estimated area represented (km^2) Resampled stations only	Estimated area represented (km^2) All stations
281	Central Commencement Bay	Urban	3.24	1.851
282	Central Commencement Bay	Urban	3.24	1.851
283	Outer Commencement Bay	Urban	3.24	1.851
284	Outer Commencement Bay	Urban	3.24	1.851
285	S. Shoreline Commencement Bay	Urban	0.786	0.786
286	S. Shoreline Commencement Bay	Urban	0.786	0.786
287	S. Shoreline Commencement Bay	Urban	0.786	0.786
288	S.E. Commencement Bay	Urban	1.054	0.791
289	S.E. Commencement Bay	Urban	1.054	0.791
290	S.E. Commencement Bay	Urban	1.054	0.791
291	N.E. Commencement Bay	Urban	1.108	0.831
292	N.E. Commencement Bay	Urban	1.108	0.831
293	N.E. Commencement Bay	Urban	1.108	0.831
294	Thea Foss Waterway	Harbor	0.126	0.126
295	Thea Foss Waterway	Harbor	0.126	0.126
296	Thea Foss Waterway	Harbor	0.126	0.126
297	Middle Waterway	Harbor	0.016	0.016
298	Middle Waterway	Harbor	0.016	0.016
299	Middle Waterway	Harbor	0.016	0.016
300	Blair Waterway	Harbor	0.387	0.387
301	Blair Waterway	Harbor	0.387	0.387
302	Blair Waterway	Harbor	0.387	0.387
303	Hylebos Waterway	Harbor	0.223	0.223
304	Hylebos Waterway	Harbor	0.223	0.223
305	Hylebos Waterway	Harbor	0.223	0.223
4	N.E. Commencement Bay	Urban		0.831
88	East Commencement Bay	Urban		0.791
222	Outer Commencement Bay	Urban		1.851
318	Central Commencement Bay	Urban		1.851
380	Outer Commencement Bay	Urban		1.851
Overall	**Sampling stratum type**	**Number of stations**	**Area (km^2)**	**Percentage**
	Harbor	12	2.25	9.37%
	Urban	18	21.80	90.63%
	Total	30	24.06	100%

Table 2. Chemical and physical parameters measured in sediments collected for the 2008 Urban Waters Initiative study.

Physical Parameters
Grain Size
Total Organic Carbon

Metals
Arsenic
Cadmium
Chromium
Copper
Lead
Mercury
Nickel
Selenium
Silver
Tin
Zinc

Polycyclic Aromatic Hydrocarbons
Low Molecular Weight (LPAH)
1,6,7-Trimethylnaphthalene
1-Methylnaphthalene
2,6-Dimethylnaphthalene
2-Methylnaphthalene
2-Methylphenanthrene
Acenaphthene
Acenaphthylene
Anthracene
Biphenyl
Dibenzofuran
Dibenzothiophene
Fluorene
Naphthalene
Phenanthrene
Retene
Total LPAH (calculated value[1, 2])

High Molecular Weight (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 (calculated value[1])
Total HPAH (calculated value[1, 2])
Total PAH (calculated value[2])

Base/Neutral/Acid Semivolatiles (BNA)
1,2,4-Trichlorobenzene
1,2-Dichlorobenzene
1,3-Dichlorobenzene
1,4-Dichlorobenzene
2,4-Dimethylphenol
2-Chloronaphthalene
2-Methylphenol
4-Methylphenol
Benzoic acid
Benzyl alcohol
Bis(2-ethylhexyl)phthalate
Butylbenzylphthalate
Caffeine
Carbazole
Cholesterol
Coprostanol
Di-n-butylphthalate
Di-n-octylphthalate
Diethylphthalate
Dimethylphthalate
Hexachlorobenzene (Method 8270)
Hexachlorobutadiene
Isophorone
N-nitrosodiphenylamine
P-nonylphenol
Pentachlorophenol
Phenol

Chlorinated Pesticides
2,4'-DDD
2,4'-DDE
2,4'-DDT
4,4'-DDD
4,4'-DDE
4-4'DDT
Aldrin
Cis-chlordane (Alpha-chlordane)
Dieldrin
Endosulfan I (Alpha-endosulfan)
Endosulfan II (Beta-endosulfan)
Endosulfan Sulfate
Endrin
Endrin Aldehyde
Endrin Ketone
Gamma- BHC (Lindane)
Heptachlor
Heptachlor epoxide
Hexachlorobenzene
Mirex
Oxychlordane
Toxaphene
Trans-chlordane (Gamma-chlordane)

Polychlorinated Biphenyls (PCB)
PCB Aroclors
1016
1221
1232
1242
1248
1254
1260
1262
1268
Total Aroclors (calculated value[1])

PCB Congeners
8
18
28
44
52
66
77
101
105
118
126
128
138
153
169
170
180
187
195
206
209 (Decachlorobiphenyl)
Total Congeners (calculated value[2])

Polybrominated Diphenylethers (PBDE)
PBDE Congeners
47, 49, 66, 71, 99, 100, 138, 153, 154, 183, 184, 191, 209

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[1]Total values are calculated according to the procedures specified in the Sediment Management Standards (Washington State Department of Ecology, 1995).

[2]Total values are calculated according to the procedures specified in Long *et al.* (1995), for comparison to Effects Range-Median values.

Table 3. Field and laboratory Measurement Quality Objectives (sediment grain size, total organic carbon, and chemistry analyses). *Explanatory notes follow table.*

Parameter	**Field Blank**	**Field Replicate (Split Sample)**	**Analytical (Laboratory) Replicate**	**Laboratory Control Sample**	**Reference Material**[1]	**Method Blank**	**Matrix Spike (and Matrix Spike Duplicates)**	**Surrogate Spike**[2]
Measurement Frequency	Conducted in 1997	Duplicate analysis for 5% of samples	Triplicate analysis/batch of 20 samples for grain size and TOC. Duplicate analysis/batch for metals and organics samples.	1/batch of 20	1/batch of 20	1/batch of 20	1/batch of 20	every organics sample, blank, and QC sample (minimum of 3 for neutrals, 3 for acids)
MQO measured	RPD	RPD	RSD or RPD	% recovery limits	% recovery limits	comparison of analyte concentration in blank to quantification limit	% recovery limits	% recovery limits
Grain size	RPD ≤ 20%	NA	RSD ≤ 20%	NA	NA	NA	NA	NA
TOC	RPD ≤ 20%	NA	RSD ≤ 20%	Reference material serves as lab control sample	based on manufacturers set limits	Analyte concentration <MDL; if ≥ MDL, lowest analyte concn. must be ≥ 40x method blank concn. or qualified as an estimate	NA	NA
Metals	RPD ≤ 20%	RPD ≤ 20%	NA - when concentrations are low or below PQL, matrix spike/matrix spike duplicates serve as analytical duplicate	85-115	based on manufacturers set limits	Analyte concentration <MDL; if ≥ MDL, lowest analyte concn. must be ≥ 40x method blank concn. or qualified as an estimate	75-125	NA
Total mercury	RPD ≤ 20%	RPD ≤ 20%	NA - when concentrations are low or below PQL, matrix spike/matrix spike duplicates serve as analytical duplicate	85-115	based on manufacturers set limits	Analyte concentration <MDL; if ≥ MDL, lowest analyte concn. must be ≥ 40x method blank concn. or qualified as an estimate	75-125	NA

Batch = a collection of 20 or fewer samples undergoing the same analyses at the same time.
MDL = Method Detection Limit
PQL = Practical Quantitation Limit
RPD = Relative Percent Difference
RSD = Relative Standard Deviation
NA = Not Applicable

Table 3 continues on next page.

Table 3. Continued.

