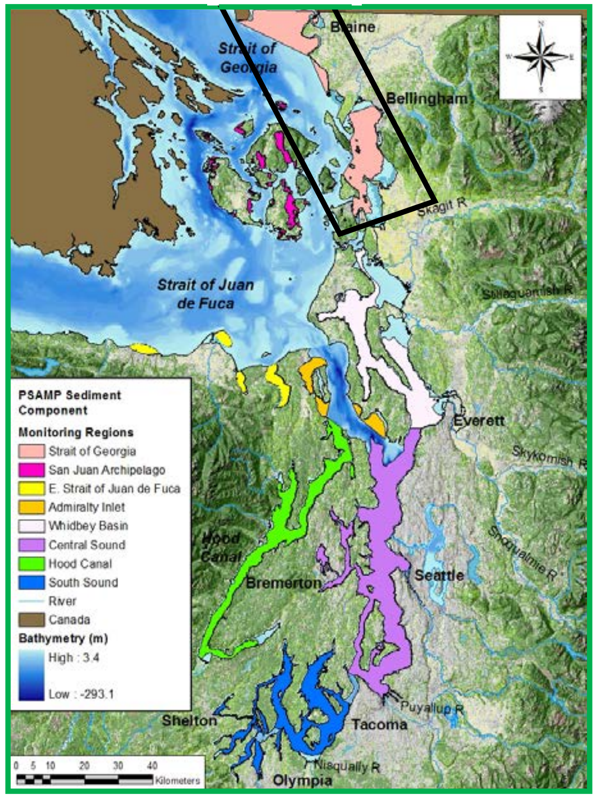

Sediment Quality Assessment of the Southern Strait of Georgia, 2006

Spatial/Temporal Sediment Monitoring Element of the Puget Sound Ecosystem Monitoring Program

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Cover photo:

Top to bottom: Squalicum Harbor Marina, Bellingham Bay; Ecology staff sampling sediments; R/V Kittiwake.
Right: Location of Strait of Georgia sediment monitoring region among eight PSEMP sediment monitoring regions.

Sediment Quality Assessment of the Southern Strait of Georgia, 2006

Spatial/Temporal Sediment Monitoring Element of the Puget Sound Ecosystem Monitoring Program

by

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Abstract

In 2006 the Washington State Department of Ecology (Ecology) surveyed sediment quality in the embayments along the southern Strait of Georgia. The objectives were to characterize region-wide sediment quality and to determine whether sediment quality had changed since a similar survey in 1997.

Sediment samples were collected at 40 stations and analyzed for the sediment quality triad of chemistry, toxicity, and benthic (sediment-dwelling) invertebrate community structure.

- No samples in 2006 had chemical contaminant concentrations exceeding Sediment Quality Standards, compared to 15% of samples in 1997.
- Responses to laboratory toxicity tests were mixed, with one test indicating more samples with toxic responses in 2006 than 1997 and another test indicating fewer.
- The proportion of samples with adversely affected benthos increased from 16% in 1997 to 46% in 2006. That is, benthic communities increasingly showed signs of stress-responses, such as reduced abundance.

The declines in benthic community health seem not to coincide with the trends in sediment chemistry or toxicity. Other factors not measured in this survey, such as dissolved oxygen, may have affected the benthos.

The chemistry, toxicity, and benthic community results were combined into the Sediment Quality Triad Index to categorize sediment quality on a 4-level scale, depending on the numbers of triad elements degraded.

- The proportion of the study area with high quality sediments (no triad elements degraded) decreased from 76% in 1997 to 56% in 2006.
- Correspondingly, intermediate quality sediments (1-2 triad elements degraded) increased from 24% to 44% of the study area, due primarily to degraded benthos.
- None of the study area had all three triad elements degraded in either year.

Some of these trends have been seen in other regions of Puget Sound. Ecology will continue to monitor sediment quality over time to determine if these trends persist.

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Executive Summary

Background and Objectives

A survey of sediment quality in the bays adjoining the southern Strait of Georgia was conducted in 2006 by the Washington Department of Ecology (Ecology) as part of the Puget Sound Assessment and Monitoring Program (PSAMP), now called the Puget Sound Ecosystem Monitoring Program (PSEMP). This region previously had been studied in a baseline survey conducted jointly by Ecology and the National Oceanic and Atmospheric Administration (NOAA) in 1997.

The primary objectives of this study were to determine:

1. The geographic patterns, incidence, and spatial extent of sediment quality degradation in the southern (U.S.) Strait of Georgia region in 2006.
2. The extent and nature of any sediment quality changes that occurred between 1997 and 2006.

Study Design

The southern Strait of Georgia monitoring region extends from the U.S./Canada border to the vicinity of Anacortes, encompassing an area of 387 km^2. Samples of the surficial sediments were collected in June 2006 at 40 randomly selected locations within this study area. Sample locations were selected according to a statistical design that enables the estimation of spatial extent of degraded environmental conditions.

Analyses were performed on all samples to determine the concentrations of potentially toxic chemicals, the degree of response in three laboratory toxicity tests, and the composition of sediment-dwelling invertebrates (i.e., resident benthos). These three measures are known as the Sediment Quality Triad. Triad results were combined into the Sediment Quality Triad Index, which characterizes sediments on a 4-level scale from high quality to degraded quality.

Sediments were classified as contaminated if chemical concentrations exceeded applicable Washington State standards. They were classified as toxic if the outcomes of one or more laboratory tests exceeded statistically derived critical values. The benthos were considered to be adversely affected if they were judged to have a combination of reduced total abundance, reduced species diversity, decreased abundance of stress-sensitive species, and increased abundance of stress-tolerant species.

Sampling methods and analytical methods were similar or identical to those used previously by Ecology and NOAA in the survey conducted in this region in 1997, allowing data comparison.

Physical Conditions

The PSEMP Strait of Georgia region consists of several shallow embayments with station depths generally < 40 m. The majority of stations in these embayments had sediments consisting mostly of silt and clay, grading toward sandy materials in the open waters of the strait. As in much of Puget Sound, organic carbon content of the sediment was generally low, below 2% by weight.

Chemical Analyses

Samples were analyzed in the laboratory for 129 potentially toxic chemicals, including metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and other organic compounds. Metals and PAHs were almost always detected and measurable in the samples. The other target organic compounds (e.g., PCBs, pesticides) were rarely detected or concentrations were below laboratory reporting limits.

None of the Washington State regulatory Sediment Quality Standards (SQS) for chemical contamination was exceeded in any of the samples collected in 2006. Compared to 1997, chemical contamination, defined as concentrations above SQS, decreased region wide. The incidence of contamination decreased from about 15% of stations in 1997 to 0% in 2006, and the spatial extent of contamination decreased from about 10% of the area of the region to 0%.

The degree of contamination, as measured by the mean SQS quotient (mSQSq), was highest in Bellingham Bay and decreased southward to Samish Bay and northward to Boundary Bay. The mSQSq is a multi-chemical index that accounts for the presence, concentrations, and potential toxicity of mixtures of chemicals. It is calculated as the average of the ratios of sample concentrations to SQS for 39 chemicals for which SQS have been determined.

Concentrations of some metals increased from 1997 to 2006 (chromium, lead, selenium, zinc), some decreased (cadmium, silver, tin), and others did not change (arsenic, copper, mercury, nickel). Among PAHs, low molecular weight PAH (LPAH) concentrations generally increased, while high molecular weight PAH (HPAH) concentrations largely remained unchanged.

Toxicity

Sediment samples were tested in the laboratory to determine if they were toxic to invertebrate organisms. Three separate tests were performed, measuring different biological responses to exposure to sediments or sediment pore water.

In total, seven samples had a significant toxic response in the tests. Those samples represented 66 km^2, or about 18% of the region. There was no overlap in the test results, i.e., no samples were toxic in more than one test. However, the tests were consistent in identifying samples which were not toxic: 33 of the 40 samples, representing about 82% of the study area, did not have a toxic response in any of the tests.

The results of the individual toxicity tests indicated:

- The test of the sperm and eggs of sea urchins exposed to the pore waters extracted from the sediments indicated no toxic response[1] in fertilization rates in any of the samples.
- The test of amphipods exposed to solid sediments indicated that survival ranged from 70% to 99%. Only 3 of the 40 samples were classified as toxic[1]. All three toxic samples were collected in Bellingham Bay. Amphipod survival tended to increase out of Bellingham Bay into Samish Bay. Survival was relatively high in southern Boundary Bay.
- The test of sand dollar embryos exposed to sediment/water mixtures indicated the greatest sensitivity. Mean combined percent normal development and survival ranged from 7% to 113% of reference sediment. Four of 40 samples were considered toxic[2] according to this test. Those samples were from inner and outer Boundary Bay.

Comparison of 1997 and 2006 toxicity yielded mixed results. There was a slight increase in the spatial extent of toxicity (i.e., percent of area with toxic sediment) based on the amphipod survival test, but not the sea urchin fertilization test. However, a more sensitive amphipod test species was used in 2006 than in 1997. The species of sea urchin used in the fertilization test was the same in both years. The sand dollar embryo test was not run in 1997.

Benthic Community Composition

Living benthic invertebrate organisms were found at all 40 locations sampled. Lowest total abundance (< 200 organisms per sample) occurred in central Bellingham Bay. Stations with the highest total abundance (> 1100 organisms per sample) occurred in outer Boundary Bay, near Point Roberts, and along the shoreline at the head of Bellingham Bay.

Taxa richness (number of taxa or species) was generally higher in Boundary Bay than in Bellingham Bay. Lowest taxa richness (< 20 taxa per sample) occurred at stations in central and inner Bellingham Bay. Two benthic assemblages from outer Boundary Bay had considerably higher taxa richness than those at any other station in the study area: 137 and 189 taxa vs. < 90 taxa in the rest of the area.

All stations in Bellingham Bay and Fidalgo Bay were numerically dominated by annelids. All stations in Samish Bay except one were dominated by molluscs. Boundary Bay stations were mixed: mostly arthropod-dominated, but some dominated by annelids or molluscs.

The benthic assemblages were judged to be adversely affected at 19 stations among the 40 sampled in 2006. That is, the benthos were judged to have been 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. Those 19 stations represented an estimated 159 km^2, or 44% of the study area.

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[1] Less than 80% of response in control samples and statistically significantly different from control response.
[2] Less than 85% of response in control samples and statistically significantly different from reference samples.

Total benthic invertebrate abundance and abundance of all major taxonomic groups decreased considerably from the values observed in 1997. However, two indices of benthic diversity were similar to or higher than those calculated in the 1997 survey of the same region.

The spatial extent of adversely affected benthos increased from 15% of the study area in 1997 to 44% in 2006. The cause(s) of the changes in benthic invertebrate condition are unknown and may be due to natural and/or anthropogenic factors.

Sediment Quality Triad

The Sediment Quality Triad Index (SQTI) combines the evidence from the triad of measures (chemistry, toxicity, benthos) and classifies sediment quality according to the number of triad elements indicating degradation. In 2006, 19 of the 40 samples were classified as High quality, with none of the triad elements indicating degraded conditions. Those 19 stations represented 188 km^2, or about 52% of the study area. No samples were classified as Degraded quality, with all three triad elements indicating degraded conditions. The other 21 stations were classified as intermediate, with either one or two triad elements indicating degraded conditions.

Fourteen of the 16 stations with Intermediate/High quality had adversely affected benthos; the other two had toxic sediment. The five stations with Intermediate/Degraded quality had both toxic sediment and adversely affected benthos. No stations had chemical concentrations higher than the SQS, the defining condition for the chemistry contribution to the SQTI.

For comparing the 1997 and 2006 results, the SQTI was recalculated with toxicity including only the two tests common to both years; therefore the 2006-comparison results differ slightly from the 2006-only results.

The spatial extent of High quality sediment decreased from 76% of the area in 1997 to 56% in 2006. The proportion of area with Intermediate/High sediment quality increased from 20% to 39%. There were no significant changes in the spatial extent of Intermediate/Degraded (3.6% vs. 5.5%) and Degraded (0% vs. 0%) sediment quality.

The contribution of chemical contamination to the SQTI decreased from 1997 to 2006, but the contribution of deteriorated benthos condition increased dramatically. The toxicity contribution was essentially unchanged.

The spatial estimates of sediment quality from the 2006 survey of the southern Strait of Georgia generally were similar to those from the 1997-2003 PSAMP Puget Sound baseline for the entire Sound. In 1997, the southern Strait of Georgia region was among the least degraded in Puget Sound. In 2006, the sediment quality conditions in the Strait of Georgia region were similar to those of the South Puget Sound region in 1999.

Recommendations

Sediment quality is recognized as an important indicator of ecosystem health by environmental managers and scientists in Puget Sound. Ecology conducts Puget Sound Ecosystem Monitoring Program (PSEMP[3]) marine sediment monitoring surveys annually, rotating through eight regions of Puget Sound over a 10-year cycle and also through selected urban bays over a 6-year cycle. The sampling design enables determination of sediment quality at bay-wide, region-wide, and sound-wide scales. The data are used for Puget Sound ecosystem management and are also reported to the public as part of the Puget Sound Partnership's "Vital Signs" of Puget Sound (www.psp.wa.gov/vitalsigns/index.php).

To continue to effectively generate and use PSEMP sediment quality triad data to determine sediment health in Puget Sound, the following actions are recommended:

- **Continue annual PSEMP sediment monitoring to determine spatial status and temporal trends.** As data come in from the current and subsequent survey cycles, Ecology can determine whether and how sediment quality has improved, deteriorated, or remained unchanged over time. This can be done only if sampling and analytical methods remain similar with time to ensure continued generation of comparable data.
- **Conduct surveys of sediment deposition, mixing, and resuspension rates in Puget Sound.** The rates and dynamics of sediment deposition, mixing and resuspension in different regions of Puget Sound should be quantified. Such information will help in interpretation of results and determination of optimal intervals between sediment sampling events.
- **Develop a benthic health index for Puget Sound.** Puget Sound is one of only a few marine and estuarine regions of the U.S. without a numerical benthic community health index. Such indices must be tailored to the benthic communities of each biogeographic area. It would be beneficial if Ecology had such a multimetric index with which to gauge benthic invertebrate condition. Work to develop a benthic index has begun but needs to be completed.
- **Determine additional environmental parameters to include in sediment monitoring.** Of concern is the increase in adversely affected benthos in this and other recent PSAMP sediment surveys. The trends in benthos seem not to coincide with trends in the environmental parameters (sediment chemistry and toxicity) already being monitored; other factors may be important. The benthos are affected by complex interplays of natural and anthropogenic variables. Further study is required to explore reasons for the decline in benthic health and to determine what other environmental parameters should be added to the PSEMP sediment monitoring.
- **Fund analyses of contaminants of emerging environmental concern.** In previous years, sediment quality research was focused on mixtures of industrial toxicants, including metals, polycyclic aromatic hydrocarbons, and chlorinated organic compounds. More recently, environmental concerns have focused on a number of other types of contaminants. Those contaminants include dioxins, perfluorinated compounds, pharmaceuticals, and personal care

[3] Previously called the Puget Sound Assessment and Monitoring Program (PSAMP).

products. Currently, they are not routinely analyzed by Ecology as part of the PSAMP (now PSEMP) monitoring, due largely to budget limitations. Therefore, we have a poor understanding of their spatial distribution, concentrations, ecotoxicological effects (if any) and temporal trends in concentrations. The PSEMP sediment quality monitoring should be expanded to add analyses for the chemicals of emerging concern.

- **Develop cross-border partnerships and indices.** The PSEMP sampling regions are part of the Salish Sea that extends into Canada. Some of the waterbodies are shared, including Boundary Bay and the Strait of Georgia. Transboundary indicators and programs have been or are being developed for a number of environmental parameters, such as air quality and marine water quality. It is important to coordinate sampling and data interpretation with Canadian and U.S. federal, provincial/state, local, and tribal partners for mutual better understanding of sediment conditions in shared waters.

Introduction

Rationale for Sediment Monitoring in Puget Sound

Toxic substances introduced into estuarine ecosystems such as Puget Sound can bind to suspended particles, settle to the bottom, and become incorporated into deposited soft sediments (NRC, 1989). Therefore, sediments that have accumulated in low-energy, depositional zones where they are not disturbed by physical processes or other factors can provide a relatively stable record of toxicant inputs (Power and Chapman, 1992; Long and Sloane, 2005). This sedimentation process tends to rid the water column of toxicants and thereby reduce the potential for toxicity in the overlying water. Toxicant concentrations in sediments can increase to the point that they eventually represent a toxicological threat to the resident benthic biota as well as organisms higher in the food chain (Burton, 1992). As a result, sediments are an important medium in which to estimate the past and present amounts of chemical contamination of estuaries.

Past and current waste discharge practices in the Puget Sound watershed have left a legacy of toxic chemicals in its sediments, as well as adverse effects on associated biota, documented in sediment baseline surveys from the late 1970s and early 1980s (summarized in Dutch et al., 2009). As a result, millions of dollars have been spent in Puget Sound over the past four decades to establish and maintain laws and programs that regulate industrial and municipal waste discharge, including the federal Clean Water Act, Washington State Water Quality Standards, and Washington State Sediment Quality Standards, to regulate stormwater runoff (Washington State Municipal Stormwater Permits), and to clean up and restore the most contaminated sites (Ecology, 2008).

Determining the effectiveness of all of these actions is dependent on having a well-established baseline of environmental conditions throughout Puget Sound, followed by a system of routine and repeated monitoring of these conditions so that improvement or further deterioration can be measured over time.

Puget Sound Ecosystem Monitoring Program – Regional Sediment Monitoring

The Puget Sound Ecosystem Monitoring Program (PSEMP), previously called the Puget Sound Assessment and Monitoring Program (PSAMP[4]), was established in the late 1980s to measure environmental baseline conditions and trends for various Puget Sound ecosystem components, including sediments (Puget Sound Water Quality Authority, 1988). The Sediment Monitoring

[4] Originally named the Puget Sound Ambient Monitoring Program (PSAMP); recently renamed the Puget Sound Ecosystem Monitoring Program (PSEMP). For currency, consistency, and clarity, in this report, samples and data collected before the December 2011 name change are called PSAMP; general and future references use PSEMP.

Component of PSEMP, conducted by the Washington State Department of Ecology (Ecology[5]) since 1989, characterizes sediment quality on multiple geographic scales (Dutch et al., 2009).

The PSEMP Sediment Component's Spatial/Temporal Monitoring element involves sediment monitoring in eight regions (Figure 1), sampling surficial sediments annually on a 10-year rotational cycle (Dutch et al., 2009). The 2006 assessment of sediment quality in the southern Strait of Georgia which is the subject of this report was conducted as part of that program.

Baseline sediment conditions throughout Puget Sound were determined as the results of PSAMP surveys conducted between 1997 and 2003. The 1997-1999 survey of Puget Sound conducted jointly by Ecology and NOAA (Long et al., 2003, 2005) assessed sediment quality throughout what are now five of the eight PSEMP regions, including the Strait of Georgia region. The remaining three PSEMP regions were surveyed by Ecology in 2002-2003 (Long et al., 2008).

Once the current regional sampling cycle finishes in 2014, updated Puget Sound-wide conditions will be available. Then the cycle will begin again.

Objectives

Broadly, the overall programmatic goals for the PSEMP Sediment Component are to assess the condition of Puget Sound sediments, to document geographic patterns and changes over time, and to provide sediment data in support of regulatory or research activities (Dutch et al., 2009). Specifically, data from the 2006 survey in the Strait of Georgia region were used to satisfy the following technical objectives:

- Determine the incidence and severity of chemical contamination, sediment toxicity, and impairment of benthic (sediment-dwelling) invertebrate assemblages; in other words, the number and percent of stations with sediment quality degradation.
- Identify geographic patterns and gradients, if any, in sediment chemical concentrations, toxicity, and benthic impairment.
- Estimate the spatial extent of chemical contamination, toxicity, and benthic impairment, as percentages of the total survey area.
- Describe the composition, abundance, and diversity of benthic invertebrate assemblages at each sampling location.
- Determine spatial patterns (if any) and extent of degraded conditions based upon a combined weight of evidence formed with the sediment quality triad of measures.
- Determine whether sediment quality in the Strait of Georgia monitoring region changed between 1997 and 2006, and describe the nature and degree of changes found.
- Compare sediment quality in the Strait of Georgia monitoring region to that in other geographic areas within Puget Sound.

[5] The Marine Sediment Monitoring Program (MSMP) within the Environmental Assessment Program of Ecology.

This study was designed to satisfy these specific programmatic goals and technical objectives. Therefore, methods were selected that were not necessarily the same as those used in enforcement or other regulatory decisions in Puget Sound (Ecology, 1995). However, the majority of methods complied with those Ecology procedures, and most followed the sampling and analytical methods of the Puget Sound Estuary Program (PSEP) protocols.

Methods

PSAMP Sediment Component sampling and analytical methods used in the 2006 survey were described in Dutch et al. (1998). That document has since been revised and expanded. The current PSAMP Sediment Component Quality Assurance Project Plan (QAPP) (Dutch et al., 2009) is more comprehensive and readily available, and is therefore the methods document cited in this report.

Sampling Design and Study Area

The PSEMP Sediment Component sample frame is divided into eight geographical regions (Figure 1) and five anthropogenic-use/geomorphological subpopulations called strata (Figure 2).

The Strait of Georgia sediment monitoring region encompasses multiple bays adjoining the southern Strait of Georgia, extending from the U.S./Canada border to the vicinity of Anacortes (Figures 1-3). It includes southern Boundary/Semiahmoo Bay, Birch Bay, Bellingham Bay, Samish Bay, Fidalgo Bay, Padilla Bay, and the area near Cherry Point. Note that Lummi Bay is too shallow to be included.

Sampling sites in this 2006 survey were selected randomly according to a generalized random-tessellation stratified (GRTS) multidensity survey design, as described by Stevens (1997) and Stevens and Olsen (1999, 2004). The 40 sites sampled are depicted on the map in Figure 3. Sample locations and amounts of area represented are listed in Table 1. The total survey area encompassed 387 km^2, of which 361 km^2 was feasible to sample, i.e., had samplable surface sediment (Table 2).

Field Sampling

Sediments were collected during June 2006 from the 42-foot research vessel *Kittiwake* (Bio-Marine Enterprises, Seattle, WA). Each station was sampled only once. Target and actual station coordinates are listed in the navigation report (Appendix C).