Parameter	Field Blank	Field Replicate (Split Sample)	Analytical (Laboratory) Replicate	Laboratory Control Sample	Reference Material[1]	Method Blank	Matrix Spike (and Matrix Spike Duplicates)	Surrogate Spike[2]
Measurement Frequency	Conducted in 1997	Duplicate analysis for 5% of samples	Triplicate analysis/batch of 20 samples for grain size and TOC. Duplicate analysis/batch for metals and organics samples.	1/batch of 20	1/batch of 20	1/batch of 20	1/batch of 20	every organics sample, blank, and QC sample (minimum of 3 for neutrals, 3 for acids)
MQO measured	RPD	RPD	RSD or RPD	% recovery limits	% recovery limits	comparison of analyte concentration in blank to quantification limit	% recovery limits	% recovery limits
Base/Neutral/ Acid Organic Compounds	RPD $\leq$ 20%	RPD $\leq$ 20%	Compound specific RPD $\leq$ 40%	50-150	50-150	Analyte concentration <MDL; if $\geq$ MDL, lowest analyte concn. must be $\geq$ 10x method blank concn.	50-150	See detail in Table 5b
Polynuclear Aromatic Hydrocarbons	RPD $\leq$ 20%	RPD $\leq$ 20%	Compound specific RPD $\leq$ 40%	40-140	40-140	Analyte concentration <MDL; if $\geq$ MDL, lowest analyte concn. must be $\geq$ 10x method blank concn.	40-140	20-200
Chlorinated Pesticides	RPD $\leq$ 20%	RPD $\leq$ 20%	Compound specific RPD $\leq$ 40%	50-150	See Detail in Table 5a	Analyte concentration <MDL; if $\geq$ MDL, lowest analyte concn. must be $\geq$ 10x method blank concn.	50-150	50-150
PCB Arochlors and PCB Congeners	RPD $\leq$ 20%	RPD $\leq$ 20%	Compound specific RPD $\leq$ 40%	50-150	See Detail in Table 5a	Analyte concentration <MDL; if $\geq$ MDL, lowest analyte concn. must be $\geq$ 10x method blank concn.	50-150	50-150
Polybrominated Dichloroethylene (PBDE)	RPD $\leq$ 20%	RPD $\leq$ 20%	Compound specific RPD $\leq$ 40%	50-150	50-150	Analyte concentration <MDL; if $\geq$ MDL, lowest analyte concn. must be $\geq$ 10x method blank concn.	50-150	50-150

Batch = a collection of 20 or fewer samples undergoing the same analyses at the same time.
MDL = Method Detection Limit
PQL = Practical Quantitation Limit
RPD = Relative Percent Difference
RSD = Relative Standard Deviation
NA = Not Applicable

Explanations for Table 3.

Method Blanks: Analyzed to assess possible laboratory contamination of samples associated with all stages of preparation and analysis of sample extracts.

Surrogate Spike Compounds: A type of check standard that is added to each sample in a known amount prior to extraction or purging.

Analytical replicates: Provide precision information on the actual samples. Useful in assessing potential samples heterogeneity and matrix effects.

Matrix Spikes: Percent recoveries of matrix spikes are reported, should include a wide range of representative analyte types. Compounds should be spiked about 5x the concentration of compounds in the sample or 5x the quantification limit.

Laboratory Control Samples: Sometimes called check standards or laboratory control samples, are method blanks spiked with surrogate compounds and analytes. Useful in verifying acceptable method performance prior to and during routine analysis of samples.

Reference Materials: A material or substance whose property values are sufficiently well established to be used for calibration of an apparatus, the assessment of a measurement method, or for assigning values to materials

Certified Reference Material: A reference material, provided by standard setting organizations such as NIST, CRM, etc., accompanied by or traceable to a certificate or other documentation that is issues by a certifying body

[1] Recovery limits for standard and certified reference material (SRM/CRM) are based on the low and high confidence limits for each analyte, and are listed in Dutch et al. (2009).
[2] Surrogate specific recovery limits are listed in Dutch et al. (2009).

Table 4. Benthic invertebrate indices calculated to characterize the assemblages identified for the 2008 Urban Waters Initiative sediment study.

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 the 30 samples collected for the 2008 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	Estimated area (km^2)	Percent of total study area
Sand	> 80	< 20	0.9	1	0.786	3.27
Silty sand	60 to 80	20 to >40	0.1 – 12.2	3	1.708	7.10
Mixed	20 to < 60	40 to 80	0.1 – 4.4	16	11.78	48.98
Silt + clay	< 20	> 80	0.1 - .9	10	9.78	40.65

Table 6. Summary statistics for TOC concentrations for sediment monitoring strata types at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.

Stratum type	N	Minimum	Maximum	Mean	Standard deviation	Median
Entire study area	30	0.53	4.74	1.24	0.78	1.07
Harbor	12	0.59	4.74	1.53	1.11	1.37
Urban	18	0.53	1.94	1.04	0.36	1.0

Table 7. Summary statistics for concentrations of metals and organic compounds from sediments collected at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.
RL = reporting limit; ND = nondetect; CDF = cumulative distribution function.

Parameter	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)
Metals (mg/kg dry weight)													
Arsenic	30	30	0		6.617	3.789	5.735	2.55	23.6		1	5.26	8.22
Cadmium	30	30	0		0.188	0.200	0.120	0.056	1.16		1	0.11	0.18
Chromium	30	30	0		17.927	3.98	17.65	11.5	29.4		1	17.96	22.50
Copper	30	30	0		52.3	91.4	28.8	16.3	524		1	25.79	42.12
Lead	30	30	0		16.71	20.16	10.34	3.37	109		1	8.44	12.95
Mercury	30	30	0		0.109	0.122	0.062	0.021	0.623		1	0.05	0.11
Nickel	30	30	0		12.988	3.257	12.7	8.17	23.6		1	13.05	18.82
Selenium	30	4	26	0	0.190	0.323	0.070	0.004	1.6	0.5		0	0.52
Silver	30	29	1	0	0.168	0.193	0.110	0.032	1.07	0.05		0.09	0.14
Tin	30	30	0		1.149	1.238	0.83	0.32	6.87		1	0.64	1.10
Zinc	30	30	0		48.31	29.98	39.3	23	181		1	36.29	47.24
Organic Compounds (µg/kg dry weight)													
Polycyclic Aromatic Hydrocarbons (PAH)													
LPAH													
1,6,7-Trimethylnaphthalene	30	30	0		52.83	52.02	41.5	18	306		1	35.56	58.97
1-Methylnaphthalene	30	30	0		119.1	360.3	42	17	2010		1	40.48	55.65
2,6-Dimethylnaphthalene	30	30	0		138.9	363	62	21	2040		1	54.59	81.42
2-Methylnaphthalene	30	30	0		152.7	476.4	52	19	2650		1	47.02	68.46
2-Methylphenanthrene	30	30	0		146	367.6	63	22	2040		1	52.63	78.68
Acenaphthene	30	30	0		100.2	364.4	21	5.6	2020		1	13.81	34.62
Acenaphthylene	30	30	0		138.5	438.8	23.5	4.8	2340		1	12.26	44.87
Anthracene	30	30	0		348	1204	38	10	6580		1	20.76	103.98
Biphenyl	30	30	0		62.3	212.5	14	6.8	1180		1	12.60	20.08

Parameter	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)
LPAH (continued)													
Dibenzofuran	30	30	0		94.3	197.9	41	12	1090		1	32.50	57.96
Dibenzothiophene	30	30	0		113.3	467.8	13.5	5.4	2580		1	10.52	23.81
Fluorene	30	30	0		105.4	324.2	22.5	8.2	1780		1	15.26	34.10
Naphthalene	30	30	0		301	726	91	30	3910		1	61.36	160.60
Phenanthrene	30	30	0		815	3165	108	40	17400		1	70.79	205.82
Retene	30	30	0		313.5	182.8	297	70	803		1	266.88	431.32
HPAH													
Benzo(a)anthracene	30	30	0		304	927	54	12	5060		1	28.03	167.50
Benzo(a)pyrene	30	30	0		558	2008	60	15	11000		1	29.36	238.58
Benzo(b)fluoranthene	30	30	0		617	2138	96	15	11800		1	45.68	305.46
Benzo[e]pyrene	30	30	0		369	1255	57	13	6920		1	30.23	201.24
Benzo(g,h,i)perylene	30	30	0		372	1403	41	11	7720		1	25.68	145.35
Benzo(k)fluoranthene	30	30	0		235	759	37	2	4170		1	16.51	108.44
Chrysene	30	30	0		566	1692	96	28	9260		1	49.34	320.48
Dibenzo(a,h)anthracene	30	30	0		34.5	70.2	8.5	2.1	348		1	4.51	29.43
Fluoranthene	30	30	0		835	2660	160	32	14600		1	80.04	450.45
Indeno(1,2,3-c,d)pyrene	30	30	0		315	1190	41	8	6560		1	22.04	129.48
Perylene	30	30	0		224.3	425.5	132	35	2400		1	97.20	187.71
Pyrene	30	30	0		1118	3978	156	30	21900		1	78.12	494.01
Base/Neutral/Acid (BNA) Semivolatile Compounds													
Chlorinated Alkenes													
Hexachlorobutadiene	30	4	26	26						14	3,4,5	0	0.09
Chlorinated and Nitro-substituted Phenols													
Pentachlorophenol	30	0	30							280	2	0	0
Chlorinated Aromatic Compounds													
1,2,4-Trichlorobenzene	30	0	30							14	2	0	0