Sediment samples were collected with a double 0.1-m^2 van Veen grab. The entire contents of a grab (one side) were taken for analysis of benthic invertebrates. The surface 2-3 cm of sediment from multiple deployments of the grab were taken and composited for grain size, chemistry, and toxicity analyses. Detailed procedures are described in the QAPP (Dutch et al., 2009).

Grain Size Analyses

Grain size analyses were conducted by Analytical Resources, Incorporated (ARI) in Tukwila, WA, 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 2006 ARI laboratory report (Appendix E).

Chemical Analyses

Laboratory analyses for total organic carbon content (TOC) and 129 potentially toxic chemicals were performed by Ecology's Manchester Environmental Laboratory, Manchester, WA (Table 3). Laboratory analytical methods and reporting limits for quantification of chemical concentrations followed those specified in the QAPP (Table 4; PSEP, 1986, 1997a,b; Dutch et al., 2009).

Analytical procedures provided data quality that met or exceeded objective performance criteria specified in the QAPP (Table 4; 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 chemical concentrations at or below those limits, and the sample results were qualified as being undetected. Case narratives for all of the chemical analyses, including quality assurance results, are given in Appendix F.

Toxicity Testing

Multiple toxicity tests were performed to provide a weight of evidence with which to evaluate the toxicological condition of each sample. Tests were selected for which there were a range of endpoints and widely accepted protocols (Table 5; Dutch et al., 2009) that would represent the toxicological conditions within different phases (partitions) of the sediments.

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

Amphipod survival tests were conducted by Vizon SciTec Inc. (later named CANTEST Ltd. and now Maxxam Analytics) in Vancouver, BC. Detailed methods for this toxicity test and associated quality assurance procedures are included in the Vizon laboratory report (Appendix G-1).

Sand Dollar Embryo Development in Sediment/Water Mixtures (Elutriates) Tested with *Dendraster excentricus*

Tests of sand dollar embryo development with *Dendraster excentricus* also were conducted by Vizon SciTec Inc. The Vizon laboratory report details methods, results, and quality assurance procedures (Appendix G-1).

Sea Urchin (*Strongylocentrotus purpuratus*) Fertilization in Pore Water

Tests of fertilization success of sea urchin gametes in sediment pore waters were conducted by the U.S. Geological Survey (USGS). Detailed methods for this toxicity test as well as quality assurance procedures are included in the U.S. Geological Survey (USGS) laboratory report (Appendix G-2).

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). Sorting and taxonomy QA reports are given in Appendix H.

Data Analyses

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, i.e., concentrations below the reporting limits, were censored at the reporting limits (quantitation limits) specific to those samples.

Summary statistics 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).

Estimation of Spatial Extent

Spatial extent of a given condition (e.g., contaminant concentration higher than regulatory standard) was calculated as the sum of the areas represented (Table 1) by the samples with the specified conditions. Spatial extent is expressed as area (km^2) or percent of total study area.

Cumulative distribution functions (CDF) and 95% confidence bands, based on Horvitz-Thompson estimates of variance for the unequally weighted samples (Stevens and Olsen, 2003; Kincaid, 2006), were generated to describe the distribution of spatial extent of each parameter of interest. The CDF-generation programs used were developed by the U.S. Environmental Protection Agency (EPA) (Diaz-Ramos et al., 1996; EPA, undated) and written for the S-PLUS[6] statistical software language. Nondetects were excluded from CDF analyses.[7]

Comparison to Regulatory Sediment Quality Standards

Chemistry

Sediment contaminant concentrations were compared to the Washington State Sediment Management Standards (SMS) (Ecology, 1995) applicable to those contaminants. Nondetects

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[6] S-PLUS v.7, Insightful Corporation.
[7] Since metals and PAHs were detected almost always, and other organic compounds were detected only infrequently, CDF analyses were conducted only for metals, PAHs, and the few organic compounds with sufficient frequency of detection.

were treated as specified in those regulations[8]. Where one or more of the Sediment Quality Standard (SQS) values were exceeded, samples were classified as contaminated; otherwise, they were classified as not contaminated.

SQS quotients, ratios of chemical concentrations to their respective SQS values, were calculated where applicable, following methods described for generic sediment quality guidelines (Long et al., 2006). Nondetects were treated as specified in the SMS.

Means of the SQS quotients were calculated across all applicable chemicals[9] for which there were reliable and accurate data. The mean SQS quotient (mSQSq)[10] is an index of chemical contamination that takes into account both the presence and concentrations of mixtures of potential toxicants.

Data for six organic compounds were excluded from the analyses because of the relatively low reliability of the analytical results for these substances: benzoic acid, benzyl alcohol, phenol, 2-methylphenol, 4-methylphenol, and 2,4-dimethylphenol. The laboratory methods used for PSAMP were intended to analyze large suites of base/neutral/acid (BNA) organic compounds and are not optimized for these specific compounds (Huntamer, personal communication, 2006). The analytical precision and detection limits attained by the lab for analyses of these compounds were highly variable.

Toxicity

Results from the amphipod survival and sand dollar embryo development tests were analyzed as specified in the SMS (Ecology, 1995). The sea urchin fertilization test is not included in the SMS. For the sand dollar embryo test, sediment from Birch Bay was used as the reference sediment. Notes on the application of the SMS to the sand dollar embryo test are given in Appendix G-2.

Sediments were classified as toxic if one or more toxicity tests indicated toxic responses. Toxic responses were sample results that were 1) significantly different from control results and 2) less than 80% of control results (amphipod survival, urchin fertilization) or less than 85% of reference results (sand dollar embryo development).

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

[8] Nondetects omitted except in cases of summed concentrations (Total LPAH, Total HPAH, Total PCB) for which all constituent chemicals are nondetect; in such cases, the highest reporting limit among the constituent chemicals is used as the value for the sum.
[9] The SQS for Total LPAH and Total HPAH were not included in the average, so as not to double-count the contributions of the individual PAHs.

[10] $\text{mSQSq} = (1/n)\sum[\text{conc'n chemical}_i]/\text{SQS}_i$.

Swartz' Dominance Index (Table 6). These indices were used to summarize the raw data and characterize the invertebrate assemblages[11] from each station.

Non-metric multidimensional scaling (MDS) and cluster analyses were conducted in PRIMER[12] to provide graphical depictions of the relative degree of similarity among the benthic assemblages (Clarke and Warwick, 2001). 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 in PRIMER.

Benthos element of the sediment quality triad index

The benthic assemblage at each station was classified as "adversely affected" or "unaffected." Classification was based on knowledge of and experience with Puget Sound overall, and did not attempt to separate natural and anthropogenic stressors.

Because no multimetric indices of benthic community health specific to Puget Sound have been developed yet[13], 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. The use of best professional judgment by benthic experts for assessing the condition of benthic communities has been validated by Teixeira et al. (2010) as "a viable means for calibrating indices of ecosystem condition."

Best professional judgment took into account the nine benthic measures mentioned above, for the study samples and compared to Puget Sound baseline values, 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).

Sediment Quality Triad Index (SQTI)

The data from chemical analyses, toxicity tests, and benthic invertebrate assemblage analyses were compiled and merged to classify the degree of degradation in sediment quality (Long et al., 2003, 2005). The criteria indicating degradation in the three elements of the Sediment Quality Triad Index (SQTI) are:

- Chemistry: Concentrations of one or more of 41 sediment contaminants or contaminant groups higher than the respective SQS.

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[11] Because collections of invertebrates in grab samples may not reflect entire benthic invertebrate communities, they are termed assemblages.
[12] PRIMER v.6, PRIMER-E Ltd.
[13] Work is currently underway to develop habitat-specific benthic community health indices for Puget Sound. Multi-metric benthic indices have been developed 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, 2009; 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.

- Toxicity: Amphipod survival or sea urchin fertilization toxicity test results significantly different from control results and less than 80% of the control results, or sand dollar embryo survival and normal morphological development significantly different from reference and less than 85% of reference results.
- Benthos: Best professional judgment indicating that the assemblage was adversely affected.

Based on the weight of evidence from the triad of results, each station was classified as to relative sediment quality. Equal weight is given to each element of the triad. The SQTI categories are:

- **High quality:** No degradation in any triad element.
- **Intermediate/high quality:** Sediments with degradation in only one element of the triad.
- **Intermediate/degraded quality:** Sediments with degradation in two of the triad elements.
- **Degraded quality:** Degradation in all three triad elements.

Comparisons of 2006 Results to 1997 Results

The majority of field and analytical methods used in the PSAMP Spatial 2006 survey were the same as those used in the 1997-1999 joint NOAA-Ecology survey of Puget Sound, known as PSAMP/NOAA (Dutch et al., 1998, 2009; Long et al., 2003, 2005); 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. Two of the toxicity tests (amphipod survival, sea urchin fertilization) were the same, though the amphipod species differed. The same critical values or criteria were used during the interpretation of the data.

However, as described in more detail in the comparisons of the 1997 and 2006 data (*Results and Discussion*), the integration of the chemistry, toxicity, and benthos elements of the SQTI for the 2006 data was somewhat different than for the PSAMP/NOAA survey. Therefore, the PSAMP/NOAA data were reassessed (Weakland et al., 2009) using the same methods as for the 2006 data for comparison.

To determine whether parameter values region-wide had increased, decreased, or remained the same from 1997 to 2006, a weight-of-evidence approach was used. No single statistical hypothesis test combines the attributes of unequal weighting 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. Except as noted, statistical tests were conducted using Minitab[14].

- Cumulative distribution functions (CDFs) of 1997 and 2006 parameter values weighted by area represented were compared with the Wald F test (Kincaid, 2000, 2006), using a function developed by EPA (Diaz-Ramos et al., 1996; EPA, undated) and written for S-PLUS. Since

[14] Minitab v.15, Minitab Inc.

that particular CDF-comparison procedure does not take into account nondetects, it was not used when more than 10% of the samples had nondetect concentrations of a given chemical.

- The generalized Wilcoxon test (Helsel, 2005) was used to compare the Kaplan-Meier estimated parameter medians of unweighted samples for 1997 vs. 2006 when nondetects were present, using routines written by Helsel (2005) for Minitab. In the absence of nondetects, the Mann-Whitney test or equivalent Kruskal-Wallis test was used to compare medians.
- Proportions (e.g., spatial extent of conditions expressed as percent of area, incidence of SQTI categories) were compared by the two-proportion test (normal approximation), the chi-square test of homogeneity, or Fisher's exact test, as appropriate.

Results and Discussion

Results are presented first for the 2006 survey, then for the comparisons with results in the same area from a decade earlier. Finally, the results from the Strait of Georgia region are placed in context with comparable data from other regions of Puget Sound and the Sound as a whole.

Station Characteristics (2006)

Sampling station numbers, names, and locations, and the sizes of area that they represent, are listed in Table 1. Final station coordinates for all 40 stations sampled are listed in the navigation report (Appendix C). Physical and visual characteristics of each sample are included in the field notes (Appendix D).

Water depths at the 40 stations sampled in this region ranged from 4 to 37 m. Most of the shallowest stations were in the heads of Bellingham Bay and Birch Bay, whereas most of the deepest stations were in outer Boundary Bay and outer Bellingham Bay (Figure 4).

Sedimentological and Chemical Analyses (2006)

The raw grain size data for each sample are listed in Appendix E Table E-1 and depicted in bar charts in Figure E-1 of Appendix E. Tables F-1 and F-2 of Appendix F list the raw TOC and chemistry data, respectively, for each sample. Bar charts of the values by sample, indicating qualification, for every analyte are provided in Appendix F in corresponding Figures F-1 and F-2. The data met or exceeded Ecology's quality assurance criteria.

Sediment Grain Size

The majority (26) of the 40 samples were predominantly fine-grained silts and clays (Table 7, Figure 5). Those stations represented about 231 km^2, 64% of the total survey area. Stations bordering the Strait of Georgia (Cherry Point, outer Boundary and Birch Bays) and near Guemes Channel (outer Fidalgo Bay) were predominantly sandy. Otherwise, the sediments in most locations were mainly silts with some clay or sand with little or no gravel (Figure 6; Table E-1).

The sizes of the particles in sediments can be a major determinant in accumulating toxic chemicals (Pelletier et al., 2011). Small-grained particles tend to have the largest surface area-to-volume ratios and therefore tend to attract and chemically bind organic matter as it enters an estuary.

Total Organic Carbon (TOC)

Total organic carbon (TOC) content in the sediment ranged from 0.15% to 3.58%, with a mean value of 1.42% and a median of 1.55% (Table F-1). Station 379 near the mouth of Whatcom Waterway (inner Bellingham Bay) stood out as having the highest TOC content, 3.58%. At all other stations, TOC varied between 0.7% and 2.4% (Table F-1).

TOC concentrations were lowest in the most exposed areas and tended to be higher closer to populated areas (Figure 7). TOC content was less than 0.5% in the sandy locations.

Factors affecting TOC include grain size and sedimentation rate (Pelletier et al., 2011). Thus one would expect areas with finer sediments or higher deposition rates to have greater organic content, and more current-swept areas with coarser sediments to have lower organic content. Equilibrium partitioning principles, in turn, describe the physical chemistry by which organic matter binds toxic organic chemicals and controls their bioavailability in sediments (Di Toro et al., 1991).

TOC concentrations often are highest near sources of organic matter (Pelletier et al., 2011). In the southern Strait of Georgia region, TOC would be expected to be highest in the most protected bays and nearest the pulp mills, storm drains, and other sources of organic matter. The data from the 2006 survey support these suppositions.

The amounts of TOC in sediments can have a major influence on the concentrations and bioavailability of toxicants (Pelletier et al., 2011; EPA, 2003; Di Toro et al., 1991). Many toxicants are chemically charged and therefore are attracted to and readily sorb (bond) to sediments because of both the amount of fine-grained particles and the organic carbon content. Therefore, sediments with high concentrations of TOC often have higher levels of potentially toxic chemicals than those with little or no TOC. Because the TOC tends to chemically bond with the toxicants that accumulate in sediments, it can inhibit or reduce their bioavailability (Pelletier et al., 2011; EPA, 2003). However, although the relationship between TOC and grain size in sediments can be indicative of eutrophication, it is not indicative of contaminant effects or toxicity (Pelletier et al., 2011).

There is some experimental evidence that the bioavailability of sediment-sorbed toxicants can vary as a function of the kind and source of organic matter (Di Toro et al., 1991; Wenning et al., 2005). The organic matter that accumulates in sediments can originate from two major kinds of sources: dead and decaying plants and animals, and poorly treated domestic and industrial sewage and untreated rainwater runoff. The analyses performed in this PSAMP sediment survey, however, were not intended to distinguish between sources of TOC.

Chemical Contamination

With few exceptions, the metals and PAHs were detected and quantitatable. Also with few exceptions, the other organic compounds were undetected at the detection limits attained by the lab or were detected but estimated values because the concentrations were very low. Numbers of detected concentrations and nondetects for each chemical group are given in Table 8. Summary statistics are given for each contaminant in Tables F-3 (unweighted) and F-4 (weighted by area) of Appendix F.

Low levels of several analytes were found in the method blanks for PAHs, which the lab indicates is not uncommon at the low sample concentrations being analyzed (Westerlund, personal communication, 2010). All reported values were at least three times greater than the amount found in the blank. If the value detected in the samples was less than three times that in the blank, the reporting limit was raised to the detected level, and the sample value was not reported as detected, since it could be considered contamination.

Metals concentrations generally were higher in Bellingham Bay – particularly in the inner bay – than elsewhere in the region (Figure F-3). This is consistent with the known history of contamination in Bellingham Bay (Appendix B). In both Bellingham and Boundary Bays, there was a gradient of decreasing levels of several metals from inner to outer bay.

Mercury is of particular interest in Bellingham Bay because of the legacy of a chlor-alkali pulp mill that discharged its wastes into Whatcom Waterway until 2001 (Ecology, 2011). Region-wide, sediment mercury concentrations averaged 0.087 ppm in 2006 (Table F-2). In Bellingham Bay, concentrations of mercury ranged from 0.079 to 0.334 ppm and averaged 0.143 ppm. The range of mercury concentrations outside Bellingham Bay was 0.012 to 0.095 ppm (Figure F-3).

The patterns of nickel and chromium concentrations, however, were more exaggerated than those of mercury, with even higher concentrations in Bellingham Bay than in the rest of the region (Figure F-3).

In Boundary Bay, silver was detected only in the inner to central reaches and was not detected in sediments from the outer portion of the bay (Figure F-3). Selenium was not detected in most samples from Boundary Bay.

Concentrations of the PAHs for which there are Washington State Sediment Management Standards[15] were considerably higher (by one to two orders of magnitude) at a few stations in inner Bellingham Bay than anywhere else across the region (Figure F-3; Table F-2). That pattern was generally non-existent for the other PAHs in the suite reported by the lab.

PBDE congener 47 occurred throughout the study area, but concentrations were higher in Bellingham Bay than elsewhere (Figure F-3). PBDE congeners 184 and 191 were detected only in sediments from Boundary Bay, whereas PBDE congeners 153, 165, and 209 were detected only in sediments from Bellingham Bay. PBDE congener 99 occurred predominantly in Bellingham Bay.

Comparison to Washington State Sediment Management Standards

None of the Washington State Sediment Management Standards was exceeded in this survey by any of the chemicals. Therefore, the incidence of chemical contamination was zero out of 40 samples; the spatial extent (size or percent of area represented by those samples) was also zero percent.

A sediment sample can be classified as "contaminated" by a variety of methods, but all involve comparisons of the chemistry of the ambient samples with some sort of effects-based, numerical standard, criteria, guideline, or benchmark (Wenning et al., 2005). Generically, these effects-based values are referred to as "sediment quality guidelines" (SQGs) whether they were derived as informal, non-regulatory concentrations (Long et al., 1995) or as, in the case of Washington State, as regulatory standards (Ecology, 1995). Such guidelines or standards may be based on a

[15] LPAHs: 2-methylnaphthalene, acenaphthene, acenaphthylene, anthracene, fluorene, naphthalene, phenanthrene; Total LPAH = summed concentrations of all except 2-methylnaphthalene.
HPAHs: benzo(a)anthracene, benzo(a)pyrene, benzo(g,h,i)perylene, total benzofluoranthenes, chrysene, dibenzo(a,h)anthracene, fluoranthene, indeno(1,2,3-c,d)pyrene, pyrene; Total HPAH = summed concentrations.

theoretical (i.e., modeling) method or upon one of several empirical methods that rely upon matching chemical and biological data in field-collected samples (Wenning et al., 2005).

The Washington State regulatory sediment criteria (Sediment Management Standards) 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 (Ecology, 1995). Two sets of values were derived for each of 47 chemicals or chemical groups. The Sediment Quality Standards (SQS) are sediment chemical concentrations 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 concentrations above which at least moderate adverse biological effects are expected to occur. In general, the CSL is higher than the SQS for a given chemical; however, they are the same for some chemicals.

Spatial Patterns of Contamination

Although the SQS were not exceeded in this 2006 survey, the mean SQS quotients indicated a few spatial patterns in chemical contamination. The average ratio of contaminant concentrations to respective SQS – the mean SQS quotient (mSQSq) – is a useful measure of the degree of chemical contamination. This index is a multi-chemical effects-based index that accounts for both the presence and relative concentrations of chemicals for which there are state standards (Long et al., 2006).

The mSQSq was calculated for each station. Values ranged from 0.03 to 0.28, averaging 0.07 (Table 9).

There is considerable empirical evidence from PSAMP surveys of 1997-2008 that mSQSq values less than 0.10 do not represent harmful contaminant levels for benthic invertebrates in Puget Sound, based on co-occurrence analyses of sediment chemistry, toxicity, and benthos data (Long et al., in review). Higher values of mSQSq tend to be associated with increased toxicity and changes in benthic invertebrate abundance, diversity, and abundances of stress-sensitive and stress-tolerant species (Long et al., in review). All but four of the 40 samples (90%) in 2006 had mSQSq values < 0.10 (Table 9), indicating relative lack of contamination throughout most of the region.

The most obvious geographic pattern in mSQSq values was the increasing degree of contamination from outer to inner Bellingham Bay, especially at three stations near or within Whatcom Waterway, near the former Georgia-Pacific alkali plant (Figure 8). The degree of contamination decreased southward out of Bellingham Bay into Samish Bay.

Another pattern was the relatively low degree of contamination in southern Boundary Bay relative to Bellingham Bay (Figure 8). The spatial pattern in contamination into the Canadian reaches of Boundary Bay cannot be determined with this dataset.

Toxicity Tests (2006)

The data for amphipod and urchin fertilization tests met or exceeded Ecology's quality assurance criteria. Some of the saltwater control results in the sand dollar embryo test did not meet Ecology's quality assurance criteria and are discussed below. Notes on the application of the Washington State Sediment Management Standards to the sand dollar embryo data are included in Appendix G-1. The raw toxicity data are given in Appendices G-1 (amphipod survival and sand dollar embryo development) and G-2 (sea urchin fertilization).

Amphipod Survival in Solid Phase Sediments with *Eohaustorius estuarius*

Among the 40 test samples, mean control-adjusted amphipod (*Eohaustorius estuarius*) survival ranged from 70% to 99%. In 17 of the 40 samples, the mean survival was significantly lower than in the negative controls (Table 10).

Mean control-adjusted survival was less than 80% in three samples, and all three sample means were statistically different from the negative controls (Table 10); these samples were therefore classified as toxic. Hence, the incidence of toxicity to amphipods was 3 of 40 stations, or 7.5%.

Sediments in which mean control-adjusted survival was less than 80% are those that were most statistically significant based on power analyses of amphipod survival data accumulated for the species *Ampelisca abdita* (Thursby et al., 1997) and most likely to result in an impaired benthic assemblage (Long et al., 2001).

All three samples with statistically significant outcomes and mean amphipod survival of less than 80% (i.e., toxic responses) were collected in Bellingham Bay (Figure 9). The stations that indicated significant outcomes but mean survival greater than 80% of controls were scattered throughout Bellingham Bay, with no obvious or consistent spatial pattern.

None of the samples from the Boundary Bay area was toxic in this test (Figure 9). However, mean survival was significantly lower than in controls, in seven samples from inner and central Boundary/Semiahmoo Bay (Table 10). None of the samples from Samish Bay, Fidalgo Bay, Birch Bay, or outer Boundary Bay was toxic.