Parameter	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 Aromatic Compounds (continued)													
1,2-Dichlorobenzene	30	0	30							14	2	0	0
1,3-Dichlorobenzene	30	0	30							14	2	0	0
1,4-Dichlorobenzene	30	0	30							14	2	0	0
2-Chloronaphthalene	30	0	30							10	2	0	0
Hexachlorobenzene	30	2	28	28						14	3,4,5	0	0
Miscellaneous Extractable Compounds													
Beta-coprostanol	30	17	13	0	259.9	257.1	170	36.1	1020	56		211.75	607.75
Carbazole	30	30	0		47.7	149.2	7.9	3.2	823		1	5.33	22.43
Cholesterol	30	28	2	0	1906	1072	1655	487	4630	51		1542.86	2297.88
Isophorone	30	12	18	0	21.57	18.72	14.77	7.12	96	28		0	27.91
Organonitrogen Compounds													
Caffeine	30	0	30							14	2	0	0
N-Nitrosodiphenylamine	30	0	30							28	2	0	0
Phenols													
P-nonylphenol	30	0	30							14	2	0	0
Phthalate Esters													
Bis(2-Ethylhexyl)phthalate	30	30	0		187.8	261.8	79.5	18	1050		1	32.73	379.98
Butylbenzylphthalate	30	5	25	0	20.4	64.8	0.5	0	338	13		0	0
Diethylphthalate	30	0	30							14	2	0	0
Dimethylphthalate	30	0	30							14	2	0	0
Di-N-Butylphthalate	30	1	29	0						14	5	0	0
Di-N-Octyl Phthalate	30	1	29	0						14	5	0	0
Chlorinated Pesticides													
2,4'-DDD	30	1	29	1						2.5	3,5	0	0
2,4'-DDE	30	0	30							2.8	2	0	0
2,4'-DDT	30	0	30							0.52	2	0	0

Parameter	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 (continued)													
4,4'-DDD	30	10	20	0	1.033	2.284	0.147	0.004	11	0.51		0	0.59
4,4'-DDE	30	0	30							4	2	0	0
4,4'-DDT	30	5	25	0	0.518	1.197	0.068	0.003	4.8	1.2		0	0
Aldrin	30	0	30							0.52	2	0	0
Cis-chlordane (Alpha-chlordane)	30	1	29	0						1.2	5	0	0
Dieldrin	30	0	30							0.66	2	0	0
Endosulfan I	30	0	30							0.52	2	0	0
Endosulfan II	30	1	29	1						2.3	3,5	0	0
Endosulfan Sulfate	30	0	30							2.2	2	0	0
Endrin	30	0	30							0.52	2	0	0
Endrin Aldehyde	30	0	30							0.52	2	0	0
Endrin Ketone	30	0	30							7.6	2	0	0
Gamma-BHC (Lindane)	30	0	30							0.52	2	0	0
Heptachlor	30	0	30							0.52	2	0	0
Heptachlor Epoxide	30	0	30							0.57	2	0	0
Mirex	30	0	30							1.8	2	0	0
Oxychlordane	30	0	30							0.52	2	0	0
Toxaphene	30	3	27	0	23.96	23.49	15.17	4.8	103	39		0	0
Trans-Chlordane (Gamma)	30	1	29	0						1.6	5	0	0
Polychlorinated Biphenyls (PCB)													
PCB Congeners													
PCB Congener 8	30	1	29	1						44	3,5	0	0
PCB Congener 18	30	1	29	0						1.7	5	0	0
PCB Congener 28	30	6	24	0	0.398	0.894	0.085	0.005	4.6	0.51		0	0
PCB Congener 44	30	6	24	0	0.604	1.395	0.075	0.002	5.8	0.51		0	0

Parameter	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 (continued)													
PCB Congener 52	30	8	22	0	0.876	2.235	0.079	0.002	11	0.51		0	0
PCB Congener 66	30	5	25	0	0.556	1.284	0.111	0.007	6.4	2.2		0	0
PCB Congener 77	30	5	25	0	0.392	1.008	0.041	0.001	5.1	0.52		0	0
PCB Congener 101	30	11	19	0	1.729	3.927	0.163	0.004	18	0.51		0	0.79
PCB Congener 105	30	7	23	0	0.768	1.804	0.082	0.003	7.4	0.51		0	0
PCB Congener 118	30	8	22	0	1.557	3.395	0.171	0.005	13	0.51		0	0.28
PCB Congener 126	30	1	29	0						0.54	5	0	0
PCB Congener 128	30	6	24	0	0.409	0.897	0.069	0.003	4	0.51		0	0
PCB Congener 138	30	11	19	0	1.889	4.151	0.165	0.003	17	0.51		0	0.82
PCB Congener 153	30	11	19	0	1.898	4.045	0.183	0.004	17	0.51		0	0.81
PCB Congener 169	30	0	30							1.5	2	0	0
PCB Congener 170	29	4	26	1	0.329	0.654	0.108	0.012	3.3	4.5	3	0	0
PCB Congener 180	29	6	24	1	0.567	1.351	0.098	0.005	6.7	12	3	0	0
PCB Congener 187	30	7	23	0	0.987	2.205	0.15	0.007	11	0.51		0	0
PCB Congener 195	30	2	28	0						0.52	5	0	0
PCB Congener 206	30	8	22	0	1.748	3.898	0.106	0.002	15	0.51		0	0.71
PCB Congener 209	30	7	23	0	1.897	4.762	0.117	0.003	18	2.5		0	0.96
PCB Aroclors													
PCB Aroclor 1016	30	0	30							40	2	0	0
PCB Aroclor 1221	30	0	30							41	2	0	0
PCB Aroclor 1232	30	0	30							41	2	0	0
PCB Aroclor 1242	30	0	30							41	2	0	0
PCB Aroclor 1248	30	1	29	8						78	3,5	0	0
PCB Aroclor 1254	30	20	10	0	27.6	61.1	6.2	0.3	263	5.1		0	11.73
PCB Aroclor 1260	30	7	23	0	11.11	31.82	0.61	0.01	157	62		0	0
PCB Aroclor 1262	30	0	30							101	2	0	0
PCB Aroclor 1268	30	0	30							61	2	0	0

Parameter	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	30	28	2	0	0.849	0.872	0.48	0.082	3.5	0.2		0.39	1.16
PBDE- 49	30	4	26	0	0.151	0.292	0.039	0.002	1.4	0.21		0	0.15
PBDE- 66	30	0	30							0.21	2	0	0
PBDE- 71	30	0	30							0.21	2	0	0
PBDE- 99	30	22	8	0	0.534	0.588	0.275	0.062	2.3	0.36		0.24	0.73
PBDE-100	30	5	25	0	0.158	0.082	0.136	0.055	0.43	0.21		0	0.12
PBDE-138	30	0	30							0.41	2	0	0
PBDE-153	8	5	25	22	0.264	0.065	0.262	0.180	0.39	0.41	3	0	0
PBDE-154	30	4	26	0	0.236	0.172	0.195	0.065	0.97	0.41		0	0
PBDE-183	30	1	29	29						0.41	3,4,5	0	0
PBDE-184	30	0	30							0.41	2	0	0
PBDE-191	30	0	30							0.41	2	0	0
PBDE-209	30	21	9	0	5.65	6	3.65	0.64	23	10		2.42	5.78

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 2008 Urban Waters Initiative sediment study samples exceeding Washington State Sediment Management Standards[a] and estimated spatial extent of chemical contamination (incidence among samples and proportion of study area).
Total sampling area = 24.06 km^2.