Sea Urchin Egg Fertilization in Pore Water with *Strongylocentrotus purpuratus*

Sea urchin fertilization success was very high in all 40 samples: the mean outcomes ranged from 90% to more than 100% of the Texas reference sediment (Table 11; Figure 10). The ranges in results did not differ among the three pore water concentrations. None of the outcomes was significantly lower than in the Texas reference sediments or the Carr Inlet reference sample. Therefore, this particular test did not identify any of the 40 survey samples as toxic, and both the incidence and spatial extent of toxicity were zero.

Sand Dollar Embryo Development in Sediment/Water Elutriates with *Dendraster excentricus*

Results of the sand dollar embryo tests were reported as combined percent normal development and survival (abbreviated "combined normal survival"), normalized to seawater controls and sediment controls. Combined normal survival, adjusted for saltwater control, ranged from 6.6% to over 100% (Table 12).

However, the saltwater control results in two of the four analytical batches were outside the acceptable range (normal survival > 70%) prescribed by the Washington State Sediment Management Standards (Ecology, 1995). As a result, the sample data from those two batches may not be accurate (and are flagged as such in Table 12). Because it was not possible to re-test the samples within Ecology's stipulated sample holding times, results from all batches were included in the analyses for this report. No samples in the two suspect batches which otherwise met the criteria for toxic sediment (described below) were categorized as such because the saltwater controls were outside limits. Therefore, the incidence of toxicity may be biased low.

Normalized to sediment controls, mean combined normal survival ranged from 12% to 150% (Table 12), a very wide range compared to the outcomes of the other two toxicity tests. The standard deviations among the five replicates in some survey samples were indicative of relatively high within-sample variability.

In four of the 40 samples, the outcome was less than 85% of reference sediment, the regulatory standard for the larval test (Ecology, 1995). All of those samples were from the inner and outer reaches of Boundary/Semiahmoo Bay (Figure 11), and were analyzed in batches for which the saltwater control results met Ecology's standards. Four other samples had outcomes less than 85% of reference, in batches with acceptable saltwater controls, but were not statistically significantly different from the reference results and therefore not considered toxic (Table 12). Three of those four samples were from central Boundary/Semiahmoo Bay.

Spatial Extent of Toxicity

Because there were no samples classified as toxic in the sea urchin fertilization tests, the spatial extent of toxicity according to that test was zero. The three samples that were toxic to the amphipods represented about 20 km^2, or about 5.5% of the survey area. The four samples that passed Ecology's acceptance criteria and were classified as toxic relative to percent normal survival in the sand dollar tests represented 46 km^2, or about 13% of the study area. In all, seven samples elicited a toxic response (Table 13). These samples represented 66 km^2, or about 18% of the region.

There was no overlap in the toxic responses from the three tests. The three samples that indicated a toxic response in the amphipod survival test (only in Bellingham Bay) were different from the four samples (only in Boundary/Semiahmoo Bay) in which the sand dollar test indicated a toxic response (Figure 12). Because the three tests respond to different chemical variables and measure different mechanisms of toxicity, it is not unusual that the results are not concordant (Carr et al., 2001).

However, there was excellent agreement among the three tests regarding which samples were **not** toxic. Among the 40 samples, there were 33 (~83%) for which all three tests indicated the lack of toxicity.

Benthic Community Analyses (2006)

A primary focus of the PSEMP monitoring surveys is to evaluate the biological effects of chemicals in the sediments (Long et al., 2003, 2005). The resources at risk from chemically mediated toxicity are the benthic invertebrates, particularly the animals that burrow in or otherwise reside in the soft-bottom sediments. However, it is important to recognize that the benthos respond to a variety of natural physical and chemical factors as well as anthropogenic (human-caused) factors.

Natural factors can include differences among stations in salinity, water depth, near-bottom concentration of dissolved oxygen, amount of fine-grained particles, amount of organic matter, predation, and velocity of bottom-water currents. These factors, in turn, may interact with each other and with anthropogenic factors in complex patterns.

A number of studies include observations of the behavior of many species relative to these factors (Pearson and Rosenberg, 1978; Boesch and Rosenberg, 1981; Dauer et al., 1992; Nilsson and Rosenberg, 2000). 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. Ecology routinely calculates nine benthic indices in the PSEMP surveys: total abundance, abundance of each of five major taxonomic groups[16], taxa richness, evenness, and dominance (Dutch et al., 2009).

Habitat-specific multimetric benthic indices have been developed 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, 2009; Rosenberg et al., 2004; Smith et al., 2001, 2003; Thompson and Lowe, 2004; Van Dolah et al., 1999; Weisberg et al., 1997). Work is currently underway to develop similar indices for Puget Sound.

Assemblage Characteristics

A list of benthic infaunal taxa found in the 40 samples collected in 2006 is presented in Appendix H Table H-1. Numerical values of the benthic indices, and summary statistics, are given for all stations in Tables 14 and 15. The spatial distributions of the benthic indices are illustrated in Figures 13-18 and in Appendix H Figures H-1 to H-5 (major taxa abundances).

[16] Annelids, arthropods, echinoderms, molluscs, and miscellaneous (all other) taxa.

Total Abundance and Taxa Richness

Benthic invertebrates were found at all stations; i.e., there were no azoic samples. Among the 40 samples, 423 taxa of benthic invertebrates were identified, 301 to species level (Appendix H Table H-1).

Total abundance is the number of organisms in each 0.1-m^2 sample. Total abundance ranged from 78 to 2136 animals per 0.1-m^2 sample, averaging 530 individuals/0.1 m^2 (Table 14). Median total abundance was 412 individuals/0.1 m^2.

Lowest total abundance (< 200 organisms per sample) occurred at five stations in central Bellingham Bay (Figure 13). Stations with the highest total abundance (> 1100 organisms per sample) occurred off Point Roberts and along the shoreline of inner Bellingham Bay.

Taxa richness is the number of taxa or species in each sample. Taxa richness ranged from 14 to 189 taxa per 0.1-m^2 sample, averaging 46 taxa/0.1 m^2 (Table 14). Median richness was 37.5 taxa per sample.

Overall, taxa richness was higher in Boundary Bay than in Bellingham Bay (Figure 14). Lowest taxa richness (< 20 taxa per sample) occurred at stations in central and inner Bellingham Bay. Two stations off Point Roberts had the highest taxa richness in the study area (189 and 137 taxa/0.1 m^2, respectively).

Evenness and Dominance

Pielou's Evenness Index is a measure of the equitability of species distribution (Pielou, 1966, 1974). The index can take on values from 0 to 1. A high evenness value indicates that the total abundance of organisms in a sample is distributed relatively equally among the species.

Evenness ranged from 0.29 to 0.83 among the 40 stations sampled in 2006 (Table 14). The two lowest index values (0.29 and 0.40) occurred in inner Bellingham Bay (Figure 15). Most of the highest index values (> 0.75) were at stations in Boundary Bay and Samish Bay.

Swartz' Dominance Index (SDI) is the minimum number of taxa accounting for 75% of the total invertebrate abundance in a sample (Swartz et al., 1985). Low values indicate that a community is dominated by only a few taxa and therefore diversity is low.

In the 40 samples in this study, SDI ranged from 1 to 32 taxa, averaging 8.9 (Table 14). The highest index values (> 20 taxa) occurred in outer Boundary Bay (Figure 16). Stations with the lowest values (< 10 taxa) were located in inner and central Bellingham Bay.

Major Taxa Abundance

The relative abundance of the major invertebrate taxonomic groups is an indicator of the structure, composition, and overall health of the benthos. In most PSEMP studies, the relative abundances of five major invertebrate groups (annelids, arthropods, echinoderms, molluscs, and miscellaneous taxa[17]) are used to evaluate the benthic assemblages.

Annelids were the most abundant taxonomic group, accounting for an average of 50% of the total abundance, and including 194 taxa (46% of all taxa) across the 40 samples (Table 15). Molluscs were the second-most abundant group, representing an average of about 24% of total abundance and 65 taxa (15% of all taxa). Ninety-six arthropod taxa (23% of all taxa) constituted 18% of the total abundance. Echinoderms in 11 taxa made up 8% of the total abundance, and 56 miscellaneous taxa made up a little over 1% of the total abundance.

Annelids and molluscs were present at all 40 stations. Arthropods were absent at one station; there were no miscellaneous taxa at five stations; and echinoderms were absent from 12 stations, mostly in inner and central Bellingham Bay. The highest abundance of echinoderms occurred in Boundary Bay and southern Bellingham Bay. Arthropods were most abundant at stations in central Boundary Bay (Figure 17).

Polychaetes had the highest percent total abundance and dominated the benthic assemblages throughout Bellingham Bay and the one station in Fidalgo Bay (Figure 18). Molluscs had the highest percent total abundance in Samish Bay and Point Roberts. In Boundary Bay, arthropods were numerically dominant at some stations, but annelids and molluscs dominated other stations.

Benthic Invertebrate Assemblages

Seven assemblages of benthic invertebrates emerged from the data at 38% similarity[18] with all species included (Figures 19-21). These assemblages are designated below by the most common and abundant taxa:

Mediomastus spp./*Galathowenia oculata* (2 stations)

> This assemblage occurred at the mouth of Boundary Bay at Stations 309 and 437. These stations were characterized by somewhat lower salinity (26-27 psu), moderate depth (< 40 m), and had coarse sandy sediment with up to 31% gravel, the highest gravel content of all the samples. The infaunal assemblage at these stations had high total abundance (> 1100 animals) and SDI (> 25 taxa), and the highest taxa richness of all the samples (> 130 taxa per sample). All of the major taxonomic groups were well represented in these two samples, though echinoderm abundance was relatively low.

Spiophanes bombyx (1 station)

> Found at Station 325 at the mouth of Fidalgo Bay, this assemblage was dominated by the polychaete *Spiophanes bombyx*, which made up 21% of the total abundance. This station was relatively shallow (19 m) with sandy sediment and low TOC. Total abundance, taxa richness, and SDI were moderate at this station; and annelids, molluscs, arthropods, and miscellaneous taxa were relatively abundant.

[17] All other phyla.
[18] Bray-Curtis similarity.

Rochefortia tumida/Nutricola lordi (2 stations)

Molluscs, particularly the bivalves *Rochefortia tumida*, *Nutricola lordi*, and *Tellina modesta*, numerically dominated two very shallow (< 5 m) sandy stations, one located off Point Roberts and one in northern Birch Bay. These stations exhibited high total abundance and taxa richness and low SDI. Very few miscellaneous taxa or echinoderms were found in these samples.

Aphelochaeta spp. (14 stations)

Polychaetes of the genus *Aphelochaeta* were abundant or very common at 14 shallower (< 35 m) stations located throughout much of Bellingham Bay, including Whatcom Waterway. These stations had silty sediments and moderate to high TOC. The *Aphelochaeta* assemblage exhibited high total abundance and low taxa richness, with abundant annelids and few arthropods, echinoderms, and miscellaneous taxa.

Prionospio (Minuspio) lighti (1 station)

This assemblage, dominated by the spionid polychaete *Prionospio lighti,* occurred at Station 125, in Birch Bay. Station 125 was very shallow (5.8 m) and had mixed silt and sand sediment. Total abundance was moderate at this station and taxa richness was low. Annelids and arthropods were the most abundant groups in this assemblage, with few echinoderms.

Amphiodia spp./*Euphilomedes producta* (3 stations)

The echinoderm *Amphiodia* spp. and the ostracod *Euphilomedes producta* were abundant at Stations 189, 539, and 667. These stations, located in southern Boundary Bay off Birch Bay Point, were relatively shallow, with mostly sand and some silt. The infaunal assemblage at these stations had high total abundance, taxa richness, and SDI. All of the major taxonomic groups were abundant in these samples, with a predominance of polychaetes, arthropods, and echinoderms.

Eudorella pacifica/*Amphiodia* spp. (17 stations)

The cumacean *Eudorella pacifica* and the echinoderm *Amphiodia* spp. were prevalent in a group of stations in central Boundary Bay, Cherry Point, and Samish Bay. These stations were shallow with silty sediments. The infaunal assemblage at these stations had a high total abundance and taxa richness. The total abundance was distributed fairly evenly among the annelids, arthropods, and molluscs.

Adversely Affected Benthos

The benthic assemblages at 19 of the 40 stations, representing an estimated 44% of the study area, were classified as adversely affected (Table 16). That is, the benthos were judged to have been 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 21 stations were considered to have unaffected benthic assemblages (Table 16). The classifications of benthos as adversely affected or unaffected are carried forward into the sediment quality triad analyses.

All 14 assemblages dominated by *Aphelochaeta* spp. were considered to be adversely affected. One of the two *Rochefortia tumida/Nutricola lordi* assemblages was adversely affected, as were four of the 17 *Eudorella pacifica*/*Amphiodia* spp.-dominated assemblages.

Three stations in the *Eudorella pacifica*/*Amphiodia* spp. group with affected benthos had toxic sediment: one according to the amphipod survival test and two according to the echinoderm larval development test. The other two stations with toxic sediment according to the amphipod survival test were among the 14 *Aphelochaeta*-dominated stations (all with affected benthos). Neither of the two *Mediomastus* spp./*Galathowenia oculata* assemblages was considered to be adversely affected, but both had toxic sediment according to the echinoderm development test.

With one exception, the stations with adversely affected benthos were rather tightly clustered within Bellingham Bay and Semiahmoo Bay (nearshore Boundary Bay) (Figure 22). One station along the north shore of Birch Bay had an affected benthic assemblage.

Stations with unaffected benthic assemblages were located in the mouth of Boundary Bay, one toward the middle of Birch Bay, and several in the Samish Bay/Fidalgo Bay area.

Samples judged as having adversely affected benthos were quite different from those classified as unaffected (Figure 23, Table 16). Most of the benthic metrics indicated relatively large differences between the 19 affected stations and the 21 unaffected stations (Table 16).[19] Most of the metrics of diversity and abundance were substantially lower in the affected stations, compared to the unaffected stations. Total abundance and taxa richness were notably lower in affected stations. Median echinoderm abundance was 43 organisms/0.1 m^2 in the unaffected stations and 0 in the affected stations. Median arthropod abundance was about an order of magnitude lower in the affected stations than in the unaffected.

In a survey such as this, it is neither possible to assign causes to benthic conditions nor even to distinguish between natural and anthropogenic effects. The large percentage of stations (almost 50%) with adversely affected assemblages in the Strait of Georgia study region is in contrast to the small proportion of stations (10%) with mSQSq values above 0.1, which tend – over all of the Puget Sound area – to co-occur with negative conditions in the benthos. The condition of invertebrate samples in this 2006 survey may well reflect other variables not measured in the survey or included in the co-occurrence analysis of Long et al. (in review), such as hypoxia or contamination by chemicals for which protective standards have not yet been established.

Triad Synthesis (2006): A Compilation of Chemistry, Toxicity, and Benthos Data

The overall quality of the sediments at each station was estimated with a compilation of chemistry, toxicity and benthic information, using a multiple-line-of-evidence approach often called the Sediment Quality Triad (Long and Chapman, 1985; Bay and Weisberg, 2008, 2010).

[19] These differences are descriptive only. No inferences can be made (i.e., no hypothesis-testing can be done) from these comparisons because of the circularity of the distinctions—the benthic assemblages were characterized as adversely affected or unaffected based partly on these differences.

In this scheme, the data from each line of evidence were assigned equal weight. This scheme has been used throughout the Sound in previous studies and described in both an Ecology technical publication and peer-reviewed journal articles (Long et al., 2003, 2005).

Among the 40 stations, 19 were classified as having High sediment quality, with none of the elements of the triad indicating a degraded condition (Table 17, Figure 24). Sixteen stations were classified as having Intermediate/High sediment quality, with only one element of the triad indicating a degraded condition. Five stations were classified as having Intermediate/Degraded sediment quality, with two triad elements indicating degraded conditions. No stations were classified as having Degraded sediment quality, with all three elements of the triad indicating degraded conditions.

The spatial extent decreased as the degree of degradation increased: the proportions of the study area in each of the four sediment quality categories were: High, 52%; Intermediate/High, 33%; Intermediate/Degraded, 15%; and Degraded, 0% (Table 17).

None of the stations were degraded as a result of elevated chemistry. Two stations, both in outer Boundary Bay, were classified as having Intermediate/High quality sediment based on toxicity according to the echinoderm larval development test. The majority of stations with intermediate sediment quality were classified as such because of the condition of the benthos, 14 due to benthos alone and five due to both benthos and toxicity (Table 17).

The geographic patterns in sediment quality based on the SQTI closely followed the patterns observed with the benthic classifications alone. Stations classified as High quality occurred throughout Boundary Bay and in the Samish Bay/Padilla Bay/Fidalgo Bay area (Figure 24). The 16 stations classified as Intermediate/High quality occurred mostly in Bellingham Bay, with a few scattered throughout Boundary Bay. The five stations classified as Intermediate/Degraded were located in inner Boundary Bay, inner Bellingham Bay, and outer Bellingham Bay. There was a tendency toward sediment degradation closer to more-populated areas – Bellingham and Blaine – and higher-quality sediments away from anthropogenic influence.

Comparisons with 1997

In this section, we compare the results from the 2006 PSAMP Spatial survey to those from the PSAMP/NOAA survey within the same geographical boundaries. In the 1997 PSAMP/NOAA survey of Puget Sound (Long et al., 2003), 61 stations were sampled in the area now identified as the PSAMP (now PSEMP) Strait of Georgia region.

Graphical representations of the comparisons of the data for 1997 and 2006 are given in Appendices E (grain size), F (chemical parameters), and H (benthos). CDFs (weighted) and unweighted boxplots (censored where chemical nondetects were present) are shown side-by-side.

Data reassessments

In order for comparisons of the 1997 and 2006 results to be based on a consistent set of parameters, both the 2006 survey data and the PSAMP/NOAA data were reassessed. Hence some of the 2006 results differ slightly from those presented in the previous sections of this report, and some of the 1997 results differ from those presented in the original PSAMP/NOAA reports (Long et al., 1999, 2003). In particular:

- The condition of the 1997 benthos was reassessed, as part of the recent reassessment of all of the samples making up the PSAMP 1997-2003 baseline (Weakland et al., 2009). Benthos data from all PSAMP surveys from 1997 through 2008 were assessed together for consistency across studies (Weakland et al., 2009).
- The results of only the two toxicity tests common to both years (amphipod survival and sea urchin fertilization) were used.
- The amount of study area, originally estimated by planimeter for PSAMP/NOAA, was recalculated using GIS for the PSAMP (now PSEMP) Sediment Component redesign (Dutch et al., 2009). Therefore, the spatial extent estimates (km^2 or % of area) differ somewhat from those published in the original PSAMP/NOAA reports (Long et al., 1999, 2003).

Sampling designs

The sampling stations were not the same in the two surveys. An independent draw of target coordinates was performed for the 2006 survey. In both the 1997 and 2006 surveys there were stations in southern Boundary Bay, Birch Bay, Bellingham Bay, Samish Bay, and off Anacortes and Cherry Point (Figure 25). Padilla Bay and Drayton Harbor were sampled in 1997 but not in 2006, because no stations fell in those two embayments in the 2006 random sample draw.

The GRTS multidensity survey design employed for the PSEMP Spatial sediment monitoring program is designed to select sample sites so that patterns in the sample results will strongly resemble those in the population (Stevens and Olsen, 2004). The design is structured so that subpopulations are sampled with different intensities, according to their environmental importance (Stevens and Olsen, 2004).

The PSAMP/NOAA survey design, a stratified random design, was slightly different. The study area was divided into irregularly-shaped strata based on waterbody boundaries and on relatively homogeneous depth, salinity, sediment grain size, and general land use (Long et al., 2003). More and smaller strata were defined in urban bays and industrial harbors, where sediment contamination was known or expected to be high, and where heterogeneous conditions or gradients were expected. Fewer and larger strata were defined in areas far removed from point sources of contaminants, and where sediment contaminant levels were known or expected to be low. The individual strata were sampled with the same intensity (three samples per stratum), regardless of stratum size.

The harbor, basin, rural, urban, and passage subpopulation types within the PSEMP regions were based on the original PSAMP/NOAA strata. The sampling intensities of these five subpopulations (“strata”) were specified in the design of the PSAMP (now PSEMP) Spatial program to obtain estimates of those subpopulations for the entire Puget Sound (Dutch et al., 2009).

Thus, although the focus, and therefore the spatial placement of sampling sites, of the two surveys was slightly different, both survey designs were intended to provide estimates of overall population conditions, with sample results weighted according to the amount of area they represented. Again, as mentioned above, the overall patterns for the region appear to have changed substantially over the intervening decade, driven largely by changes in Bellingham and Boundary Bays.

Examination of subpopulations

In the CDF comparisons and in unweighted generalized Wilcoxon or Kruskal-Wallis comparisons, the 2006 results were quite different from the 1997 results for the majority of parameters, prompting concerns that the changes may have been a function of different survey design realizations, i.e., the change of sample design and location of new random stations. However, subsequent analyses conducted on two subpopulations (Figures 26, 27) revealed similar patterns. In most cases the results of the subpopulation analyses were the same as for the entire dataset.

This finding indicates that most of the differences between the 1997 and 2006 results for the entire region were real and not an artifact of the unequal geographic placement of the sample stations. It also suggests that results for the region were driven by conditions in Boundary and Bellingham Bays.

About 70% of the unweighted change/no-change indications for individual parameters for the sample area excluding Fidalgo and Padilla Bays (Figure 26) were the same as for the region as a whole; the remaining 30% were mostly matters of degree of significance. More than 85% of the weighted change indications, however, were consistent for the subpopulation and the entire sample area. There were no opposite indications (increase vs. decrease) in subpopulation and whole population for either weighted or unweighted comparisons.

For the sample area excluding the passage stratum (Figure 27), both weighted and unweighted change indications for individual parameters were consistent for about 75% of those for the region as a whole. Again, there were no indications of opposite trends.

Grain Size and TOC (1997 vs. 2006)

Although the overall mean, median, and minimum silt-clay content (percent fines) increased slightly between 1997 and 2006, the changes were not statistically significant (Table 18). The proportions of gravel, sand, silt, and clay also did not change significantly from 1997 to 2006. The spatial patterns of grain size in the 2006 survey were similar to those found in 1997 (Long et al., 2003).