Analyte	Criterion	> SQS[b]				Criterion	> CSL[b]			
		No.	Estim. Area (km^2)	% of Total Area	Station Number		No.	Estim. Area (km^2)	% of Total Area	Station Number
Trace Metals (ppm dry weight)										
Arsenic	57	none				93	none			
Cadmium	5.1	none				6.7	none			
Chromium	260	none				270	none			
Copper	390	1	0.13	0.52	294	390	1	0.13	0.52	294
Lead	450	none				530	none			
Mercury	0.41	1	0.79	3.27	286	0.59	1	0.79	3.27	286
Silver	6.1	none				6.1	none			
Zinc	410	none				960	none			
Combined total for any individual trace metals	n.a.	2	1.19	7.95	286, 294	n.a.	2	1.19	7.95	286, 294
Organic Compounds										
LPAH (ppm organic carbon)										
2-Methylnaphthalene	38	1	0.13	0.52	294	64	none			
Acenaphthene	16	1	0.13	0.52	294	57	none			
Acenaphthylene	66	none				66	none			
Anthracene	220	none				1200	none			
Fluorene	23	2	0.25	1.05	294, 296	79	none			
Naphthalene	99	none				170	none			
Phenanthrene	100	2	0.25	1.05	294, 296	480	none			
Combined total for any individual LPAH	n.a.	2	0.25	1.05	294, 296	n.a.	none			
Total LPAH (ppm organic carbon)										
Sum of 6 LPAH (WA Ch. 173-204 RCW)	370	2	0.25	1.05	294, 296	780	none			
HPAH (ppm organic carbon)										
Benzo(a)anthracene	110	1	0.13	0.52	294	270	none			
Benzo(a)pyrene	99	2	0.25	1.05	294, 296	210	1	0.126	0.52	294
Benzo(g,h,i)perylene	31	2	0.25	1.05	294, 296	78	1	0.126	0.52	294
Chrysene	110	2	0.25	1.05	294, 296	460	none			
Dibenzo(a,h)anthracene	12	1	0.13	0.52	296	33	none			
Fluoranthene	160	2	0.25	1.05	294, 296	1200	none			
Indeno(1,2,3-c,d)pyrene	34	2	0.25	1.05	294, 296	88	1	0.126	0.52	294
Pyrene	1000	none				1400	none			
Total Benzofluoranthenes	230	1	0.13	0.52	294	450	none			

Analyte	Criterion	> SQS[b]				Criterion	> CSL[b]			
		No.	Estim. Area (km^2)	% of Total Area	Station Number		No.	Estim. Area (km^2)	% of Total Area	Station Number
Combined total for any individual HPAH	n.a.	2	0.25	1.05	294, 296	n.a.	1	0.126	0.52	294
Total HPAH (ppm organic carbon)										
Sum of 9 HPAH (WA Ch. 173-204 RCW)	960	2	0.25	1.05	294, 296	5300	none			
All PAHs (ppm organic carbon)										
Combined total for any individual PAH	n.a.	2	0.252	1.05	294, 296	n.a.	none			
Phenols (ppb dry weight)										
Pentachlorophenol	360	none				690	none			
Phthalate Esters (ppm organic carbon)										
Bis(2-ethylhexyl) phthalate	47	2	2.24	9.31	282, 300	78	2	2.24	9.31	282, 300
Butylbenzylphthalate	4.9	3	0.27	1.11	294, 296, 297	64	none			
Diethylphthalate	61	none				110	none			
Dimethylphthalate	53	none				53	none			
Di-N-Butyl Phthalate	220	none				1700	none			
Di-N-Octyl Phthalate	58	none				4500	none			
Combined total for any individual phthalate esters	n.a.	5	2.51	10.42	282, 294, 296, 297, 300	n.a.	2	2.24	9.31	282, 300
Total PCB (ppm organic carbon)										
Total Aroclors (WA Ch. 173-204 RCW)	12	1	0.22	0.93	303	65	none			
Miscellaneous Compounds (ppm organic carbon)										
1,2-Dichlorobenzene	2.3	none				2.3	none			
1,2,4-Trichlorobenzene	0.81	none				1.8	none			
1,4-Dichlorobenzene	3.1	none				9	none			
Dibenzofuran	15	none				58	none			
Hexachlorobenzene	0.38	1	0.22	0.93	304	2.3	none			
Hexachlorobutadiene	3.9	none				6.2	none			
N-Nitrosodiphenylamine	11	none				11	none			
***Combined total for all individual chemicals (metals and organics)**	n.a.	8	3.74	15.54	282, 286, 294, 296, 297, 300, 303, 304	n.a.	4	3.15	13.09	282, 286, 294, 300

[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 2008 Urban Waters Initiative sediment study in which Washington State Sediment Management Standards[a] were exceeded.

The mean ERM quotient is the average of all chemical concentrations divided by their respective ERMs[b].

Sample	Sample location	Estimated sampled-weighted area (km^2)	Mean ERM quotient	Number of SQS exceeded	Chemicals exceeding SQS	Number of CSL exceeded	Chemicals exceeding CSL
4	N.E. Commencement Bay	0.831	0.13	0	*none*	0	*none*
88	East Commencement Bay	0.791	0.03	0	*none*	0	*none*
222	Outer Commencement Bay	1.851	0.04	0	*none*	0	*none*
281	Central Commencement Bay	1.851	0.03	0	*none*	0	*none*
282	Central Commencement Bay	1.851	0.04	1	Bis(2-ethylhexyl)phthalate	1	Bis(2-ethylhexyl)phthalate
283	Outer Commencement Bay	1.851	0.03	0	*none*	0	*none*
284	Outer Commencement Bay	1.851	0.03	0	*none*	0	*none*
285	S. Shoreline Commencement Bay	0.786	0.04	0	*none*	0	*none*
286	S. Shoreline Commencement Bay	0.786	0.08	1	Mercury	1	Mercury
287	S. Shoreline Commencement Bay	0.786	0.10	0	*none*	0	*none*
288	S.E. Commencement Bay	0.791	0.03	0	*none*	0	*none*
289	S.E. Commencement Bay	0.791	0.03	0	*none*	0	*none*
290	S.E. Commencement Bay	0.791	0.02	0	*none*	0	*none*
291	N.E. Commencement Bay	0.831	0.03	0	*none*	0	*none*
292	N.E. Commencement Bay	0.831	0.04	0	*none*	0	*none*
293	N.E. Commencement Bay	0.831	0.10	0	*none*	0	*none*

Sample	Sample location	Estimated sampled-weighted area (km^2)	Mean ERM quotient	Number of SQS exceeded	Chemicals exceeding SQS	Number of CSL exceeded	Chemicals exceeding CSL
294	Thea Foss Waterway	0.126	2.78	14	Copper, 2-Methylnaphthalene, Acenaphthene, Benzo(a)pyrene, Benzo(g,h,i)perylene, Total Benzofluoranthenes, Butylbenzylphthalate, Chrysene, Fluoranthene, Fluorene, Indeno(1,2,3-c,d)pyrene, Phenanthrene, Total LPAH, Total HPAH	4	Copper, Benzo(a)pyrene, Benzo(g,h,i)perylene, Indeno(1,2,3-c,d)pyrene
295	Thea Foss Waterway	0.126	0.27	0	*none*	0	*none*
296	Thea Foss Waterway	0.126	0.52	11	Benzo(a)pyrene, Benzo(g,h,i)perylene, Butylbenzylphthalate, Chrysene, Dibenzo(a,h)anthracene, Fluoranthene, Fluorene, Indeno(1,2,3-c,d)pyrene, Phenanthrene, Total LPAH, Total HPAH	0	*none*
297	Middle Waterway	0.016	0.13	1	Butylbenzylphthalate	0	*none*
298	Middle Waterway	0.016	0.09	0	*none*	0	*none*
299	Middle Waterway	0.016	0.11	0	*none*	0	*none*
300	Blair Waterway	0.387	0.04	1	Bis(2-ethylhexyl)phthalate	1	Bis(2-ethylhexyl)phthalate
301	Blair Waterway	0.387	0.05	0	*none*	0	*none*
302	Blair Waterway	0.387	0.04	0	*none*	0	*none*
303	Hylebos Waterway	0.223	0.26	1	Total Aroclors	0	*none*
304	Hylebos Waterway	0.223	0.10	1	Hexachlorobenzene	0	*none*
305	Hylebos Waterway	0.223	0.13	0	*none*	0	*none*

Sample	Sample location	Estimated sampled-weighted area (km^2)	Mean ERM quotient	Number of SQS exceeded	Chemicals exceeding SQS	Number of CSL exceeded	Chemicals exceeding CSL
318	Central Commencement Bay	1.851	0.04	0	*none*	0	*none*
380	Outer Commencement Bay	1.851	0.04	0	*none*	0	*none*

[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. Results of amphipod survival tests for the 30 sediment samples collected in the 2008 Urban Waters Initiative study.

Data are expressed as mean percent survival and as percentage of control. Tests were performed with Eohaustorius estuarius.