The mean and median concentrations and the ranges in TOC values were very similar in the two surveys and were not statistically significantly different (Table 18).

Sediment Contamination (1997 vs. 2006)

The incidence of contamination, as defined by concentrations higher than one or more of the SQS values, decreased from 14.8% (9 of 61 stations) in 1997 to 0% in 2006 within the same area. The spatial extent of chemical contamination decreased from 9.8% of the study area in 1997 to 0% in 2006. Both decreases were statistically significant.

The minimum and maximum mean SQS quotient (mSQSq) values increased from 1997 to 2006, though the mean and median did not.

The co-occurrence analyses of Long et al. (in review) suggest that mSQSq values less than 0.10 do not represent harmful contaminant levels for resident benthic assemblages and laboratory toxicity test animals. In 1997, 46 of the 61 samples (75.4%) had mSQSq values < 0.1, compared with 36 of the 40 samples (90%) in 2006; the increase was not statistically significant at $\alpha = 0.05$.

Metals

Both weighted and unweighted comparisons indicated statistically significant increases in the concentrations of zinc (Table 18). Chromium, lead, and selenium concentrations increased according to the unweighted, censored analysis; likewise, silver and tin concentrations decreased. There were too few detected results in either one year or the other for those five metals to conduct the weighted CDF comparisons.[20] No statistically significant change was found in the concentrations of arsenic, copper, mercury, and nickel.

Although there were statistically significant differences between the years in the concentrations of certain metals, specifically lead, selenium, and silver, the concentrations were quite low, near the detection limits, and therefore the changes may not be practically or toxicologically significant.

In 1997, metals analyses were conducted with ICP-AES (EPA method 200.7) and graphite furnace atomic absorbance (GFAA; EPA methods 239.2 and 270.2), whereas ICP-MS (EPA method 200.8) was used in 2006. All are EPA-certified, comparable methods for quantitating metals.

For some metals, e.g., lead, the ICP-MS is more sensitive close to the detection limit, whereas the graphite furnace method is more sensitive for other metals, such as selenium (Momohara, personal communication, 2010). The degree of sensitivity is reflected in the degree of accuracy and precision obtained close to the lower limit of detection, and that is demonstrated in the side-by-side boxplots in Appendix F. For example, there were both more nondetects and lower detection limits for silver in 2006 (ICP-MS) than in 1997 (GFAA). On the other hand, there were both lower detection limits and more detects (i.e., fewer nondetects) for selenium in 1997 (GFAA) than in 2006 (ICP-MS).

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[20] As indicated in the Methods section, the CDF-comparison procedures do not use censoring to handle nondetects, and were not used when more than 10% of the concentrations were nondetect.

Mercury

Because of the history of pulp mill discharges of mercury (Appendix B), studies have been conducted to assess mercury concentrations in Bellingham Bay, for several decades. Bothner (1973) measured mercury concentrations of 30 ppm or higher in surface sediments close to the pulp mill outfall. In sediment cores, mercury concentrations within and near Whatcom Waterway peaked at depths of 10-20 cm, corresponding to the years of peak discharge of mercury directly into the waterway (1965-1970) (Bothner, 1973). Mercury concentrations in the early 1970s diminished rapidly with increasing distance and with time, to 1-3 ppm (Bothner, 1973). Between 1978 and 1981, Malins et al. (1982) found mercury concentrations of 1.9 and 0.870 ppm in two surficial sediment samples from Whatcom Waterway.

In the PSAMP/NOAA survey of 1997, concentrations of mercury in 21 samples from Bellingham Bay averaged 0.23 ppm. In this 2006 survey, the mean concentration of mercury in 15 samples from that bay was 0.14 ppm.

Although the sampling designs and the analytical methods differed among the surveys, the picture emerges that the concentrations of mercury in Bellingham Bay surface sediments have declined over the past four decades. Likely mechanisms for decreasing mercury in surface sediments include burial by cleaner sediment, erosion/resuspension, advection by gas bubbles, biotransformation, and bioturbation (Bothner, 1973), and site cleanup (Appendix B).

PAHs

Bay-wide concentrations increased, based on the weighted CDF comparisons, for nine of 12 LPAH compounds[21] and Total LPAH[13]. The unweighted median comparisons indicated increases in seven, possibly eight, of 14 LPAHs (Table 18). No LPAHs decreased, according to any of the statistical analyses. All of the substituted naphthalenes increased in concentration.

While the highest LPAH concentrations were found at only a few stations representing a small amount of area, concentrations at most stations were well below SQS values. LPAH concentrations were generally higher in 2006 than in 1997.

Among HPAH compounds, concentrations of perylene increased and those of indeno(1,2,3-c,d)pyrene decreased, according to both the weighted and unweighted analyses (Table 18). The concentrations of all other HPAHs in the suite measured by the lab and of Total HPAH[13] remained unchanged.

The mSQSq for LPAHs increased, but the mSQSq for HPAHs was unchanged (Table 18).

SQS values for PAH compounds (indeed, for most of the organic compounds for which SQS have been determined) are based on organic carbon-normalization (Ecology, 1995). Because TOC levels were unchanged from 1997 to 2006, the changes in PAH SQS quotients therefore reflect changes in PAH sediment concentrations.

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[21] The 1997 and 2006 CDFs of acenaphthene and naphthalene were not compared due to > 10% nondetects in one year or the other.

Slightly different methods were used for PAH analyses in 1997 and 2006. In both cases, selected ion monitoring (SIM) analysis was used. The differences are that in 1997 only one isotope was added, and that isotope was not used to recovery-correct the concentration of the analytes; whereas in 2006 (indeed, from 1998 on), the lab added deuterated isotopes of most of the PAHs to the samples prior to extraction so that their recovery could then be used to correct for the amount of the associated analyte that was extracted. These differences likely contributed to the variability in the results of the lighter-weight PAHs (Westerlund, personal communication, 2010).

Other organic compounds

Among the other organic compounds, concentrations of dibenzofuran, both weighted by area and unweighted, increased (Table 18). All other organic compounds on the list of analytes for this survey had too few detects to conduct comparison analyses.

Sediment Toxicity (1997 vs. 2006)

In the 1997-1999 PSAMP/NOAA baseline survey, 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 2006 survey, three types of toxicity tests were performed, two of which (sea urchin fertilization success and amphipod survival) were also performed in 1997.

Amphipod Survival in Solid Phase Sediments

Both a different lab and a different test species were used for the amphipod survival tests in 1997 and 2006. For the PSAMP/NOAA survey, the amphipod survival tests were conducted by Science Applications International Corporation (SAIC) using *Ampelisca abdita*, the same species used nationwide by both NOAA and EPA in numerous other estuarine sediment quality surveys. In particular, *A. abdita* was used for consistency with the NOAA National Status and Trends (NS&T) surveys, of which the Puget Sound survey (i.e., PSAMP/NOAA) was one. In 2006, Vizon SciTec Inc. (later named CANTEST Ltd. and now Maxxam Analytics) conducted the amphipod survival tests with *Eohaustorius estuarius*.

Ampelisca abdita is a native species in the estuaries of the northern Atlantic coast and is an invasive species in San Francisco Bay (ASTM, 2004a; 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 in the PSAMP/NOAA survey (Long et al., 2003). Therefore, Ecology switched to using *Eohaustorius estuarius*, a native of Pacific Northwest estuaries, as a test organism for the subsequent PSAMP (now PSEMP) surveys.

The amphipod survival test with *A. abdita* in 1997 indicated that no stations in the Strait of Georgia region were highly toxic. Hence, both the incidence and spatial extent of toxicity to amphipods was 0%. In 2006, amphipod survival tests using *E. estuarius* as a test organism indicated that three stations, representing 5.5% of the same study area, were highly toxic. Although the increase in incidence was not statistically significant, the increase in spatial extent was significant.

Some of the difference in the incidence of toxicity in these tests may have been influenced by the change in test species between the 1997 and 2006 surveys. Ecology's experience with both species has shown that *A. abdita* is not as sensitive as *E. estuarius*. Some empirical side-by-side comparison data from California provide evidence of this difference (Anderson et al., 2008).

Sea Urchin Fertilization in Pore Water

In the 1997 survey, highly significant toxicity was recorded with this test in 100% pore water concentrations in five of the 61 samples (8%) from the Strait of Georgia region, representing 2.5% of the study area. No samples in 2006 had significant toxicity with this test. The decreases in incidence and spatial extent were not statistically significant.

The USGS laboratory and the test species (*Strongylocentrotus purpuratus*) for the sea urchin fertilization sediment pore water toxicity test in 2006 were the same as for the 1997 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 urchin fertilization test has been performed by the same USGS lab, with very low within-sample variability, for many years[22]. In 2003, the protocols for this test were changed slightly to better adapt it to the natural range in pH in the samples that was non-toxic to the urchin gametes. 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 (USGS, 2003). Side-by-side comparison tests (applying both protocols to the same samples) and comparison of the EC50 values for PSAMP 2003 and 2004 samples indicated that the results generated were comparable (USGS, 2005).

Condition of the Benthos (1997 vs. 2006)

Community Composition

Prior to comparison, infauna data from 1997 and 2006 were standardized between years to account for changes in taxonomy that occurred in the intervening years. Of the 595 taxa in the combined-year species list, 236 species (40%) were found in both years; about 180 (30%) were unique to each year. Because the data were standardized between years, the same methods and equipment were used for collection in both years, and, for the most part, the same taxonomists

[22] USGS closed the Marine Ecotoxicology lab in 2011.

performed the identifications and quality assurance/quality control, the large number of species differences observed in this survey is not merely nomenclatural.

Only 40% of the taxa identified in 1997 and 2006 were found in both years. This raises the question of whether the differences reflect the different sites sampled in the two years.

Two individual stations sampled off Point Roberts in 2006, Stations 309 and 437, appear to be exceptions. These stations represented a different habitat from all the other stations from both 1997 and 2006, with high gravel content and shell hash. These two stations accounted for a total of 88 (49%) of the unique taxa for 2006, most of which were hard-substrate taxa that are not usually encountered during PSEMP sampling.

Many of the taxa unique to either 1997 or 2006 were found infrequently and in low numbers, and have been infrequently found in Puget Sound overall. Forty percent of the taxa that were unique to one year or the other occurred as a single individual at a single station. Only nine taxa occurred at 10 or more stations; 97% of the unique taxa occurred at fewer than 10 stations.

Furthermore, the 359 taxa (60% of the combined-year species list) which occurred only in one year or the other account for only a small fraction of the total abundance in the two years: 3.8% in 1997 and 8.5% in 2006. In other words, the taxa common to both years accounted for 96.2% of the total abundance in 1997 and 91.5% in 2006. The small contribution of the unique species to the overall picture is demonstrated in the fact that the results of analyses conducted on only the taxa common to both years were almost identical to those conducted on all taxa (Figure 28).

Taxonomic identifications were standardized between years. Most of the taxa that occurred in only one year or the other occurred infrequently and in very low numbers. Also, variations in habitat contributed to a considerable percentage of the taxa differences between years (gravel at stations 309 and 437). Thus, it appears that the different species collected in 1997 and 2006 simply represent natural variability, due in some part to different microhabitats in the sampling area.

Benthic Indices

Tests of differences in benthic indices between 1996 and 2007 indicated that total benthic invertebrate abundance, taxa richness, and abundances of annelids, arthropods, and echinoderms all decreased in both weighted and unweighted analyses (Table 19). Median abundance (unweighted) of miscellaneous invertebrate taxa also decreased, while unweighted median abundance of molluscs appeared to decrease (significant only at $\alpha = 0.10$).

Pielou’s Evenness and Swartz’ Dominance Index (SDI) both increased, according to the weighted CDF analyses, though the unweighted medians of those indices did not change significantly (Table 19, Figure 29). However, SDI standardized by taxa richness (SDISTD) did increase significantly, according to both weighted and unweighted analyses.

Mean total abundance decreased substantially from 1355 (median: 856) in 1997 to 530 (median: 412) in 2006 (Table 20). The decreases in total abundance appear to occur in all of the major taxonomic groups. Mean numbers of annelids were 628 in 1997 versus 265 in 2006;

387 arthropods versus 78; 220 molluscs versus 144; 102 echinoderms versus 34; and 14 miscellaneous taxa versus 8. The CDFs shifted significantly lower for annelid, arthropod, echinoderm, and total abundance, indicating larger proportions of area with smaller abundance values (Table 19).

Mean taxa richness was 51 in 1997 versus 46 in 2006; median richness decreased from 46 taxa in 1997 to 37.5 in 2006 (Table 20). The taxa richness CDF changed shape. The proportion of area with lower taxa richness (below about 40 taxa) increased from 1997 to 2006, but the highest values of taxa richness also increased, from just over 100 taxa in 1997 to almost 200 in 2006 (Figure 29). However, the high taxa richness in 2006 occurred only at Stations 309 and 437, two stations that had other unusual characteristics. If the two 2006 stations with unusually high taxa richness are excluded from the analysis, the highest taxa richness in 2006 was 89 and mean taxa richness was 40.

Evenness and dominance remained about the same between 1997 and 2006. Mean and median evenness were both 0.63 in 1997 versus 0.68 and 0.72, respectively, in 2006 (Table 20). Mean SDI was 8 taxa (median, 6) in 1997 and 8.75 (median, 7.5) in 2006. When weighted by area represented, however, these two metrics increased statistically significantly. The CDFs for evenness and SDI shifted significantly higher (Figure 29), indicating greater equitability and diversity in species distribution region-wide.

The causes of the changes in numbers and diversity of organisms between 1997 and 2006 are unknown. A host of physical, chemical, and biological factors, both natural and anthropogenic, may be responsible. Further study is needed to determine the specific factors contributing to these differences between years.

Adversely Affected Benthos

Throughout the sampled area, both incidence and spatial extent of adversely affected benthos increased significantly from 1997 to 2006. Nineteen of 40 stations (47.5%), representing about 44% of the study area, had adversely affected benthos in 2006, compared to 10 of 61 stations (16.4%) and about 15% of area in 1997 (Table 21).

The geographic patterns of adversely affected benthos remained the same (Figure 30), but there were many more instances of affected benthos in 2006 in those locations than in 1997.

Triad (1997 vs. 2006)

To reiterate, for the comparison with 1997, the toxicity element of the SQTI for 2006 incorporates the results of only the amphipod survival and sea urchin fertilization tests. Therefore, the triad results in this section differ from the triad results for 2006 alone, which incorporated the results of three types of toxicity tests (amphipod survival, urchin fertilization, and sand dollar embryo development).

The incidence (percent of stations) and spatial extent (percent of area) were similar to each other within each SQTI category (Table 21). This indicates that conditions did not vary greatly between portions of the study area which have different station weights, within each of the two time periods being compared.

There were no Degraded quality sediments in both years, and both the incidence and spatial extent of Intermediate/Degraded quality sediments remained almost the same from 1997 to 2006. However, both the incidence and spatial extent of sediment in the High sediment quality category decreased by 15-20 percentage points, with corresponding increase in the Intermediate/High category (Table 21; Figure 31).

The primary reason for those shifts was the large increase in incidence and spatial extent of adversely affected benthos (Table 21). Slightly offsetting the changes in the benthos was a decrease in the sediment contamination above the SQS.

Comparisons with Other Puget Sound Regions

Tables 22-25 compare the contamination, toxicity, benthic conditions, and triad results for the eight monitoring regions of Puget Sound and the entire sound. Results differ slightly from those in Long et al. (2003) because (1) the entire set of data from the PSAMP Sediment Component Spatial Monitoring from 1997 through 2007 was reassessed for consistency (Weakland et al., 2009) and (2) because the PSAMP/NOAA survey (1997-1999) covered only six of the now eight PSEMP regions. At time of publication of this report, five regions (Hood Canal, Strait of Georgia, Whidbey Basin, Central Puget Sound, and South Sound) have been surveyed twice. The whole-sound estimates are from the period 1997-2003. When the remaining regions are resampled over the coming few years, updated condition estimates will be available for the entire Sound.

Sediment Contamination

The Manchester Environmental Laboratory conducted the sediment chemistry analyses for all of the PSAMP sediment surveys[23] throughout Puget Sound. Most of the analytical methods used have remained the same over the years. A few modifications have been made to improve precision and reliability.

The concentrations of TOC measured in the Strait of Georgia region are typical for Puget Sound. TOC concentrations can differ considerably from place to place in Puget Sound (Long et al., 2003). Generally, TOC concentrations in Puget Sound sediments are lowest where the tidal bottom currents are strongest (e.g., in places such as Admiralty Inlet, Guemes Channel, Tacoma Narrows).

There were some distinct differences in both the percent incidence and the spatial extent of contamination among the eight regions. Overall, 15.7% of stations and 4.8% of the Puget Sound area had contaminant concentrations higher than one or more SQS (Table 22). Regions that included industrialized harbors had higher incidences of contamination, though not larger spatial extents of contamination, than regions that were more rural.

The areas in which contamination was greatest included the industrialized harbors and urban bays near the cities of Seattle, Tacoma, and Bremerton in the Central Region, Everett in the

[23] And is anticipated to do so for future PSEMP surveys.

Whidbey Basin Region, and Olympia in the South Puget Sound Region. Sediments were most degraded in inner Everett Harbor in 1997 (Long et al., 2003). In those surveys, the incidence of contamination usually exceeded the spatial extent because of the relatively small sizes of the contaminated strata.

Sediments analyzed from the industrialized harbors during 1997-1999 often were contaminated with mixtures of trace metals (e.g., copper, mercury, silver), PAHs, and chlorinated organic compounds, including PCBs. These mixtures were similar to those reported from the NOAA MESA surveys of the early 1980s (Malins et al., 1982).

However, the nature of the mixtures of potential toxicants in the urban bays and harbors differed from place to place as a function of the nature of the sources (Long et al., 2003; Malins et al., 1982). For example, PAHs were chemicals of greatest concern in Everett Harbor. Elevated mercury concentrations were most frequently found in Sinclair Inlet. PAHs, PCBs, and mercury contaminated much of Elliott Bay. Copper, mercury, PAHs, PCBs, and hexachlorobenzene contaminated some samples from the Commencement Bay waterways at Tacoma. In the southern Strait of Georgia region in 1997, there was no distinctive chemical "fingerprint", other than the presence of mercury in Bellingham Bay (Long et al., 2003) due primarily to historic pulp mill discharges.

Although 14.8% of stations and 9.8% of area in the Strait of Georgia region in 1997 were contaminated, both the incidence and spatial extent of contamination were 0% in 2006. A similar reduction in chemical contamination was found in comparisons between the 1999 and 2004 surveys in Hood Canal (Table 22; Long et al., 2010).

Recent bay-wide sediment surveys in Elliott and Commencement Bays as part of the Urban Waters Initiative have demonstrated reductions in contamination by some metals, PAHs, and PCBs compared to a decade earlier. These changes are presumed to have resulted from cleanups and source control, as well as burial by cleaner sediment (Partridge et al., 2009, 2010). The same studies indicated no changes or increases in contamination by other metals, PAHs, and phthalates.

Sediment Toxicity

Sea Urchin Tests

The USGS lab in Texas performed all of the sea urchin fertilization tests with *S. purpuratus* in all of the PSAMP surveys.

The outcome for the 2006 survey of the Strait of Georgia ranks as the least toxic among the PSEMP regions, including the 2002-2003 survey in the San Juan Islands region (Table 23). In 1997, 8.2% of the samples and 2.5% of the region were toxic in tests of 100% pore water, whereas in 2006, none (0%) of the samples were toxic in the same kind of test. In contrast, the Sound-wide baseline for 1997-2003 indicated an incidence of 10.2% and a spatial extent of 4.5%. The maximum incidence was 25.6%, in Whidbey Basin in 1997, and the maximum spatial extent was 17.7%, in Hood Canal in 2004.

Amphipod Tests

Over the years, different analytical labs have performed the amphipod survival toxicity tests, albeit with the same protocols. The tests performed for the PSAMP/NOAA baseline surveys of 1997-1999 used the species *Ampelisca abdita*. A more sensitive species, *Eohaustorius estuarius*, has been used in the amphipod toxicity tests for the PSAMP (now PSEMP) surveys since 2002.

In the 2006 survey of the Strait of Georgia region, samples from 7.5% of stations, representing about 5.5% of the area, were classified as toxic in the amphipod survival tests with *E. estuarius*. In contrast, among the 300 samples tested during the PSAMP/NOAA surveys in 1997-99 with *A. abdita*, only one from the Central region was classified as toxic in the amphipod survival tests, for an incidence of 0.3% and the spatial extent of 0.05% of the entire Puget Sound (Table 23). None were classified as toxic from the southern Strait of Georgia, Whidbey Basin, Admiralty Inlet, South Sound, or Hood Canal regions.

In the 2002-2003 surveys of the San Juan Islands, eastern Strait of Juan de Fuca, and Admiralty Inlet, one sample among 90 tested with *E. estuarius* was toxic, for an incidence of 1.1% (Long et al., 2008). The spatial extent of toxicity among those three regions combined was also 1.1%. The incidence of toxicity for the San Juan Islands region alone was 3.3%, while it was 0% in both the eastern Strait of Juan de Fuca, and Admiralty Inlet regions.

Condition of the Benthos

The same collection procedures and many of the same taxonomists have been used since the PSAMP (now PSEMP) program began in 1989. Ecology updates species identifications in the data across all years as taxonomic names change. The benthic assemblage data for all of the PSAMP sediment samples from 1997 through 2008 were assessed together in 2009 (Weakland et al., 2009) to assure that the best professional judgment of the invertebrate ecologists was applied consistently to all years. Therefore, the benthic data are internally consistent and comparable.

The incidence and spatial extent of adversely affected benthos in the Strait of Georgia region in 1997 were similar to those in Admiralty Inlet (1998-2003), and, at 16% and 15%, respectively, were second-lowest in the PSAMP Puget Sound baseline surveys (1999-2003) (Table 24). However, the condition of the Strait of Georgia benthos in 2006 was more similar to that of the South Sound region in 1999, with over 40% of the stations and area having affected benthos.

Both the percent of stations and the percent of area with adversely affected benthos have increased in the results to date from PSEMP regions that have been sampled more than once (Table 24) and in urban bays (Elliott Bay, Commencement Bay) that have been resampled (Partridge et al., 2009, 2010). In the urban bays, the condition of the benthos improved in previously highly contaminated and toxic industrial areas that had undergone remediation, but the benthos showed deterioration in outer areas of the bays that had been uncontaminated previously (Partridge et al., 2009, 2010).

The cause(s) of the changes in the indices of the benthic assemblages and in the incidence of adversely affected benthos cannot be determined in these surveys. Many other variables are not currently being measured, such as dissolved oxygen, pH, and contaminants of emerging concern.

There may be additive or multiplicative effects among variables. Other possible mechanisms include long-term natural cycles in climate, oceanography, and biology that exceed the span of our sampling cycles.

Sediment Quality Triad Index

The triad approach was initially developed with data from Puget Sound (Long and Chapman, 1985). Since 1997, it has been applied throughout all of the PSEMP monitoring regions. The data from all of the PSAMP sediment surveys were assessed in 2009 to ensure consistency in triad elements and application (Weakland et al., 2009). Because only the amphipod survival and sea urchin fertilization tests were conducted for all regions, the toxicity element of the triad results in this section is based on only those two tests.

In the 2006 survey of the Strait of Georgia region, none of the stations were classified as degraded, and the incidence and spatial extent of high quality sediments were relatively high at 71% and 76%, respectively (Table 25). Similar results were recorded in Admiralty Inlet. In the Whidbey Basin, central Puget Sound, and South Sound regions of Puget Sound, which include urban areas, both the incidence and spatial extent of degradation were higher. The spatial extent of degradation always was lower than the incidence. Although this pattern reflects the relatively small size of the areas most affected, those areas tend to be estuarine areas critically important for both the organisms inhabiting Puget Sound (e.g., nursery areas for juvenile salmon) and human activity (e.g., recreation, commerce).

Conclusions

The Strait of Georgia region is relatively uncontaminated with the metals and organics currently being monitored. Exceedances of the Washington State Sediment Quality Standards (SQS) declined from 1997 to 2006.

Likewise, the sediments in the Strait of Georgia region are largely non-toxic to benthic invertebrates in controlled laboratory tests. Comparisons of toxicity results in 2006 to those in 1997 gave mixed results.

Of concern are the large increases in incidence and spatial extent of adversely affected benthos from 1997 to 2006. Invertebrate abundance decreased significantly, as did the numbers of taxa found. On the other hand, two measures of diversity increased. Although the species lists for the two years had substantial non-overlap, the common species accounted for well over 90% of the abundance, and the non-overlapping species likely represent natural variability. However, the reasons for the decline in benthic health are not known.

The trends in benthos seem not to coincide with trends in the environmental parameters that were measured; therefore, other factors must be important. The benthic assemblages are affected by complex interplays of natural and anthropogenic variables. Further study is required to explore reasons for the deterioration in benthic health and to determine what other environmental parameters (e.g., near-bottom dissolved oxygen, pH, newer contaminants) should be added to the PSEMP sediment monitoring.

When the chemistry, toxicity, and benthos elements of the triad are combined into the Sediment Quality Triad Index (SQTI), it is evident that in the Strait of Georgia region in 2006, the SQTI results were driven largely by the condition of the benthos. Furthermore, conditions in Bellingham Bay and Boundary Bay dominated the conditions of the entire region. The spatial extent of high-quality sediment decreased from 76% of the area of the region in 1997 to 56% in 2006, with a concomitant increase in intermediate-quality sediment. This change was driven largely by the increased incidence and spatial extent of adversely affected benthos.

For the triad elements individually and collectively, there was a tendency toward sediment degradation closer to more-populated areas (Bellingham and Blaine) and higher-quality sediments away from anthropogenic influence.

Compared to the other PSEMP Puget Sound monitoring regions, the sediment contamination and toxicity in the Strait of Georgia region are relatively low and similar to those in non-urban (less-contaminated) areas; the incidence and spatial extent of adversely affected benthos are in the middle of the range; and the SQTI results are similar to those in South Sound and for the sound as a whole.

Some of the trends seen in this survey (improvements in supra-SQS-level contamination, deterioration in condition of benthic communities) have been seen in other recent surveys within Puget Sound. The Department of Ecology will continue to monitor sediment quality over time to determine if these trends persist.

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Figures

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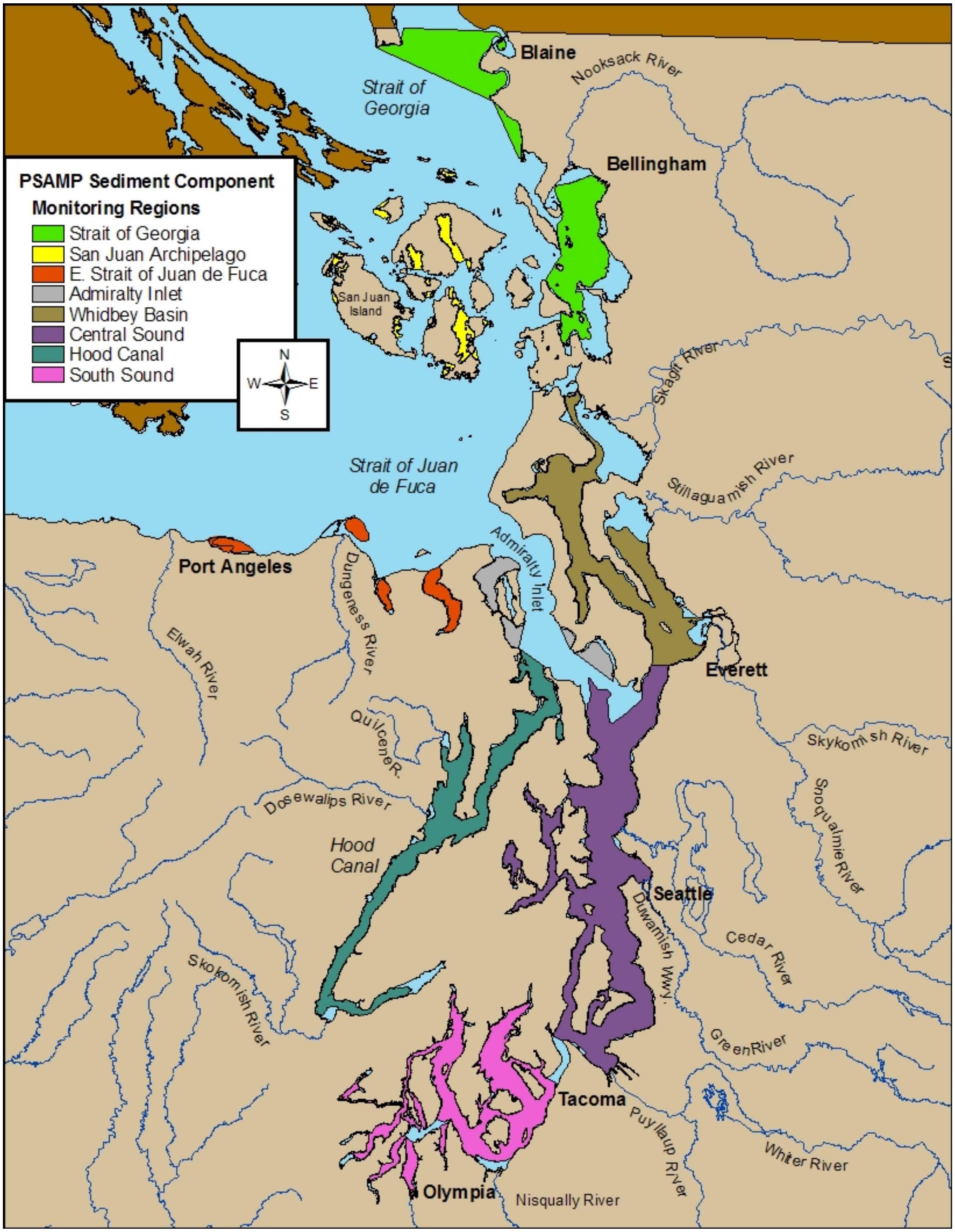


Figure 1. Eight sediment monitoring regions defined for the PSAMP (now PSEMP) Sediment Component.

The Strait of Georgia region is the subject of this report.

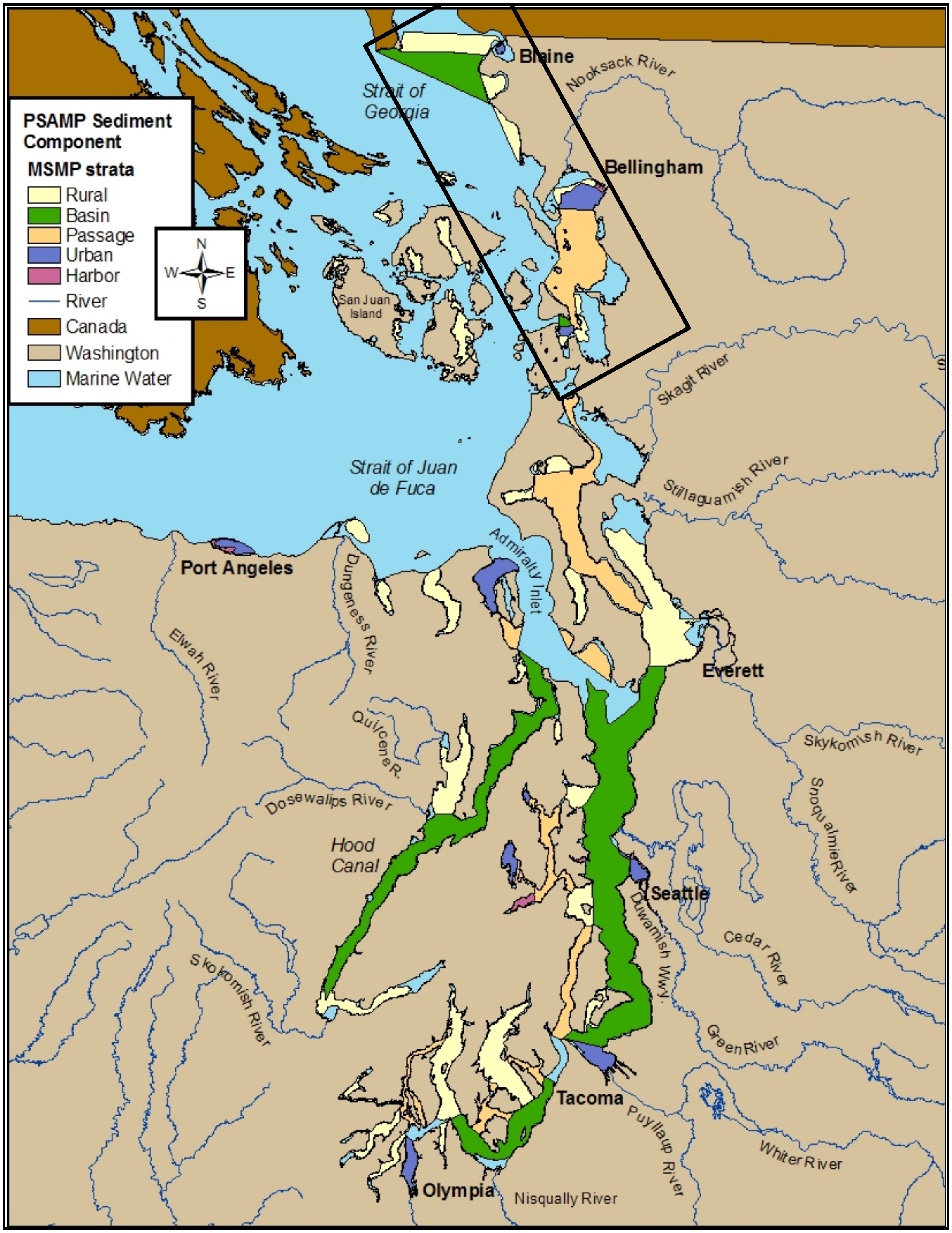


Figure 2. Five sediment monitoring strata defined for the PSAMP (now PSEMP) Sediment Component.

The outlined area is the subject of this report.

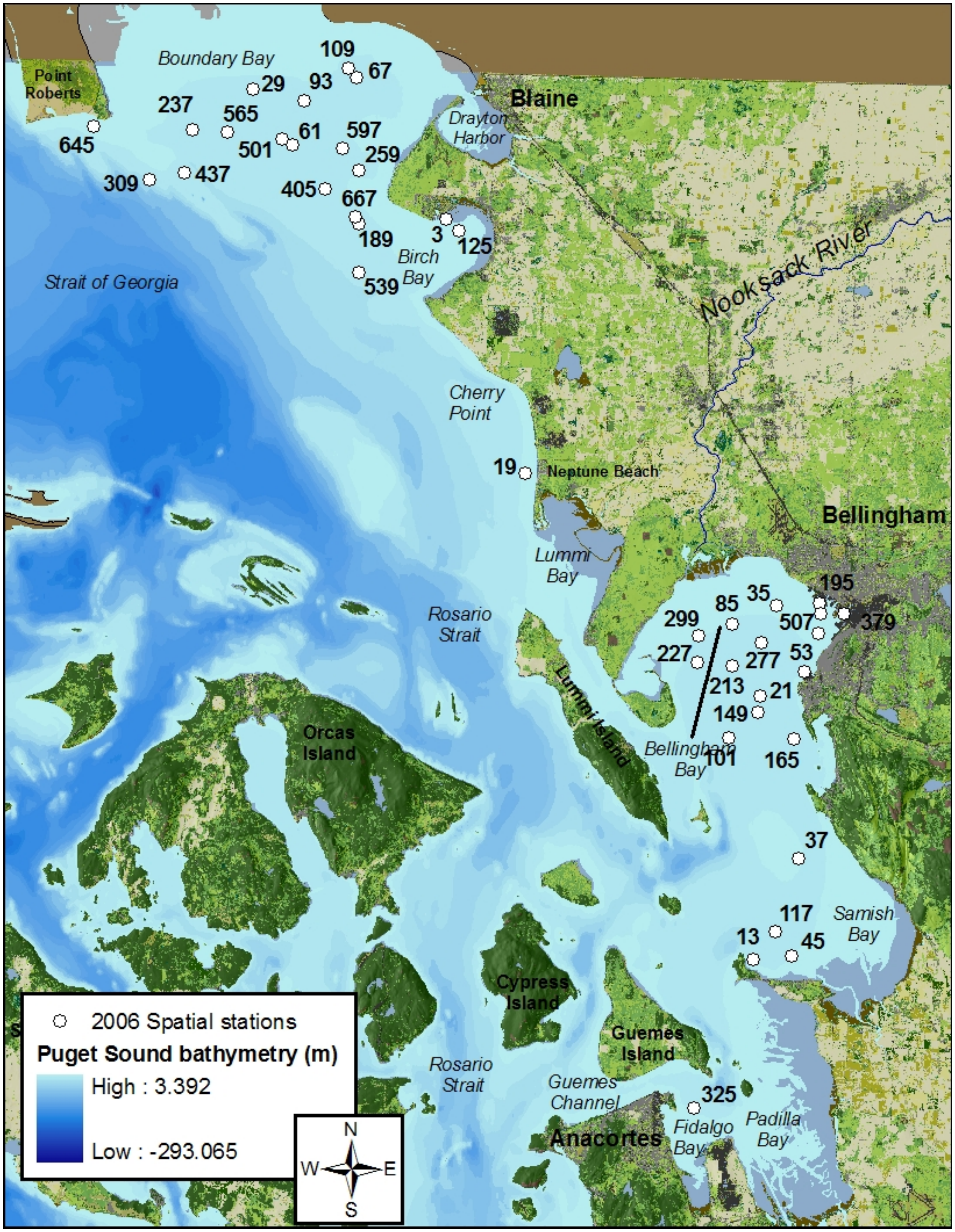


Figure 3. Station locations for the 40 stations sampled in the 2006 PSAMP sediment survey.

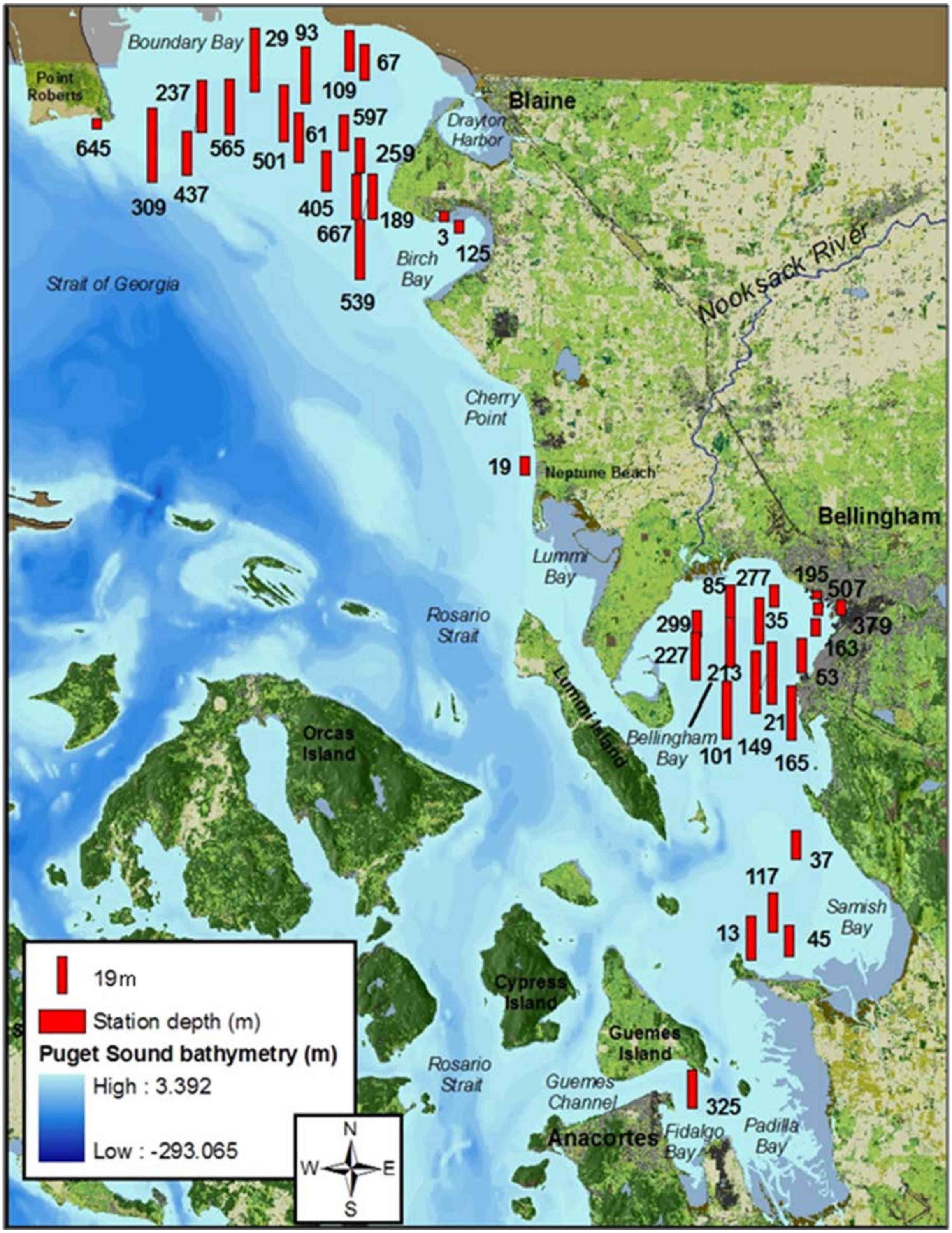


Figure 4. Water depths at the 40 stations sampled in the 2006 PSAMP sediment survey. *The numbers on the map are the station identifications.*

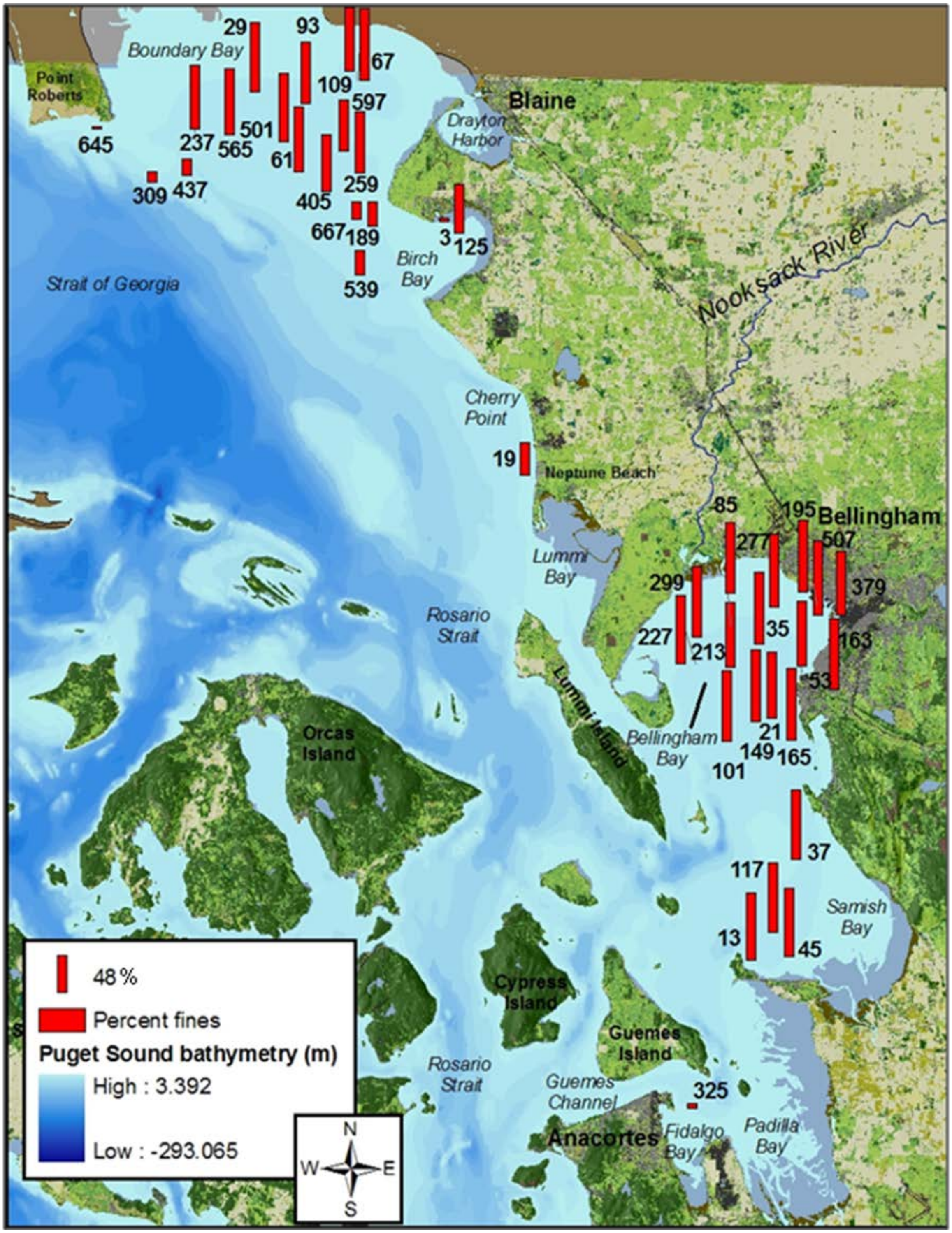


Figure 5. Spatial patterns in percent fines (silt + clay) in the 2006 PSAMP sediment survey. *The numbers on the map are the station identifications.*