Sample ID	Location	Mean amphipod survival (%)	Mean amphipod survival as % of control	Statistical significance (p value<0.05, t-test)
4	N.E. Commencement Bay	93	93	*
88	East Commencement Bay	98	98	
222	Outer Commencement Bay	95	96	
281	Central Commencement Bay	95	96	
282	Central Commencement Bay	98	99	
283	Outer Commencement Bay	93	94	*
284	Outer Commencement Bay	93	95	
285	S. Shoreline Commencement Bay	100	101	
286	S. Shoreline Commencement Bay	93	94	
287	S. Shoreline Commencement Bay	96	96	
288	S.E. Commencement Bay	96	97	
289	S.E. Commencement Bay	98	99	
290	S.E. Commencement Bay	100	101	
291	N.E. Commencement Bay	95	95	
292	N.E. Commencement Bay	93	93	
293	N.E. Commencement Bay	92	92	
294	Thea Foss Waterway	96	96	
295	Thea Foss Waterway	95	95	
296	Thea Foss Waterway	97	97	
297	Middle Waterway	97	97	
298	Middle Waterway	93	93	*
299	Middle Waterway	99	99	
300	Blair Waterway	89	90	
301	Blair Waterway	92	93	*
302	Blair Waterway	86	87	*
303	Hylebos Waterway	95	95	
304	Hylebos Waterway	93	94	
305	Hylebos Waterway	94	94	
318	Central Commencement Bay	95	96	
380	Outer Commencement Bay	98	99	

*Results statistically significant.

** Results statistically significant and mean percent survival <80% of control.

Table 11. Results of sea urchin fertilization tests in undiluted and diluted porewaters from the 30 sediment samples collected in the 2008 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)
4	N.E. Commencement Bay	99.2	100.9			99.0	99.9			98.4	100.2	
88	East Commencement Bay	99.8	101.5			99.2	100.1			97.6	99.4	
222	Outer Commencement Bay	99.0	100.7			98.4	99.3			98.4	100.2	
281	Central Commencement Bay	99.4	101.1			98.2	99.1			96.5	98.3	
282	Central Commencement Bay	99.4	101.1			99.6	100.5			98.8	100.6	
283	Outer Commencement Bay	99.0	100.7			98.6	99.5			97.0	98.8	
284	Outer Commencement Bay	99.2	100.9			99.0	99.9			98.4	100.2	
285	S. Shoreline Commencement	99.6	101.3			99.6	100.5			99.0	100.8	
286	S. Shoreline Commencement	99.6	101.3			99.6	100.5			99.2	101.0	
287	S. Shoreline Commencement	99.6	101.3			98.8	99.7			98.4	100.2	
288	S.E. Commencement Bay	100.0	101.7			99.2	100.1			98.4	100.2	
289	S.E. Commencement Bay	99.4	101.1			99.0	99.9			99.0	100.8	
290	S.E. Commencement Bay	99.8	101.5			99.0	99.9			97.8	99.6	
291	N.E. Commencement Bay	99.4	101.1			99.2	100.1			98.2	100.0	
292	N.E. Commencement Bay	99.6	101.3			97.2	98.1			95.8	97.6	+
293	N.E. Commencement Bay	98.2	99.9			97.6	98.5			97.6	99.4	
294	Thea Foss Waterway	83.0	84.4	*		91.8	92.6	++		99.4	101.2	
295	Thea Foss Waterway	99.4	101.1			99.2	100.1			98.6	100.4	
296	Thea Foss Waterway	99.8	101.5			98.6	99.5			99.2	101.0	
297	Middle Waterway	99.4	101.1			99.8	100.7			99.4	101.2	
298	Middle Waterway	100.0	101.7			99.6	100.5			99.2	101.0	
299	Middle Waterway	99.6	101.3			99.0	99.9			98.6	100.4	
300	Blair Waterway	99.6	101.3			99.0	99.9			98.6	100.4	
301	Blair Waterway	99.2	100.9			99.6	100.5			98.6	100.4	
302	Blair Waterway	99.8	101.5			100.0	100.9			99.2	101.0	
303	Hylebos Waterway	97.8	99.5			98.4	99.3			98.4	100.2	
304	Hylebos Waterway	98.2	99.9			98.8	99.7			98.6	100.4	
305	Hylebos Waterway	82.6	84.0	*		96.6	97.5	++		98.6	100.4	
318	Central Commencement Bay	100.0	101.7			98.2	99.1			98.6	100.4	
380	Outer Commencement Bay	99.8	101.5			99.4	100.3			98.8	100.6	

*, ** Results statistically significantly different from control and meet Detectable Significance Criteria at $\alpha \leq 0.05, 0.01$, respectively (Appendix H).

+, ++ Results statistically significantly different from control at $\alpha < 0.05, 0.01$, respectively.

Table 12. Total abundance, taxa richness, Pielou's Evenness, and Swartz' Dominance Index calculated for the 30 stations sampled in the 2008 Urban Waters Initiative sediment study.

Station	Location	Total Abundance (# indiv/0.1 m^2)	Taxa Richness (# taxa/0.1 m^2)	Pielou's Evenness (J')	Swartz' Dominance Index (SDI) (# taxa)
4	N.E. Commencement Bay	1652	72	0.65	9
88	East Commencement Bay	843	47	0.63	7
222	Outer Commencement Bay	785	83	0.70	13
281	Central Commencement Bay	342	43	0.69	7
282	Central Commencement Bay	251	51	0.70	9
283	Outer Commencement Bay	293	53	0.79	15
284	Outer Commencement Bay	367	71	0.78	20
285	S. Shoreline Commencement Bay	768	115	0.76	23
286	S. Shoreline Commencement Bay	573	67	0.61	10
287	S. Shoreline Commencement Bay	1443	105	0.59	9
288	S.E. Commencement Bay	560	45	0.58	5
289	S.E. Commencement Bay	544	54	0.46	3
290	S.E. Commencement Bay	165	32	0.70	6
291	N.E. Commencement Bay	558	43	0.57	4
292	N.E. Commencement Bay	1038	56	0.57	4
293	N.E. Commencement Bay	1175	86	0.68	10
294	Thea Foss Waterway	816	66	0.73	12
295	Thea Foss Waterway	476	65	0.73	14
296	Thea Foss Waterway	334	61	0.77	15
297	Middle Waterway	1771	89	0.61	8
298	Middle Waterway	995	109	0.80	24
299	Middle Waterway	1629	80	0.59	7
300	Blair Waterway	578	53	0.61	8
301	Blair Waterway	535	59	0.75	12
302	Blair Waterway	525	28	0.62	4
303	Hylebos Waterway	961	51	0.55	4
304	Hylebos Waterway	512	55	0.74	11
305	Hylebos Waterway	950	55	0.58	5
318	Central Commencement Bay	428	40	0.59	5
380	Outer Commencement Bay	461	65	0.61	8
	Mean	744.3	63.3	0.66	9.7
	Median	566.5	57.5	0.64	8.5
	Min	165	28	0.46	3
	Max	1771	115	0.80	24
	Range	1606	87	0.34	21

Table 13. Total abundance, major taxa abundance, and major taxa percent abundance calculated for the 30 stations sampled in the 2008 Urban Waters Initiative sediment study.
Abundance is stated in numbers of individuals per 0.1-m^2 sample.

Station	Total abundance	Annelida	Annelida % of total abundance	Arthropoda	Arthropoda % of total abundance	Mollusca	Mollusca % of total abundance	Echino-dermata	Echino-dermata % of total abundance	Misc. taxa	Misc. taxa % of total abundance
4	1652	711	43.04	27	1.63	803	48.61	101	6.11	10	0.61
88	843	570	67.62	5	0.59	261	30.96	2	0.24	5	0.59
222	785	526	67.01	214	27.26	26	3.31	9	1.15	10	1.27
281	342	111	32.46	30	8.77	193	56.43	3	0.88	5	1.46
282	251	118	47.01	21	8.37	109	43.43	0	0.00	3	1.20
283	293	93	31.74	68	23.21	126	43.00	3	1.02	3	1.02
284	367	158	43.05	34	9.26	148	40.33	12	3.27	15	4.09
285	768	294	38.28	66	8.59	326	42.45	68	8.85	14	1.82
286	573	168	29.32	21	3.66	366	63.87	0	0.00	18	3.14
287	1443	403	27.93	155	10.74	866	60.01	8	0.55	11	0.76
288	560	406	72.50	16	2.86	135	24.11	0	0.00	3	0.54
289	544	408	75.00	25	4.60	111	20.40	0	0.00	0	0.00
290	165	116	70.30	30	18.18	17	10.30	0	0.00	2	1.21
291	558	157	28.14	20	3.58	380	68.10	1	0.18	0	0.00
292	1038	672	64.74	12	1.16	337	32.47	8	0.77	9	0.87
293	1175	738	62.81	22	1.87	396	33.70	8	0.68	11	0.94
294	816	327	40.07	87	10.66	396	48.53	0	0.00	6	0.74
295	476	365	76.68	22	4.62	78	16.39	6	1.26	5	1.05
296	334	271	81.14	5	1.50	40	11.98	12	3.59	6	1.80
297	1771	448	25.30	57	3.22	950	53.64	301	17.00	15	0.85
298	995	529	53.17	54	5.43	297	29.85	87	8.74	28	2.81
299	1629	539	33.09	22	1.35	932	57.21	115	7.06	21	1.29
300	578	256	44.29	8	1.38	296	51.21	15	2.60	3	0.52