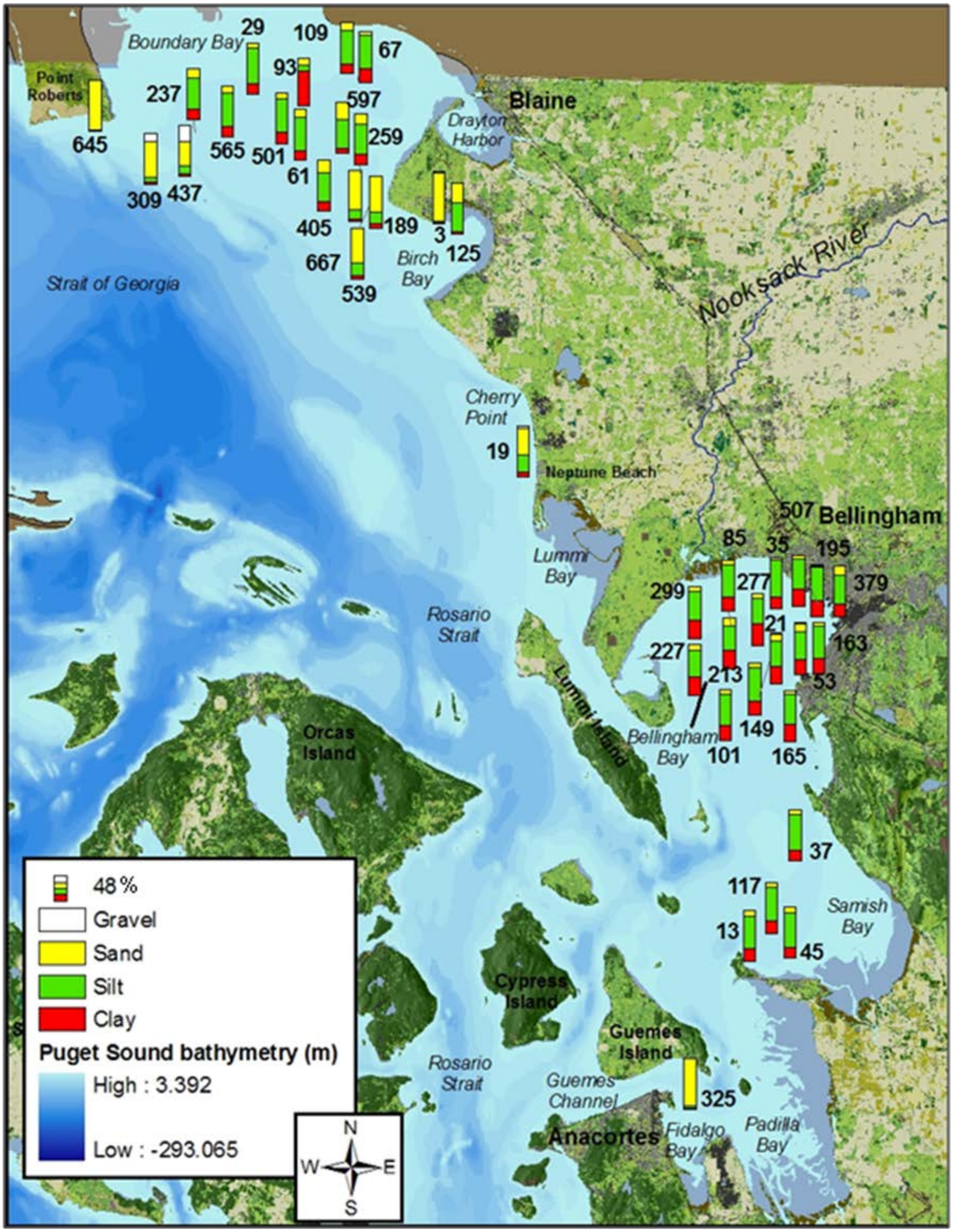


Figure 6. Spatial patterns in four particle size classes (percent gravel, sand, silt, and clay) in the 2006 PSAMP sediment survey.

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

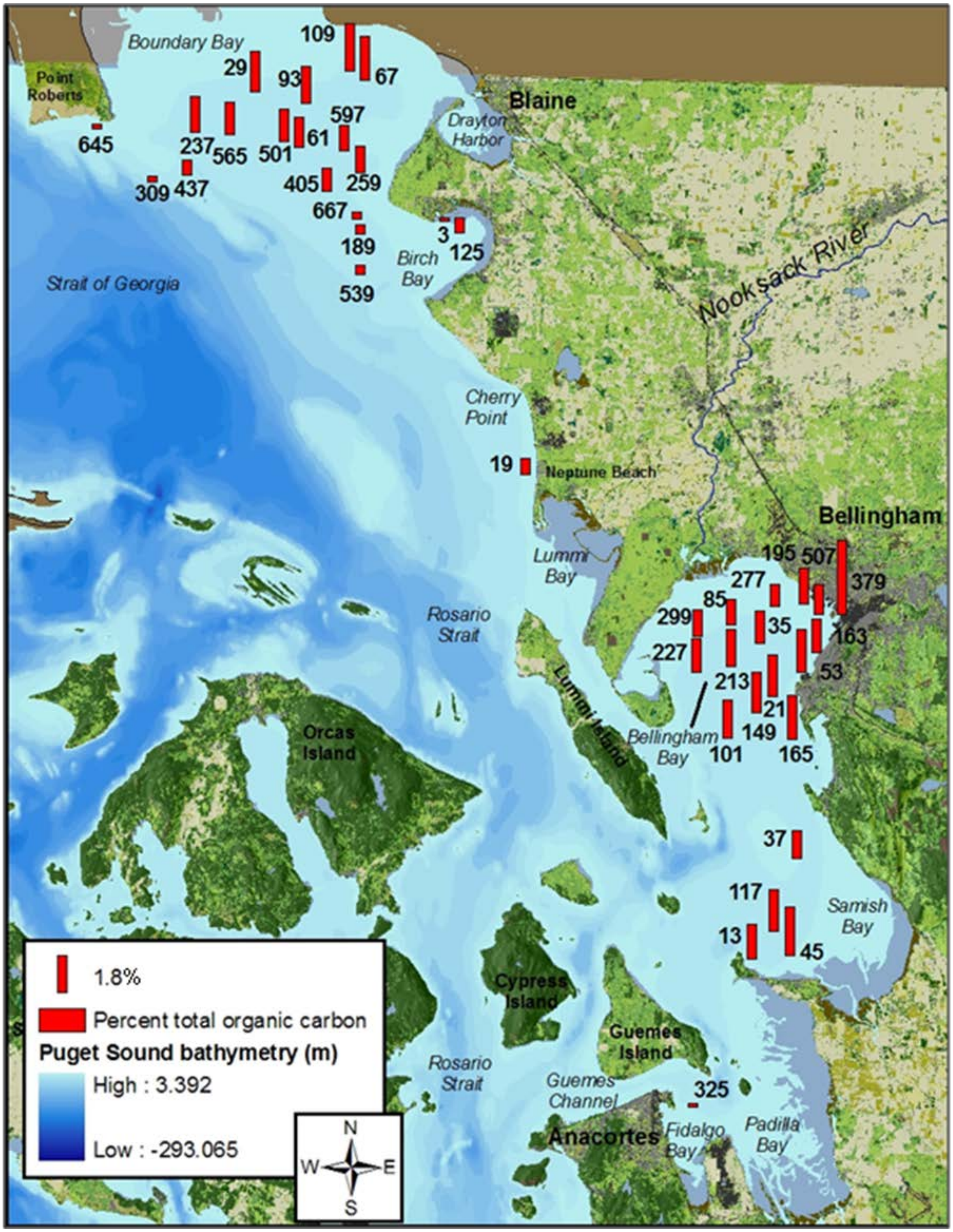


Figure 7. Spatial patterns in total organic carbon (% by weight) in the 2006 PSAMP sediment survey.

The numbers on the map are the station identifications.

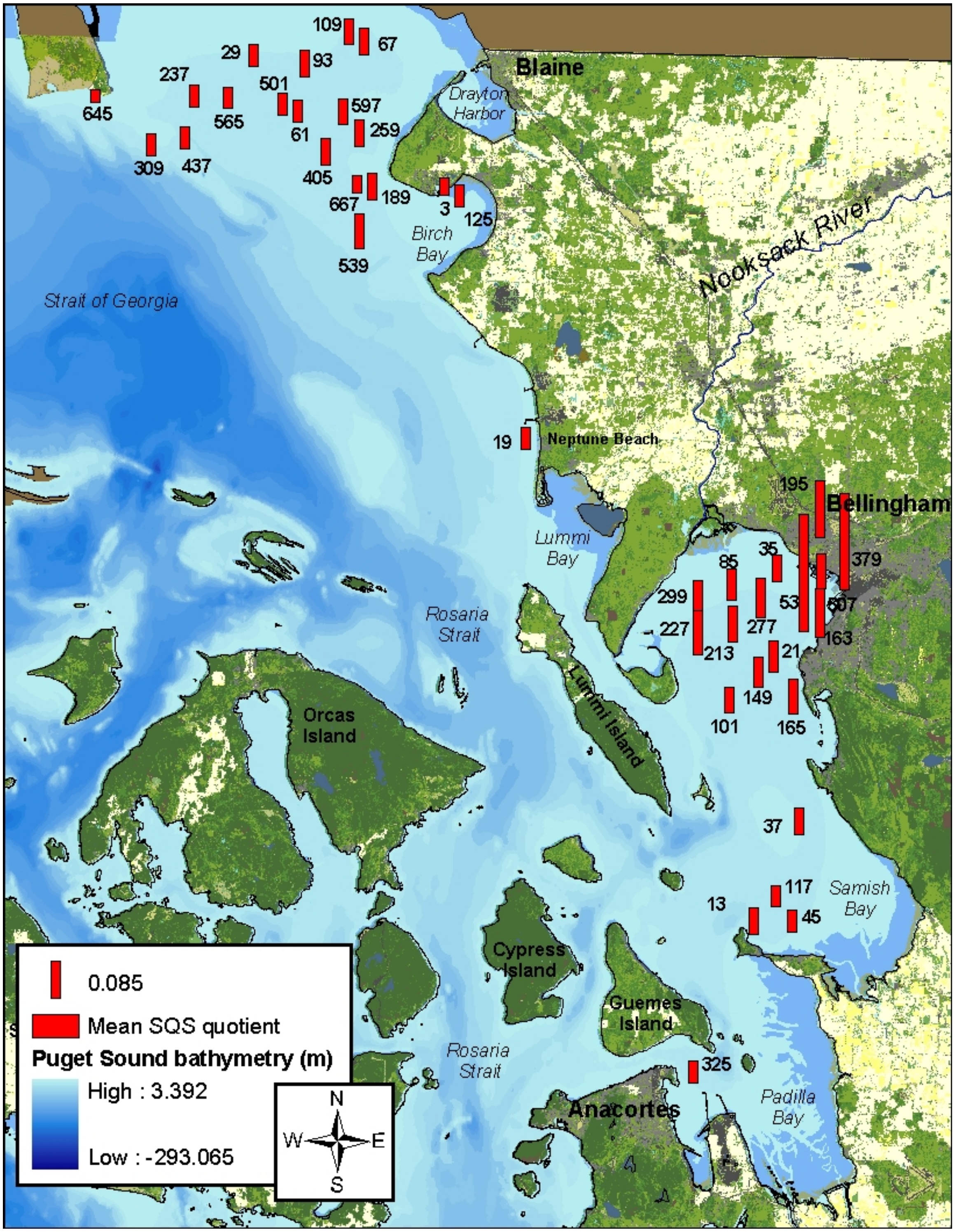


Figure 8. Spatial patterns in Mean SQS Quotients in the 2006 PSAMP sediment survey. *The numbers on the map are the station identifications.*

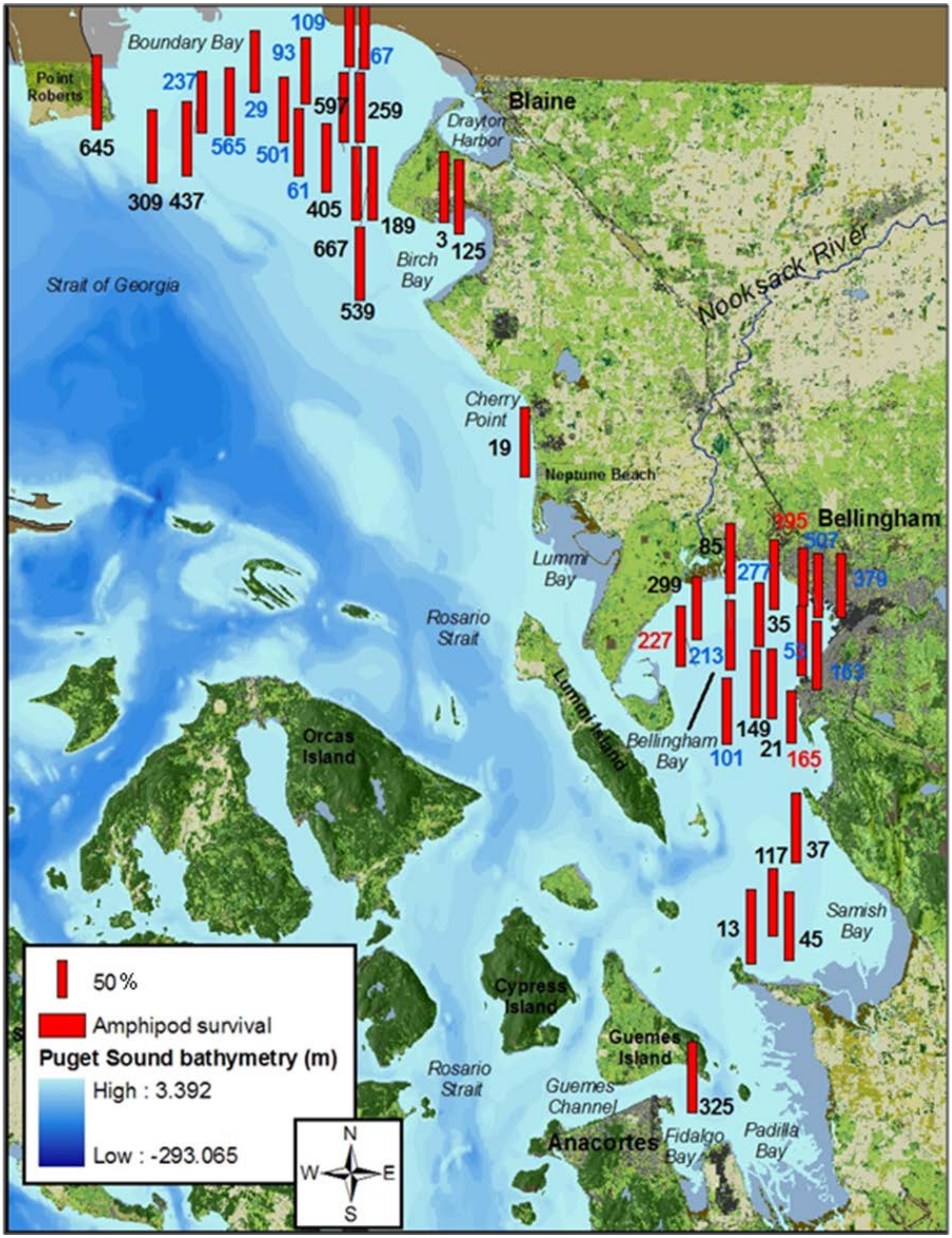


Figure 9. Spatial patterns in sediment toxicity determined with the amphipod *Eohaustorius estuarius* (control-corrected % survival) in the 2006 PSAMP sediment survey.

The numbers on the map are the station identifications. Blue station numbers indicate results statistically significant (t-test, p-value <0.05). Red station numbers indicate results statistically significant (t-test, p-value <0.05) and mean survival<80% of control.

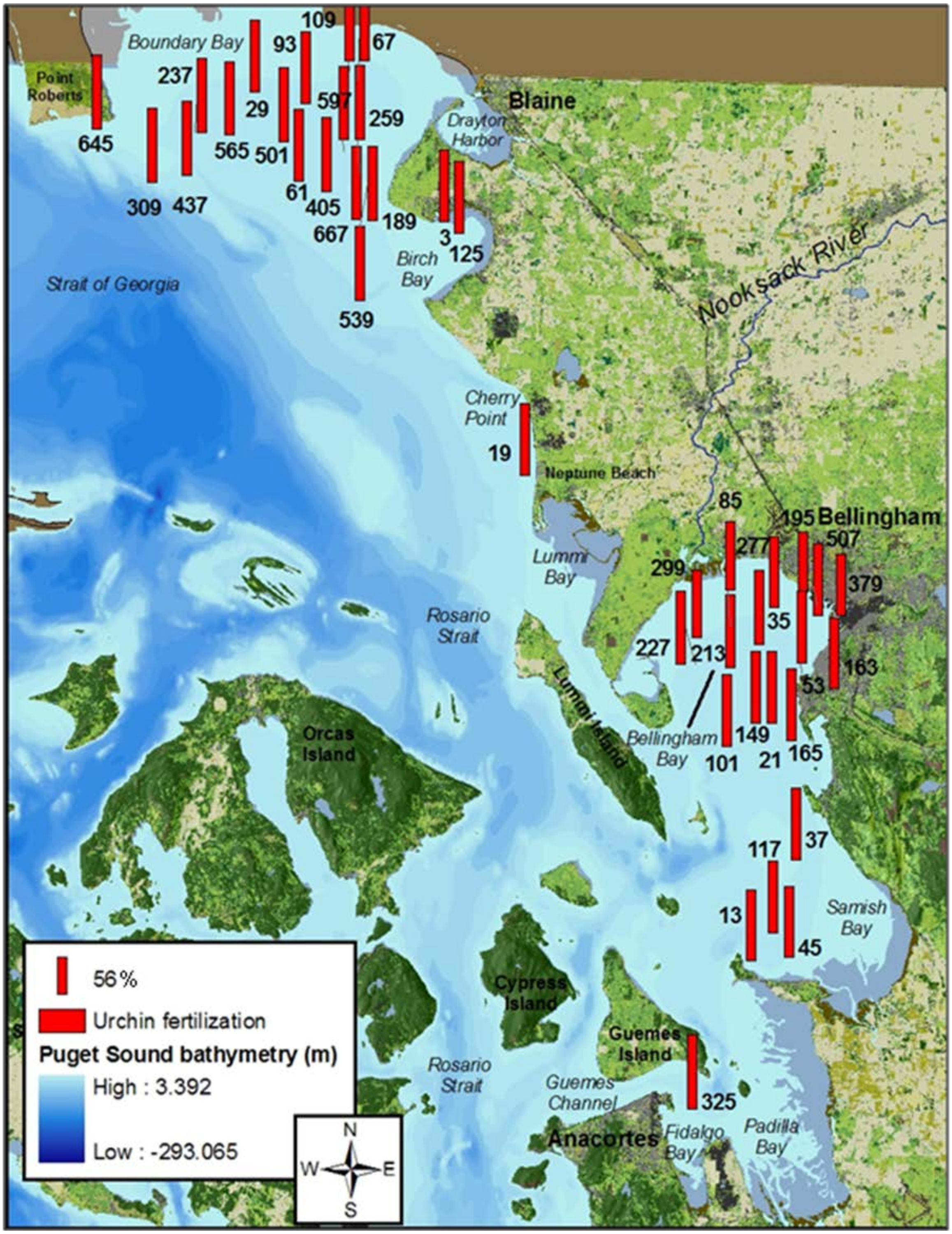


Figure 10. Spatial patterns in sediment pore water toxicity determined with the sea urchin *Strongylocentrotus purpuratus* (control-corrected % fertilization) in the 2006 PSAMP sediment survey.

The numbers on the map are the station identifications. No results were statistically significant (t-test, p-value <0.05).

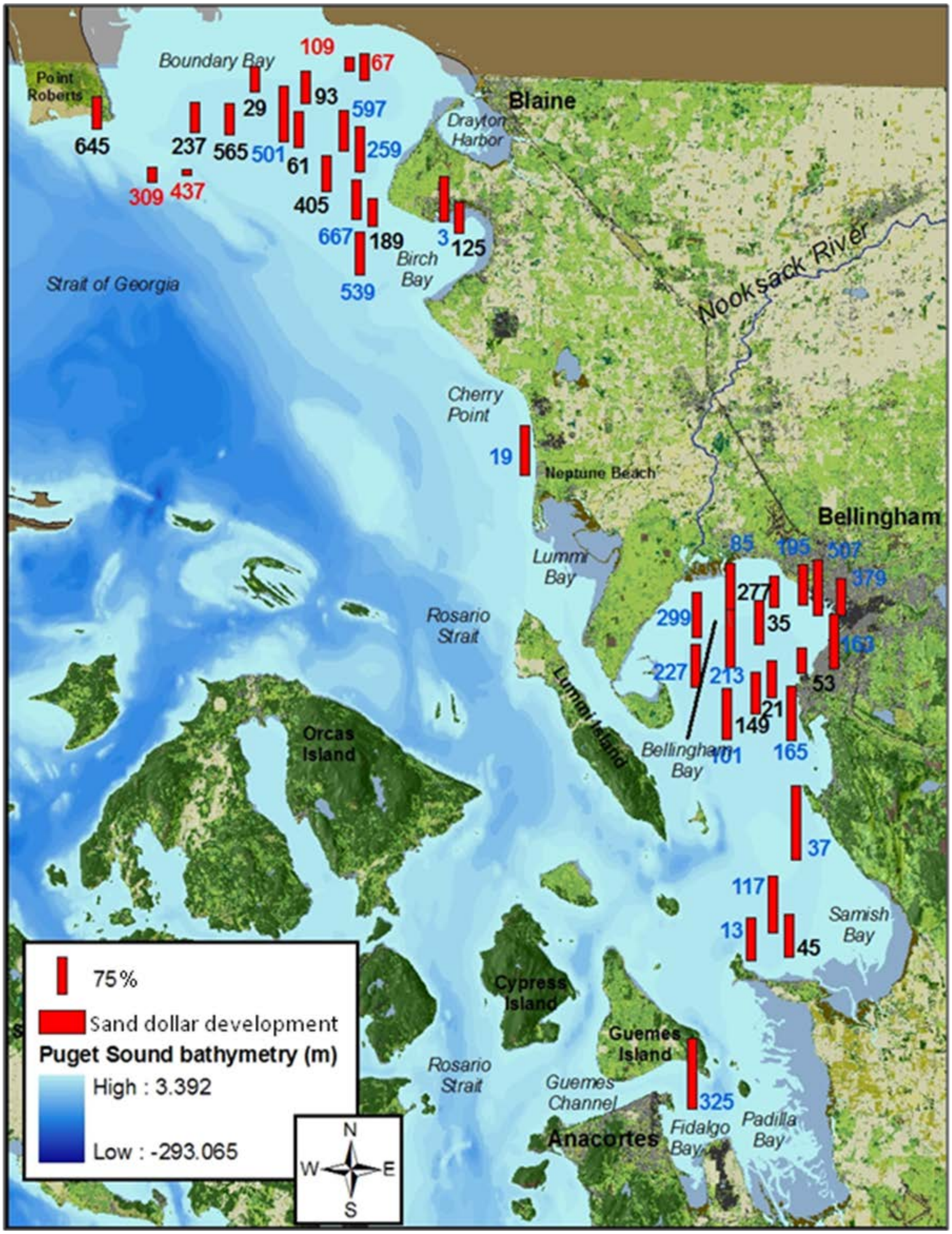


Figure 11. Spatial patterns in sediment elutriate toxicity determined with the sand dollar *Dendraster excentricus* (control-corrected % combined normal survival and development) in the 2006 PSAMP sediment survey.

The numbers on the map are the station identifications. Blue station numbers indicate results statistically significant (t-test, p-value <0.05). Red station numbers indicate results statistically significant (t-test, p-value <0.05) and <85% of reference.

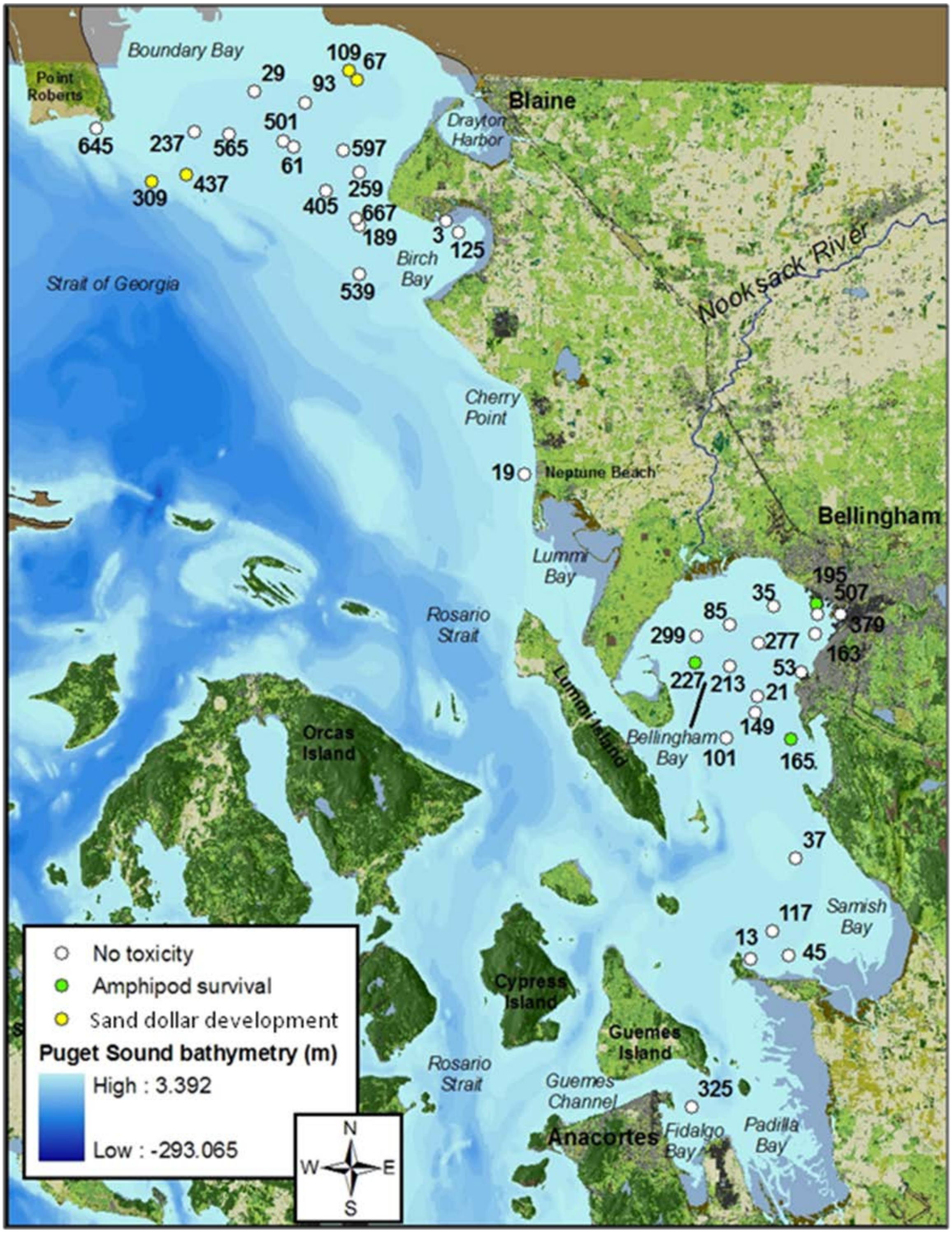


Figure 12. Spatial patterns in significant toxicity responses in the 2006 PSAMP sediment survey.

The numbers on the map are the station identifications.

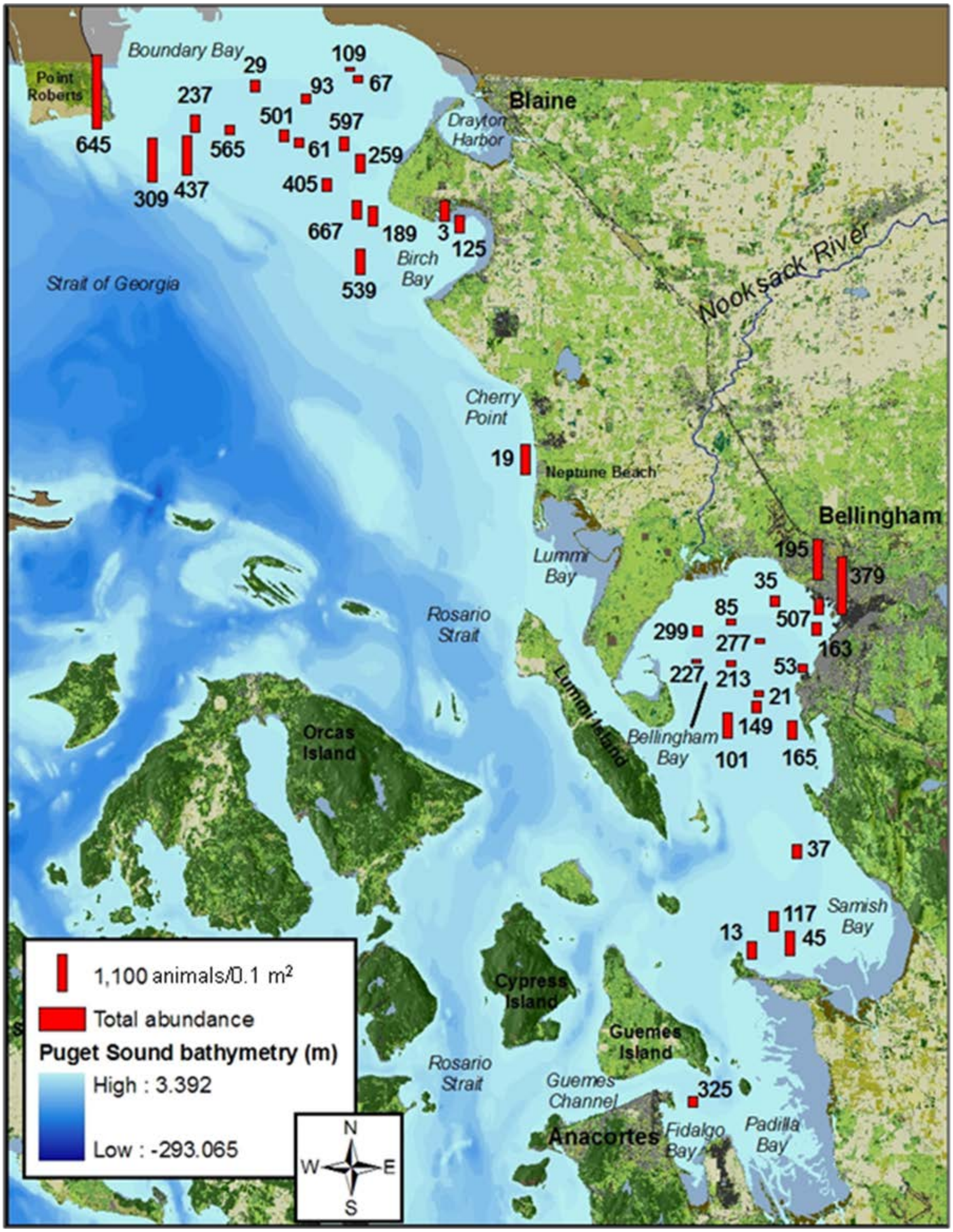


Figure 13. Spatial patterns in total benthic invertebrate abundance (number of animals/0.1 m^2) in the 2006 PSAMP sediment survey.

The numbers on the map are the station identifications.

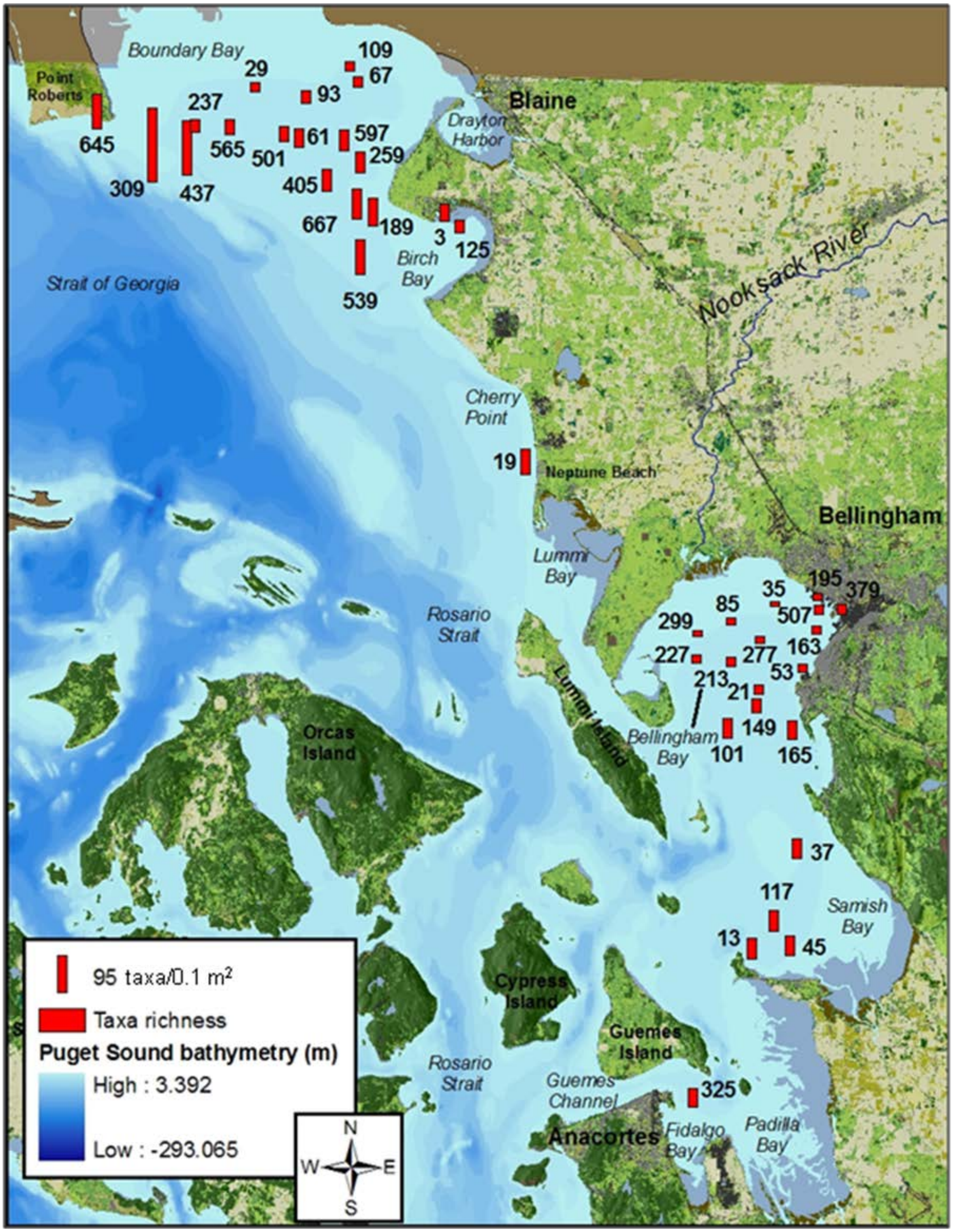


Figure 14. Spatial patterns in taxa richness (number of taxa/0.1 m^2) in the 2006 PSAMP sediment survey.

The numbers on the map are the station identifications.

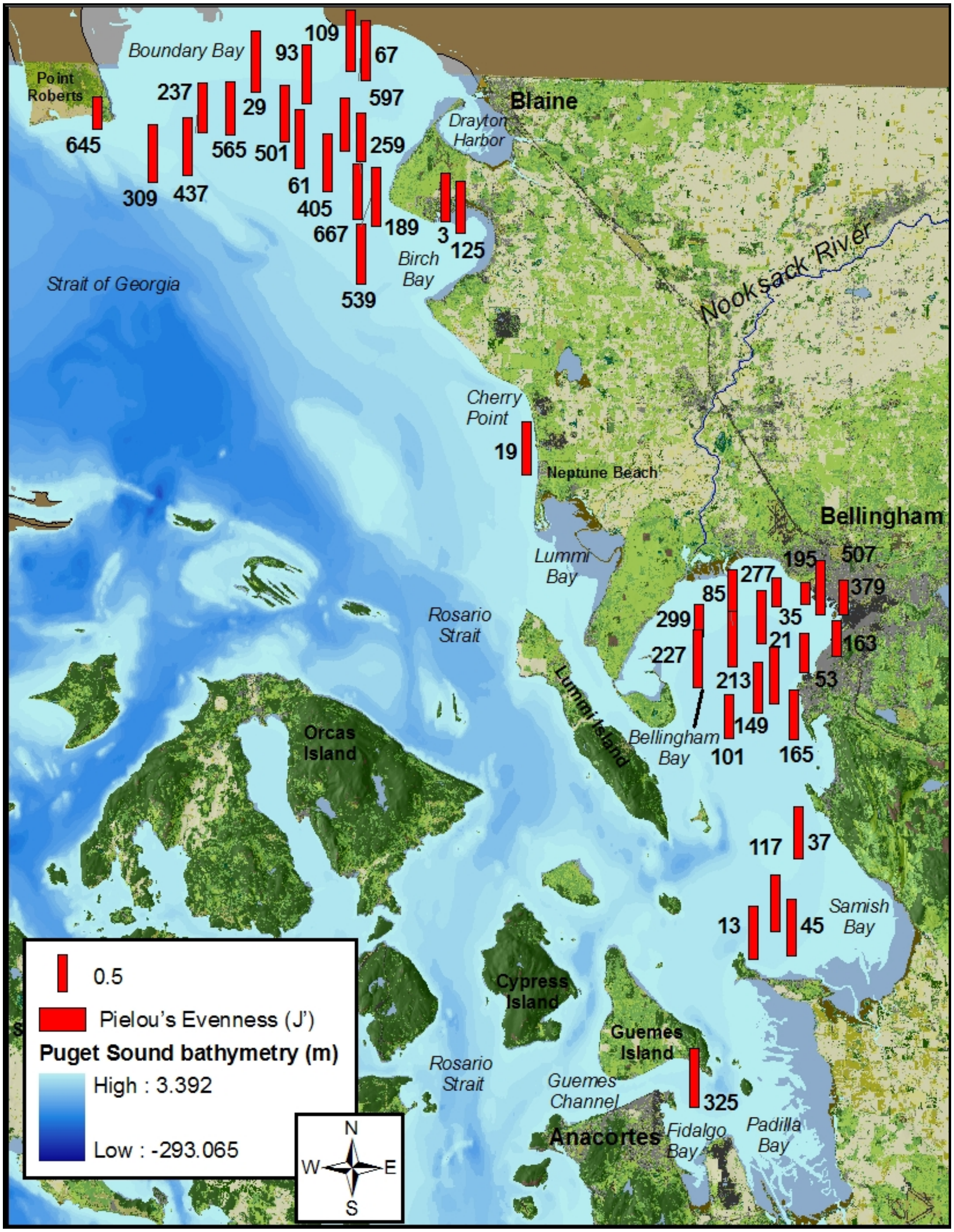


Figure 15. Spatial patterns in Pielou's Evenness (J') (Pielou, 1966) in the 2006 PSAMP sediment survey.

The numbers on the map are the station identifications.

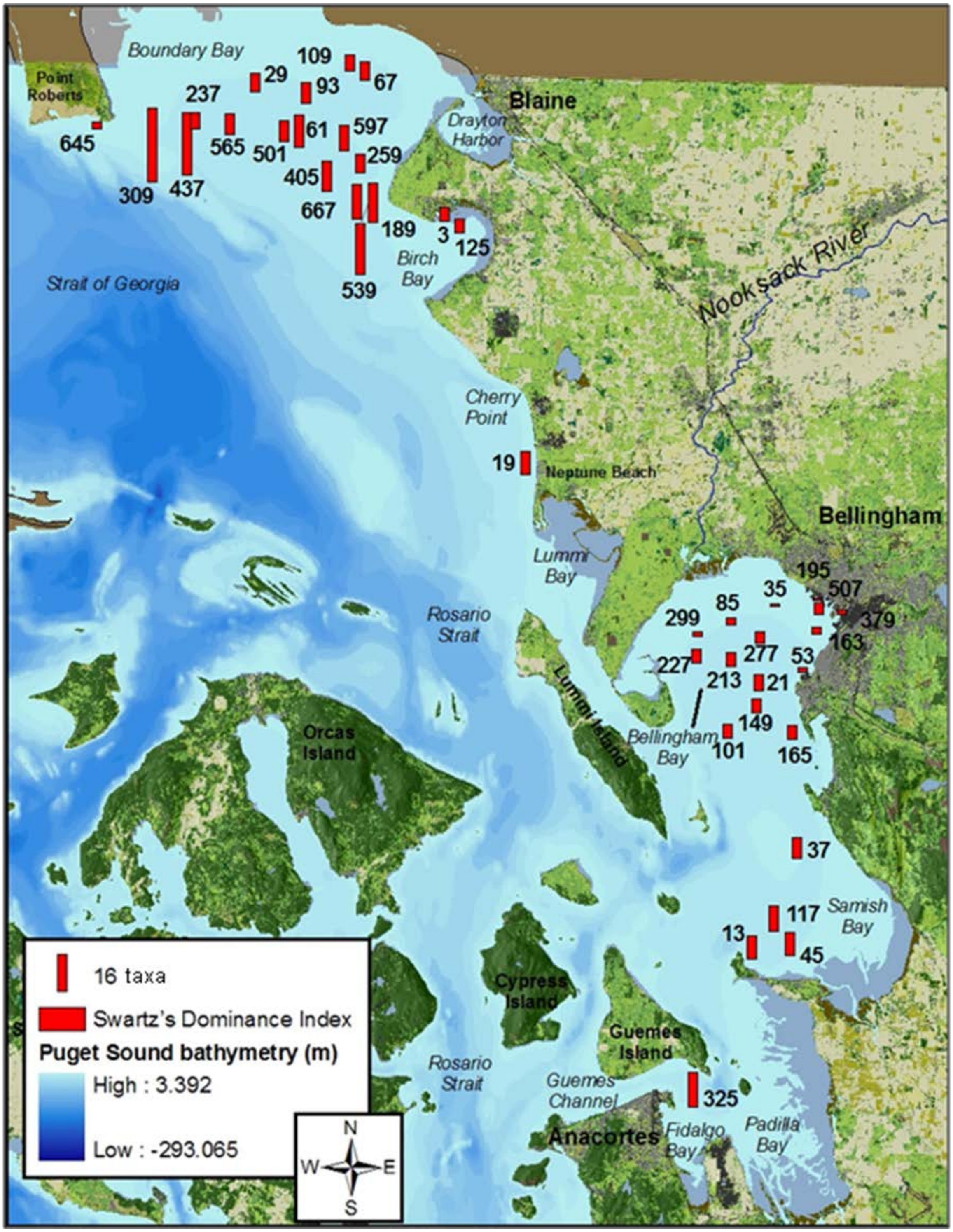


Figure 16. Spatial patterns in Swartz's Dominance Index (number of taxa) (Swartz et al., 1985) in the 2006 PSAMP sediment survey.