Station	Total abundance	Annelida	Annelida % of total abundance	Arthropoda	Arthropoda % of total abundance	Mollusca	Mollusca % of total abundance	Echino-dermata	Echino-dermata % of total abundance	Misc. taxa	Misc. taxa % of total abundance
301	535	320	59.81	26	4.86	167	31.21	18	3.36	4	0.75
302	525	453	86.29	0	0.00	70	13.33	2	0.38	0	0.00
303	961	663	68.99	12	1.25	285	29.66	0	0.00	1	0.10
304	512	371	72.46	12	2.34	122	23.83	6	1.17	1	0.20
305	950	661	69.58	5	0.53	247	26.00	33	3.47	4	0.42
318	428	344	80.37	26	6.07	53	12.38	1	0.23	4	0.93
380	461	90	19.52	63	13.67	302	65.51	1	0.22	5	1.08
Mean	744.27	376.20	53.72	38.83	6.37	294.50	36.41	27.33	2.43	7.40	1.07
Median	566.50	368.00	56.49	23.50	4.13	254.00	33.08	6.00	0.82	5.00	0.90
Min	165	90.00	19.52	0.00	0.00	17.00	3.31	0.00	0.00	0.00	0.00
Max	1771	738.00	86.29	214.00	27.26	950.00	68.10	301.00	17.00	28.00	4.09
Range	1606	648.00	66.76	214.00	27.26	933.00	64.79	301.00	17.00	28.00	4.09

Table 14. Major taxa abundance and number of species in the 30 samples collected in the 2008 Urban Waters Initiative sediment study.
**Organisms were identified to species level when possible, otherwise to lowest taxonomic level possible.*

Phylum	Abundance (# indiv/0.1 m^2)	Percent	Number of Species* (# taxa/0.1 m^2)	Percent
Annelida	11,286	50.55	165	47.14
Arthropoda	1,165	5.22	90	25.71
Mollusca	8,835	39.57	61	17.43
Echinodermata	820	3.67	12	3.43
Miscellaneous	188	0.84	22	6.29
Total	22,328	100.00	350	100.00

Table 15. Condition of benthic invertebrate assemblages at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.

Station	Location	Condition of Benthos (2008)	Change from 1999?
300	Blair Waterway	Affected	No
302	Blair Waterway	Affected	No
303	Hylebos Waterway	Affected	No
293	N.E. Commencement Bay	Affected	No, but improved
296	Thea Foss Waterway	Affected	No, but improved
304	Hylebos Waterway	Affected	No, but improved
305	Hylebos Waterway	Affected	No, but improved
282	Central Commencement Bay	Affected	Yes
288	S.E. Commencement Bay	Affected	Yes
289	S.E. Commencement Bay	Affected	Yes
290	S.E. Commencement Bay	Affected	Yes
281	Central Commencement Bay	Unaffected	No
283	Outer Commencement Bay	Unaffected	No
284	Outer Commencement Bay	Unaffected	No
285	S. Shoreline Commencement Bay	Unaffected	No
286	S. Shoreline Commencement Bay	Unaffected	No
287	S. Shoreline Commencement Bay	Unaffected	No
291	N.E. Commencement Bay	Unaffected	No
292	N.E. Commencement Bay	Unaffected	No
294	Thea Foss Waterway	Unaffected	Yes
295	Thea Foss Waterway	Unaffected	Yes
297	Middle Waterway	Unaffected	Yes
298	Middle Waterway	Unaffected	Yes
299	Middle Waterway	Unaffected	Yes
301	Blair Waterway	Unaffected	Yes
318	Central Commencement Bay	Affected	Not sampled
4	N.E. Commencement Bay	Unaffected	Not sampled
88	East Commencement Bay	Unaffected	Not sampled
222	Outer Commencement Bay	Unaffected	Not sampled
380	Outer Commencement Bay	Unaffected	Not sampled

Table 16. Estimated incidence and spatial extent of degraded sediments, as measured with the Sediment Quality Triad Index at the 30 stations sampled for the 2008 Urban Waters Initiative sediment study.

Sediment Quality Triad Index Category	Incidence No. (%) of stations		Spatial extent km^2 (%) of study area	
Total Study Area	30	(100.0)	24.06	(100.0)
High[1]	15	50	14.66	60.91
Intermediate/high[2]	10	33.33	6.59	27.40
Chemistry	3	10.00	0.93	3.87
Toxicity	0	0.00	0.00	0.00
Benthos	7	23.33	3.81	15.85
Intermediate/degraded[3]	5	16.67	2.81	11.68
Chemistry/toxicity	0	0.00	0.00	0.00
Chemistry/benthos	5	16.67	2.81	11.68
Benthos/toxicity	0	0.00	0.00	0.00
Degraded[4]	0	0.00	0.00	0.00
By Triad Element[5]				
Chemistry	8	26.67	3.74	15.54
Toxicity	0	0.00	0.00	0.00
Benthos	12	40.00	8.48	35.22

[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 1999 PSAMP/NOAA and 2008 Urban Waters Initiative sediment grain size, TOC, and chemistry results.

See Methods section of report for details of comparison methods. Significance level α = 0.05 unless indicated otherwise.

↓ = decrease; ↑ = increase; -- = no change; x = too few detected values to test; ? indicates 0.05 < p-value ≤ 0.10.

Test:	WSRT[1] (weighted differences compared to zero)	PPW[2] or paired WSRT[2]	Kruskal-Wallis test (comparing medians)		CDF comparisons (Wald F test)		Overall assessment of change
Weighted?	Weighted	Unweighted	Unweighted		Weighted		
Paired?	Paired	Paired	Unpaired		Unpaired		
Treatment of Nondetects (ND):	ND=0	Censored	ND=0		ND=0		
Parameter	Resampled stations only	Resampled stations only	All stations	Resampled stations only	All stations	Resampled stations only	
Grain Size							
Percent Fines	--	--	--	--	--	--	no change
Organic Carbon Content							
Total Organic Carbon	↓	↓	↓	↓	↓	↓	decrease
Metals							
Arsenic	↓	↓	↓	↓	↓	↓	decrease
Cadmium	--	--	--	--	--	--	no change
Chromium	--	--	--	--	--	--	no change
Copper	↓	↓	↓	↓	↓	↓	decrease
Lead	↓	↓	↓	↓	↓	↓	decrease
Mercury	↓	↓	↓	↓?	↓	↓	decrease
Nickel	↓	↓	↓	↓	↓	↓	decrease
Selenium	x	--	x	x	x	x	no change
Silver	↓	↓	↓	↓	↓	↓	decrease
Tin	↓	↓	↓	↓	↓	↓	decrease
Zinc	↓	↓	↓	↓	↓	↓	decrease

Table continues on next page

Test:	WSRT[1] (weighted differences compared to zero)	PPW[2] or paired WSRT[2]	Kruskal-Wallis test (comparing medians)		CDF comparisons (Wald F test)		
Weighted?	Weighted	Unweighted	Unweighted		Weighted		
Paired?	Paired	Paired	Unpaired		Unpaired		
Treatment of Nondetects (ND):	ND=0	Censored	ND=0		ND=0		
Parameter	Resampled stations only	Resampled stations only	All stations	Resampled stations only	All stations	Resampled stations only	**Overall assessment of change**
Polycyclic Aromatic Hydrocarbons							
LPAH							
1,6,7-Trimethylnaphthalene	↓	↓	↓	↓	↓	↓	decrease
1-Methylnaphthalene	↓	↓	↓	↓	↓	↓	decrease
2,6-Dimethylnaphthalene	--	--	--	--	--	--	no change
2-Methylnaphthalene	↓	↓	↓	↓	↓	↓	decrease
2-Methylphenanthrene	↓	↓	↓	↓?	↓	↓	decrease
Acenaphthene	↓	↓	↓	↓?	↓	↓	decrease
Acenaphthylene	--	--	--	--	--	--	no change
Anthracene	↓	↓	↓	--	↓?	↓?	decrease
Biphenyl	↓	↓	↓	↓	↓	↓	decrease
Dibenzothiophene	↓	↓	↓?	--	--	--	possible decrease
Dibenzofuran	x	↓?	--	--	--	--	no change
Fluorene	↓	↓	↓	↓	↓	↓	decrease
Naphthalene	↓	↓	↓	↓?	↓	↓	decrease
Phenanthrene	↓	↓	↓	↓	↓	↓	decrease
Retene	↓	↓	↓	↓	↓	↓	decrease
HPAH							
Benzo(a)anthracene	↓	↓	↓	↓	↓	↓	decrease
Benzo(a)pyrene	↓	↓	↓	↓	↓	↓	decrease
Benzo(b)fluoranthene	--	--	--	--	mixed	mixed	no change
Benzo[e]pyrene	↓	↓	↓	↓?	↓	↓	decrease
Benzo(g,h,i)perylene	↓	↓	↓	↓	↓	↓	decrease
Benzo(k)fluoranthene	↓	↓	↓	↓	↓	↓	decrease
Chrysene	↓	↓	↓	↓?	↓	↓	decrease
Dibenzo(a,h)anthracene	↓	↓	↓	↓	↓	↓	decrease
Fluoranthene	↓	↓	↓	↓?	↓	↓	decrease
Indeno(1,2,3-c,d)pyrene	↓	↓	↓	↓	↓	↓	decrease
Perylene	↓?	↓	↓	↓?	--	↓?	possible decrease
Pyrene	↓	↓	↓	↓?	↓	↓	decrease

Test:	WSRT[1] (weighted differences compared to zero)	PPW[2] or paired WSRT[2]	Kruskal-Wallis test (comparing medians)		CDF comparisons (Wald F test)		
Weighted?	Weighted	Unweighted	Unweighted		Weighted		
Paired?	Paired	Paired	Unpaired		Unpaired		
Treatment of Nondetects (ND):	ND=0	Censored	ND=0		ND=0		
Parameter	Resampled stations only	Resampled stations only	All stations	Resampled stations only	All stations	Resampled stations only	**Overall assessment of change**
Base/Neutral/Acid Semivolatile Compounds (BNA)							
Chlorinated Alkenes							
Hexachlorobutadiene	x	--	--	--	x	x	no change
Chlorinated and Nitro-Substituted Phenols							
Pentachlorophenol	x	x	?	?	x	x	no change
Chlorinated Aromatic Compounds							
1,2,4-Trichlorobenzene	x	↓	--	--	x	x	no change
1,2-Dichlorobenzene	x	--	--	--	x	x	no change
1,3-Dichlorobenzene	x	--	--	--	x	x	no change
1,4-Dichlorobenzene	x	--	↓?	↓	x	x	no change
2-Chloronaphthalene	x	x	x	x	x	x	no change
Hexachlorobenzene							not compared
Miscellaneous Extractable Compounds							
Carbazole	--	--	--	--	x	x	no change
Organonitrogen Compounds							
N-Nitrosodiphenylamine	x	--	--	--	x	x	no change
Phenols							
P-nonylphenol	x	x	--	--	x	x	no change
Phthalate Esters							
Bis(2-ethylhexyl)phthalate	x	↑	↑	↑	↑	↑?	increase
Butylbenzylphthalate	x	--	--	--	x	x	no change
Diethylphthalate	x	↓?	--	--	x	x	no change
Dimethylphthalate	x	↓	?	?	x	x	no change
Di-N-Butylphthalate	x	--	--	--	x	x	no change
Di-N-Octyl Phthalate	x	x	--	--	x	x	no change

Table continues on next page.

Test:	WSRT[1] (weighted differences compared to zero)	PPW[2] or paired WSRT[2]	Kruskal-Wallis test (comparing medians)		CDF comparisons (Wald F test)		
Weighted?	Weighted	Unweighted	Unweighted		Weighted		
Paired?	Paired	Paired	Unpaired		Unpaired		
Treatment of Nondetects (ND):	ND=0	Censored	ND=0		ND=0		
Parameter	Resampled stations only	Resampled stations only	All stations	Resampled stations only	All stations	Resampled stations only	**Overall assessment of change**
Chlorinated Pesticides							
2,4'-DDD	x	↓	--	--	x	x	no change
2,4'-DDE	x	x	--	x	x	x	no change
2,4'-DDT	x	x	--	x	x	x	no change
4,4'-DDD	x	↓	--	--	x	x	no change
4,4'-DDE	x	↓	?	?	x	x	no change
4,4'-DDT	x	--	--	--	x	x	no change
Aldrin	x	x	--	x	x	x	no change
Cis-chlordane (Alpha-chlordane)	x	↓?	--	--	x	x	no change
Dieldrin	x	↑	--	--	x	x	no change
Endosulfan I	x	--	--	--	x	x	no change
Endosulfan II	x	--	--	--	x	x	no change
Endosulfan Sulfate	x	x	--	x	x	x	no change
Endrin	x	↑?	--	--	x	x	no change
Endrin Ketone	x	↓	--	--	x	x	no change
Gamma-BHC (Lindane)	x	x	--	x	x	x	no change
Heptachlor	x	x	--	x	x	x	no change
Heptachlor Epoxide	x	x	--	x	x	x	no change
Mirex	x	x	--	x	x	x	no change
Oxychlordane	x	--	?	?	x	x	no change
Toxaphene	x	↑?	--	--	x	x	no change
Trans-Chlordane (Gamma)	x	--	--	--	x	x	no change

Table continues on next page.

Test:	WSRT[1] (weighted differences compared to zero)	PPW[2] or paired WSRT[2]	Kruskal-Wallis test (comparing medians)		CDF comparisons (Wald F test)		
Weighted?	Weighted	Unweighted	Unweighted		Weighted		
Paired?	Paired	Paired	Unpaired		Unpaired		
Treatment of Nondetects (ND):	ND=0	Censored	ND=0		ND=0		
Parameter	Resampled stations only	Resampled stations only	All stations	Resampled stations only	All stations	Resampled stations only	**Overall assessment of change**
Polychlorinated Biphenyls (PCB)							
PCB Congeners							
PCB Congener 8	x	--	--	--	x	x	no change
PCB Congener 18	x	--	--	--	x	x	no change
PCB Congener 28	x	--	--	--	x	x	no change
PCB Congener 44	x	--	--	--	x	x	no change
PCB Congener 52	x	↓	--	--	x	x	no change
PCB Congener 66	x	--	--	--	x	x	no change
PCB Congener 77	x	--	--	--	x	x	no change
PCB Congener 101	x	↓	--	--	x	x	no change
PCB Congener 105	x	--	--	--	x	x	no change
PCB Congener 118	x	↓?	--	--	x	x	no change
PCB Congener 126	x	--	--	--	x	x	no change
PCB Congener 128	x	↓	--	--	x	x	no change
PCB Congener 138	x	↓	↓	↓?	x	x	possible decrease
PCB Congener 153	x	↓	↓	↓	x	x	possible decrease
PCB Congener 170	x	--	?	--	x	x	no change
PCB Congener 180	x	--	?	?	x	x	no change
PCB Congener 187	x	↓	--	--	x	x	no change
PCB Congener 195	x	--	--	--	x	x	no change
PCB Congener 206	x	--	--	--	x	x	no change
PCB Congener 209	x	↓	--	--	x	x	no change
PCB Aroclors							
PCB Aroclor 1016	x	x	--	--	x	x	no change
PCB Aroclor 1221	x	x	--	--	x	x	no change
PCB Aroclor 1232	x	x	--	--	x	x	no change
PCB Aroclor 1242	x	x	--	--	x	x	no change
PCB Aroclor 1248	x	↓	?	?	x	x	no change
PCB Aroclor 1254	x	--	--	--	x	x	no change
PCB Aroclor 1260	x	--	↓	↓?	x	x	no change
PCB Aroclor 1262	x	x	--	--	x	x	no change
PCB Aroclor 1268	x	↓	--	?	x	x	no change

Test:	WSRT[1] (weighted differences compared to zero)	PPW[2] or paired WSRT[2]	Kruskal-Wallis test (comparing medians)		CDF comparisons (Wald F test)		
Weighted?	Weighted	Unweighted	Unweighted		Weighted		
Paired?	Paired	Paired	Unpaired		Unpaired		
Treatment of Nondetects (ND):	ND=0	Censored	ND=0		ND=0		
Parameter	Resampled stations only	Resampled stations only	All stations	Resampled stations only	All stations	Resampled stations only	**Overall assessment of change**
TOC-Normalized PAHs							
LPAH							
2-Methylnaphthalene	↓	↓	↓	↓	↓	↓	decrease
Acenaphthene	--	--	--	--	--	--	no change
Acenaphthylene	--	--	--	--	--	--	no change
Anthracene	↓?	--	--	--	--	--	no change
Fluorene	↓	↓	↓	--	↓	↓	decrease
Naphthalene	--	↓?	--	--	--	--	no change
Phenanthrene	↓	↓	↓	--	↓?	--	possible decrease
Total LPAH	↓?	↓?	↓?	--	--	--	likely no change
HPAH							
Benzo(a)anthracene	↓	↓	↓	↓?	↓	↓	decrease
Benzo(a)pyrene	↓	↓	↓?	--	mixed	--	likely decrease
Benzo(g,h,i)perylene	↓	↓	↓	--	↓	↓?	likely decrease
Chrysene	↓	↓	↓?	--	mixed	↓?	likely decrease
Dibenzo(a,h)anthracene	↓	↓	↓	--	↓?	↓?	likely decrease
Fluoranthene	↓	↓	↓?	--	--	--	likely decrease
Indeno(1,2,3-c,d)pyrene	↓	↓	↓	↓?	↓	↓	likely decrease
Pyrene	↓	↓	↓?	--	--	--	likely decrease
Total Benzofluoranthenes	↓	--	↓?	--	mixed	↓?	likely decrease
Total HPAH	↓	↓	↓	--	--	↓?	likely decrease
Miscellaneous TOC-Normalized Organic Compounds							
Total PCB Aroclors	--	--	--	--	--	--	no change
Bis(2-ethylhexyl)phthalate	--	↑	↑?	↑?	↑	↑	likely increase
Butylbenzylphthalate	x	--	--	--	x	x	no change

[1] Wilcoxon signed rank test applied to weighted differences.
[2] Prentice-Wilcoxon test or Wilcoxon signed rank test applied to unweighted differences.

Table 18. Summary of statistical comparisons of 1999 PSAMP/NOAA and 2008 Urban Waters Initiative benthic invertebrate indices.
See Methods section of report for details of comparison methods.
Significance level α = 0.05 unless indicated otherwise.
↓ *= decrease;* ↑ *= increase;* -- *= no change; ? indicates 0.05 < p-value ≤ 0.10.*

Parameter	Paired differences weighted by area, resampled stations only[1]	CDF comparison weighted, unpaired, all stations[2]	CDF comparison weighted, unpaired, resampled stations only[2]	Overall assessment of change
Total Abundance	↓	--	↓	decrease
Taxa Richness	--	↓	↓	decrease
Pielou's Evenness (J')	↑	--	--	possible increase
Swartz' Dominance Index (SDI)	--	--	--	no change
Annelid Abundance	↓	↓?	--	possible decrease
Arthropod Abundance	↓	↓	↓	decrease
Echinoderm Abundance	--	↑?	--	likely no change
Mollusc Abundance	--	↓	--	possible decrease
Abundance of Miscellaneous Taxa	--	--	↓	possible decrease

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

Table 19. Sediment Quality Triad Index by station, comparing 1999 PSAMP/NOAA and 2008 Urban Waters Initiative results. *C(#) = chemistry hit (number of chemicals > SQS); T = toxicity hit; B = benthos hit.*

Station	Location	1999			2008		
		Area (km^2)	Triad Hits	Sediment Quality Classification (Reassessed)	Area (km^2)	Triad Hits	Sediment Quality Classification
285	S. Shoreline Commencement Bay	0.786	none	High	0.786	none	High
287	S. Shoreline Commencement Bay	0.786	none	High	0.786	none	High
291	N.E. Commencement Bay	1.108	none	High	0.831	none	High
292	N.E. Commencement Bay	1.108	none	High	0.831	none	High
281	Central Commencement Bay	3.24	none	High	1.851	none	High
283	Outer Commencement Bay	3.24	none	High	1.851	none	High
284	Outer Commencement Bay	3.24	none	High	1.851	none	High
286	S. Shoreline Commencement Bay	0.786	none	High	0.786	C(1)	Intermediate/High
288	S.E. Commencement Bay	1.054	none	High	0.791	B	Intermediate/High
289	S.E. Commencement Bay	1.054	none	High	0.791	B	Intermediate/High
290	S.E. Commencement Bay	1.054	none	High	0.791	B	Intermediate/High
282	Central Commencement Bay	3.24	none	High	1.851	C(1), B	Intermediate/Degraded
298	Middle Waterway	0.016	B	Intermediate/High	0.016	none	High
301	Blair Waterway	0.387	B	Intermediate/High	0.387	none	High
297	Middle Waterway	0.016	B	Intermediate/High	0.016	C(1)	Intermediate/High
302	Blair Waterway	0.387	B	Intermediate/High	0.387	B	Intermediate/High
293	N.E. Commencement Bay	1.108	B	Intermediate/High	0.831	B	Intermediate/High
300	Blair Waterway	0.387	B	Intermediate/High	0.387	C(1), B	Intermediate/Degraded
299	Middle Waterway	0.016	C(16), B	Intermediate/Degraded	0.016	none	High
295	Thea Foss Waterway	0.126	C(1), B	Intermediate/Degraded	0.126	none	High
305	Hylebos Waterway	0.223	C(1), B	Intermediate/Degraded	0.223	B	Intermediate/High
296	Thea Foss Waterway	0.126	C(2), B	Intermediate/Degraded	0.126	C(11), B	Intermediate/Degraded
303	Hylebos Waterway	0.223	C(2), B	Intermediate/Degraded	0.223	C(1), B	Intermediate/Degraded
304	Hylebos Waterway	0.223	C(2), B	Intermediate/Degraded	0.223	C(1), B	Intermediate/Degraded
294	Thea Foss Waterway	0.126	C(10), T, B	Degraded	0.126	C(14)	Intermediate/High

Station	Location	1999			2008		
		Area (km^2)	Triad Hits	Sediment Quality Classification (Reassessed)	Area (km^2)	Triad Hits	Sediment Quality Classification
4	N.E. Commencement Bay	Stations not sampled in 1999			0.831	none	High
88	East Commencement Bay				0.791	none	High
222	Outer Commencement Bay				1.851	none	High
380	Outer Commencement Bay				1.851	none	High
318	Central Commencement Bay				1.851	B	Intermediate/High

Table 20. Changes in Sediment Quality Triad Index for Commencement Bay from 1999 to 2008.
↑ = *increase,* ↓ = *decrease,* -- = *no change statistically significant at* $\alpha = 0.05$.

Sediment Quality Triad Element	1999 # Stations	2008 # Stations	Signif. Change[1]	1999 Area (km^2)	2008 Area (km^2)	1999 % of Area	2008 % of Area	Signif. Change[2]
Chemistry > SQS	7	8	--	1.06	3.74	4.42	15.54	--
Toxicity	1	0	--	0.13	0.0	0.53	0.0	--
Affected Benthos	13	12	--	3.36	8.48	13.99	35.22	--
Triad Index								
High (no triad elements)	12	15	--	20.70	14.66	86.02	60.91	--
Intermediate/High (1 triad element)	6	10	--	2.30	6.59	9.56	27.40	--
Intermediate/Degraded (2 triad elements)	6	5	--	0.94	2.81	3.89	11.68	--
Degraded (all 3 triad elements)	1	0	--	0.13	0.0	0.52	0.0	--

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

Table 21. Comparison of Sediment Quality Triad Index for 1999 PSAMP/NOAA and 2008 Urban Waters Initiative stations, PSAMP sediment monitoring Central Sound region (1998-1999), and entire Puget Sound baseline (1997-2003).

All Stations	Incidence (Percent of Stations)					Spatial Extent (Percent of Area)			
	Commencement Bay		PSAMP Central Region	Puget Sound Baseline		Commencement Bay		PSAMP Central Region	Puget Sound Baseline
	1999	2008				1999	2008		
Number of Stations:	25	30	128	381	Area (km^2):	24.06	24.06	683.92	2294.15
High	48.0%	50.0%	53.9%	52.5%		86.0%	60.9%	90.9%	62.4%
Intermediate/High	24.0%	33.3%	22.7%	31.5%		9.6%	27.4%	6.8%	31.5%
Intermediate/Degraded	24.0%	16.7%	19.5%	13.4%		3.9%	11.7%	2.0%	5.8%
Degraded	4.0%	0.0%	6.7%	6.0%		0.5%	0.0%	0.3%	1.4%