The numbers on the map are the station identifications.

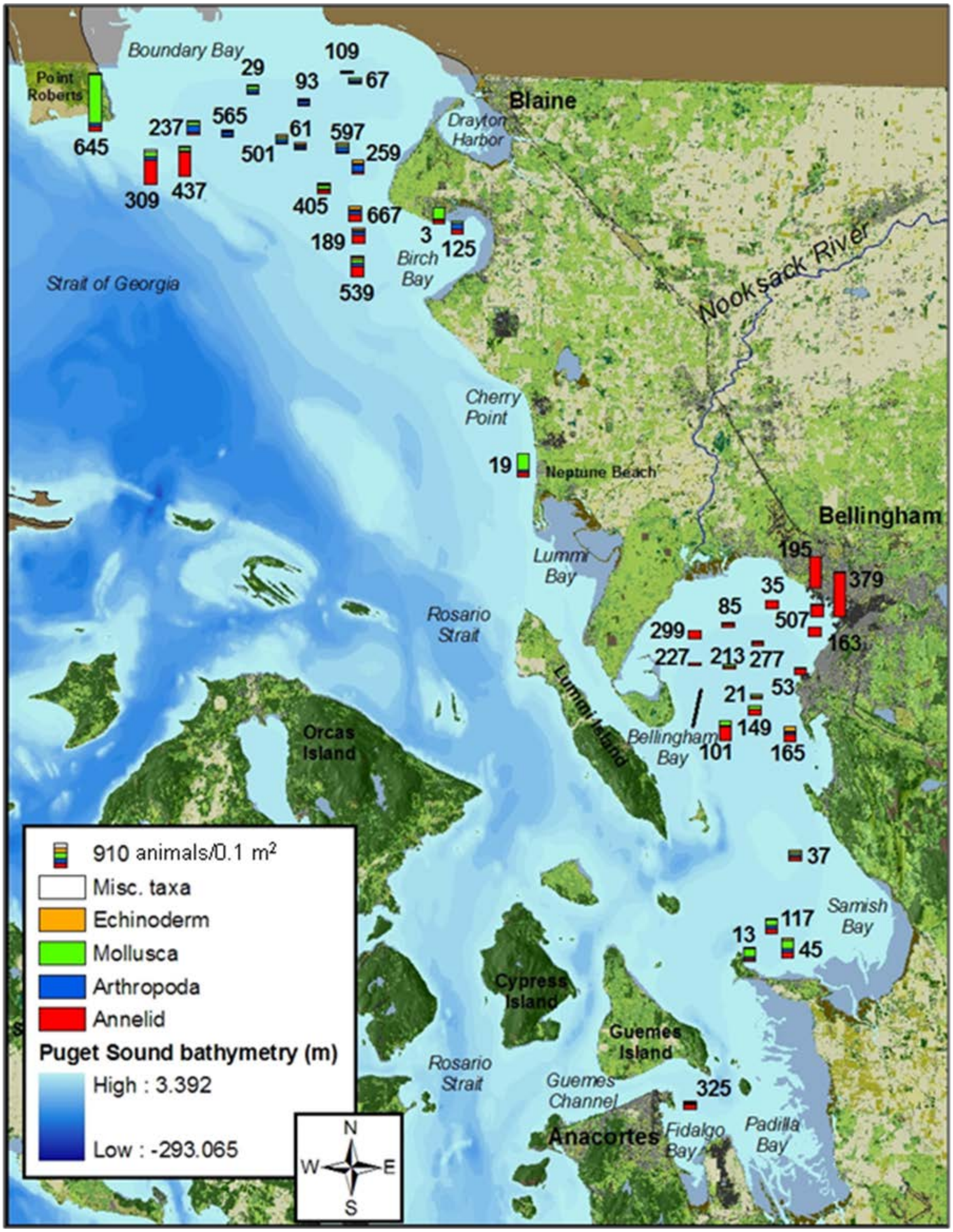


Figure 17. Spatial patterns in major taxa abundance (number of animals/0.1 m^2) in the 2006 PSAMP sediment survey.

The numbers on the map are the station identifications.

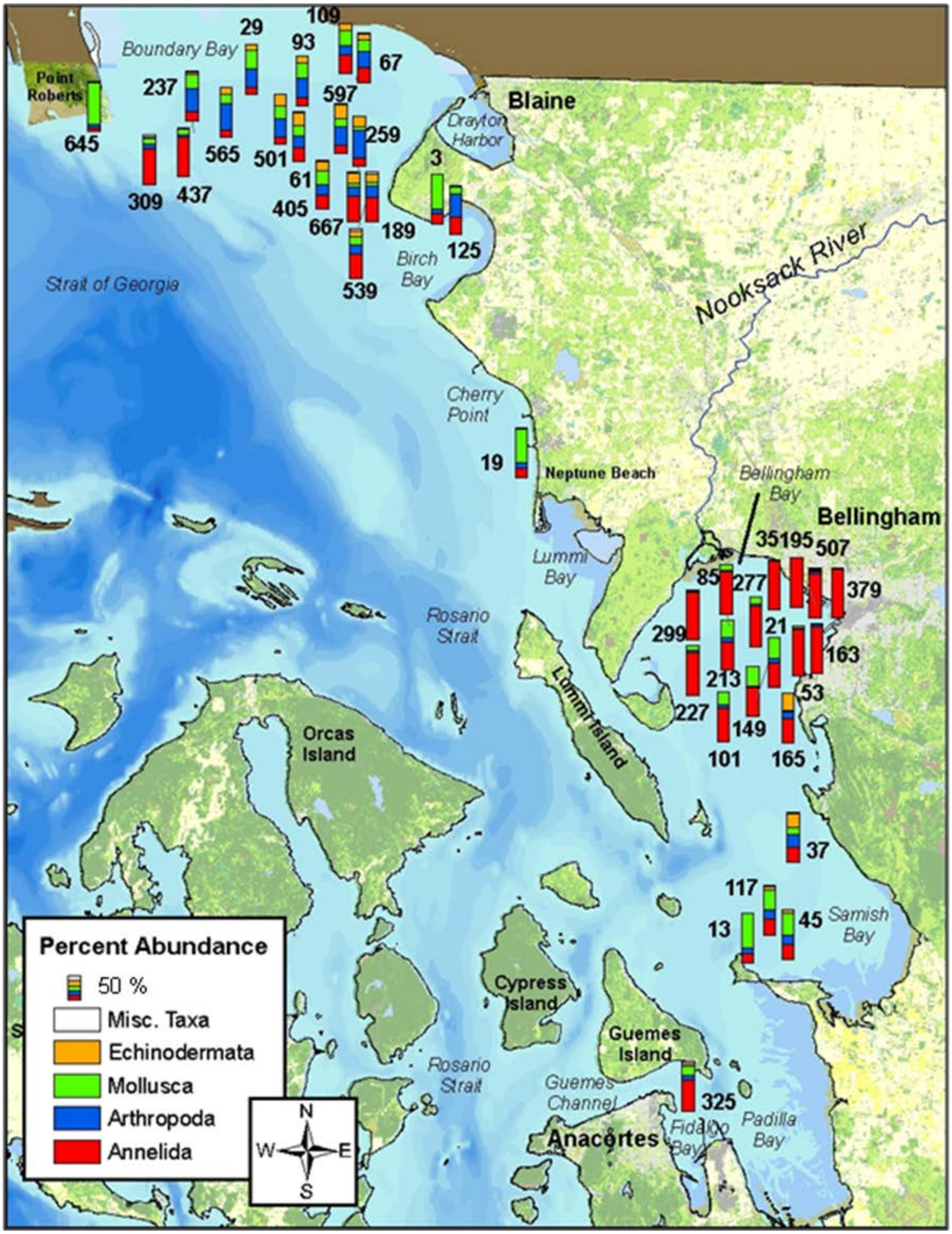


Figure 18. Spatial patterns in major taxa relative abundance (percent) in the 2006 PSAMP sediment survey. The percentages sum to 100%.

The numbers on the map are the station identifications.

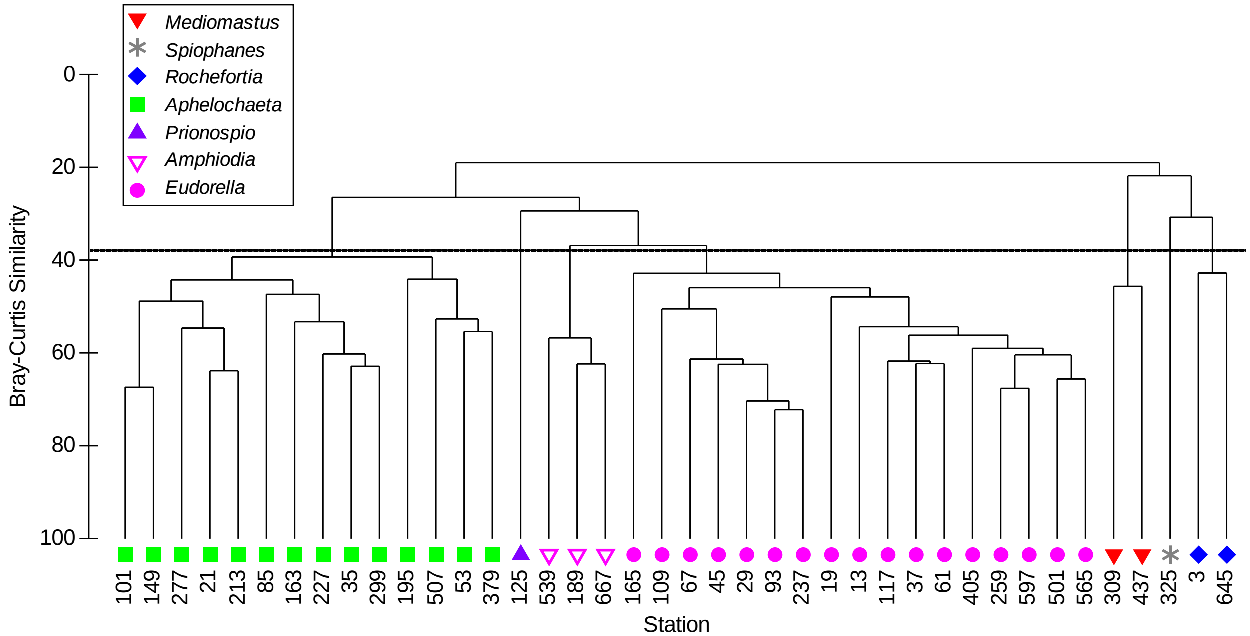


Figure 19. Cluster dendrogram of benthic invertebrate assemblage types at the 40 stations sampled in the 2006 PSAMP sediment survey.

The clusters are based on Bray-Curtis similarities of 4th-root-transformed species abundances (all species included), using group-average linkage. A line indicating 38% similarity level is drawn across the dendrogram. The clusters at 38% similarity are identified by the most common or most abundant taxa. (The same clusters are depicted in two dimensions, from a nonmetric multidimensional scaling analysis, in Figure 20.) These clusters are:

- *Mediomastus* spp./*Galathowenia oculata*
- *Spiophanes bombyx*
- *Rochefortia tumida*/*Nutricola lordi*
- *Aphelochaeta* spp.
- *Prionospio (Minuspio) lighti*
- *Amphiodia* spp./*Euphilomedes producta*
- *Eudorella pacifica*/*Amphiodia* spp.

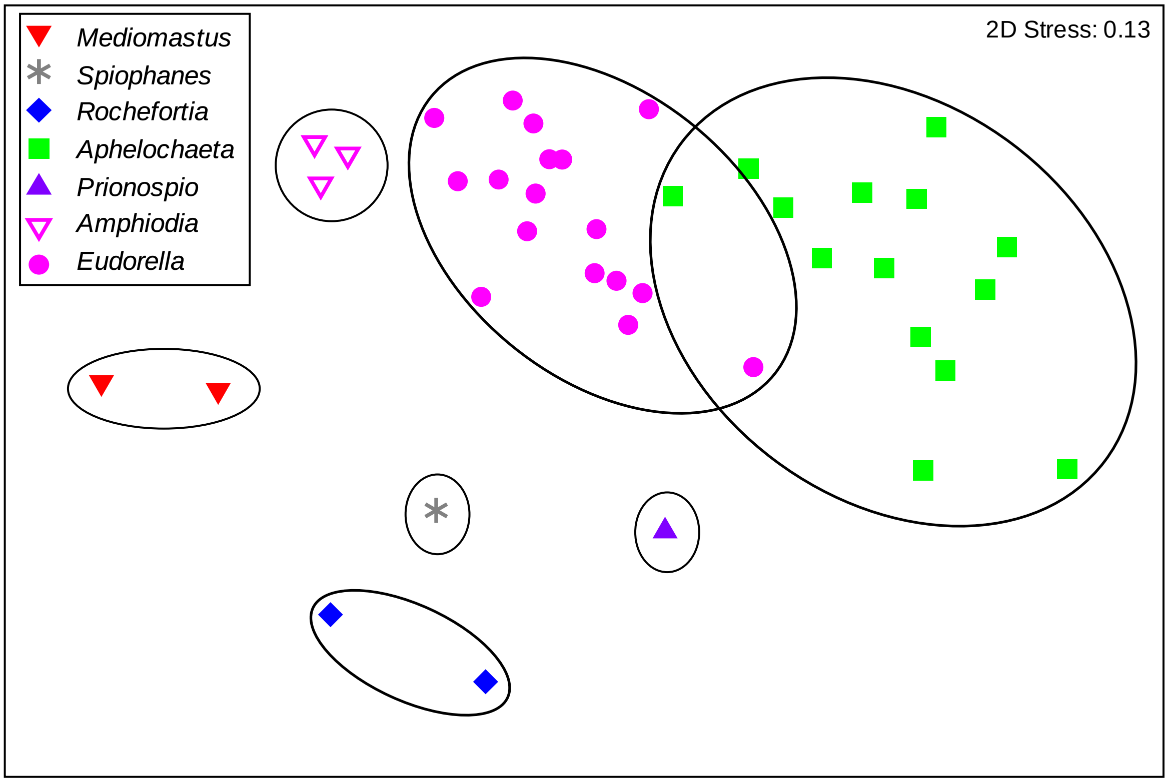


Figure 20. Multidimensional scaling (MDS) map of benthic invertebrate assemblage types at the 40 stations sampled in the 2006 PSAMP sediment survey.

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 4^{th}-root-transformed species abundances (all species included). Overlaid on the MDS map are clusters at 38% similarity (see cluster dendrogram in Figure 19). The clusters are identified by the most common or most abundant taxa.

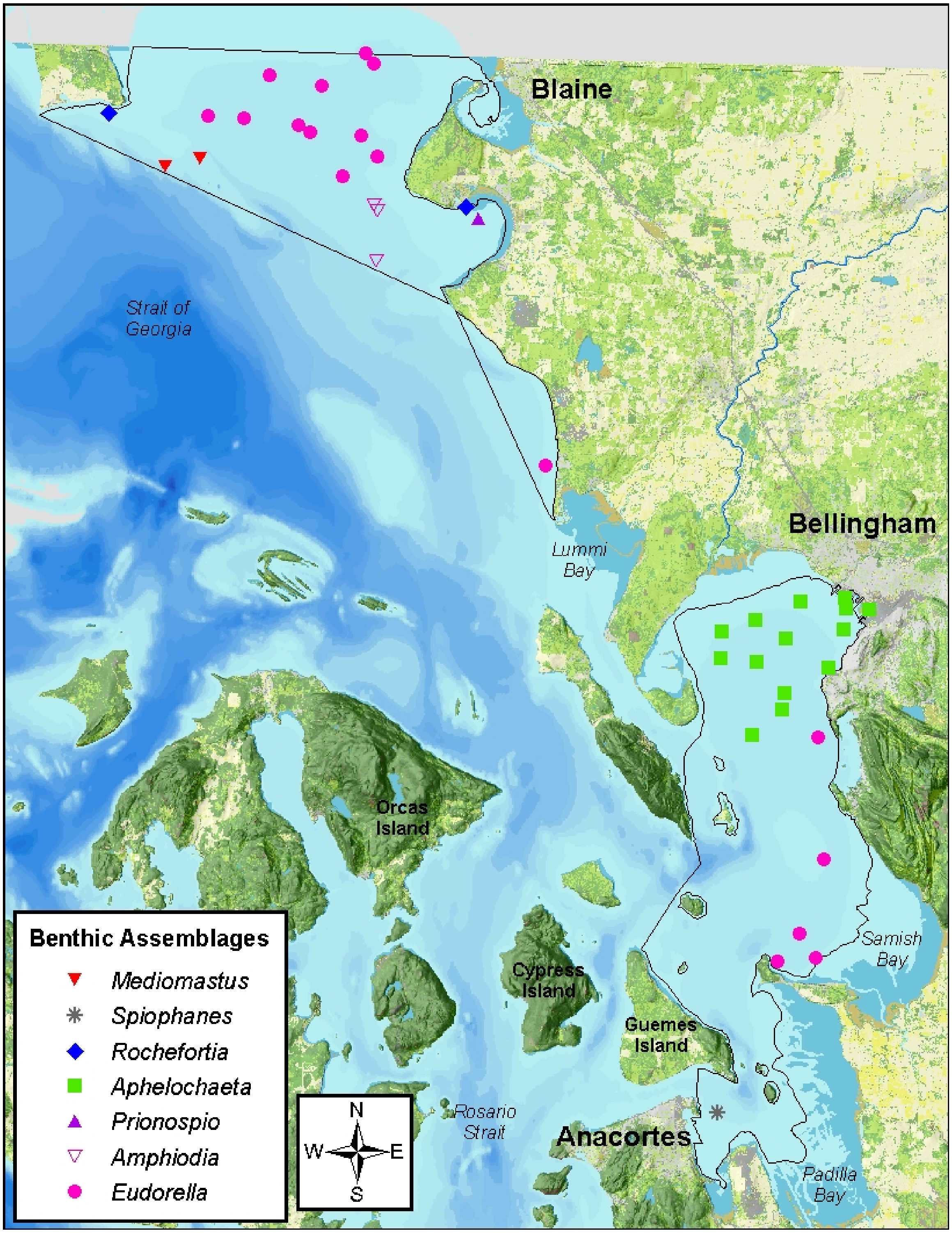


Figure 21. Spatial patterns in benthic invertebrate assemblage types in the 2006 PSAMP sediment survey, labeled by the most common or most abundant taxa. Type distinctions were based on cluster analysis (Figure 19).

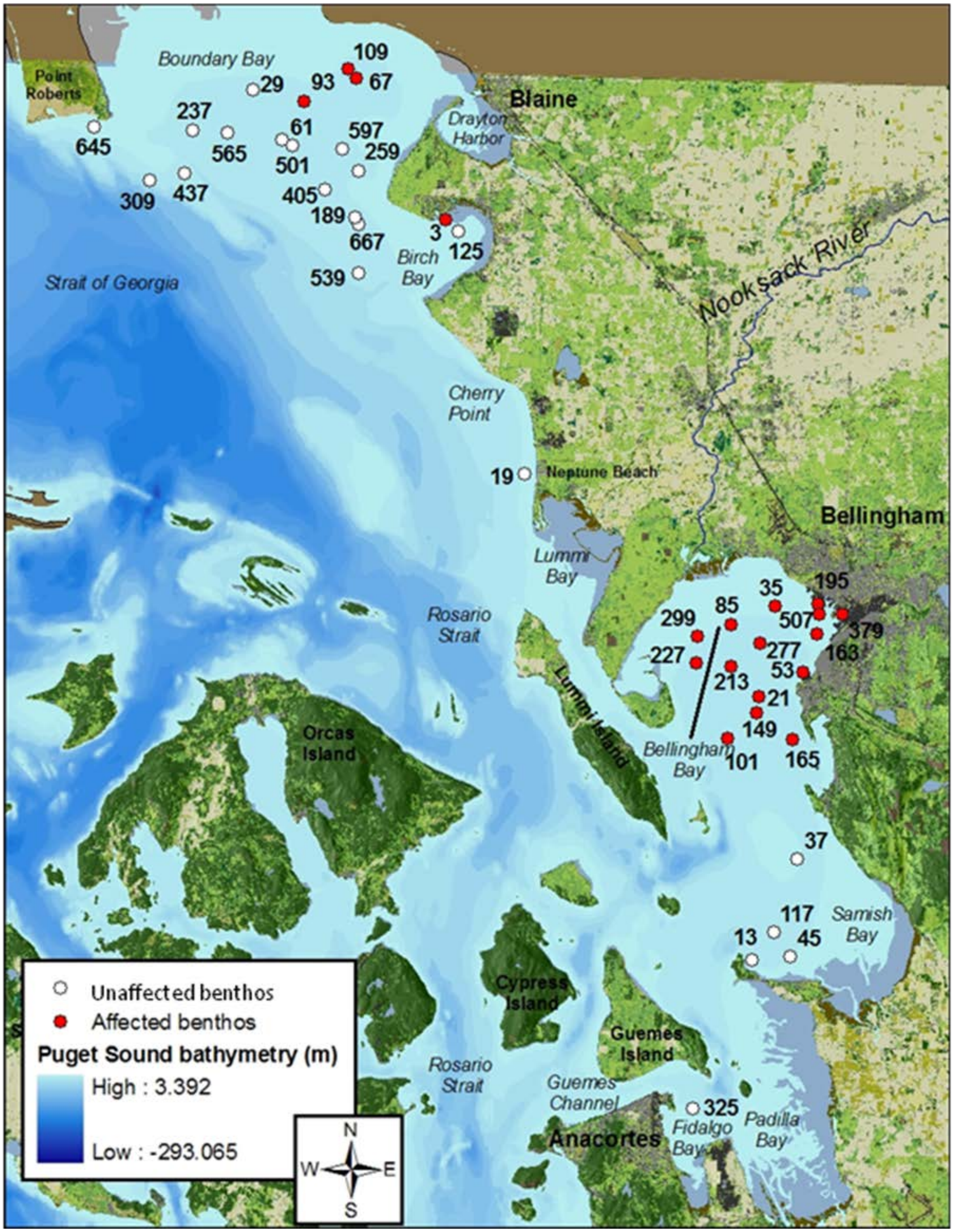


Figure 22. Spatial patterns in adversely affected benthic invertebrate assemblages in the 2006 PSAMP sediment survey.

The numbers on the map are the station identifications.

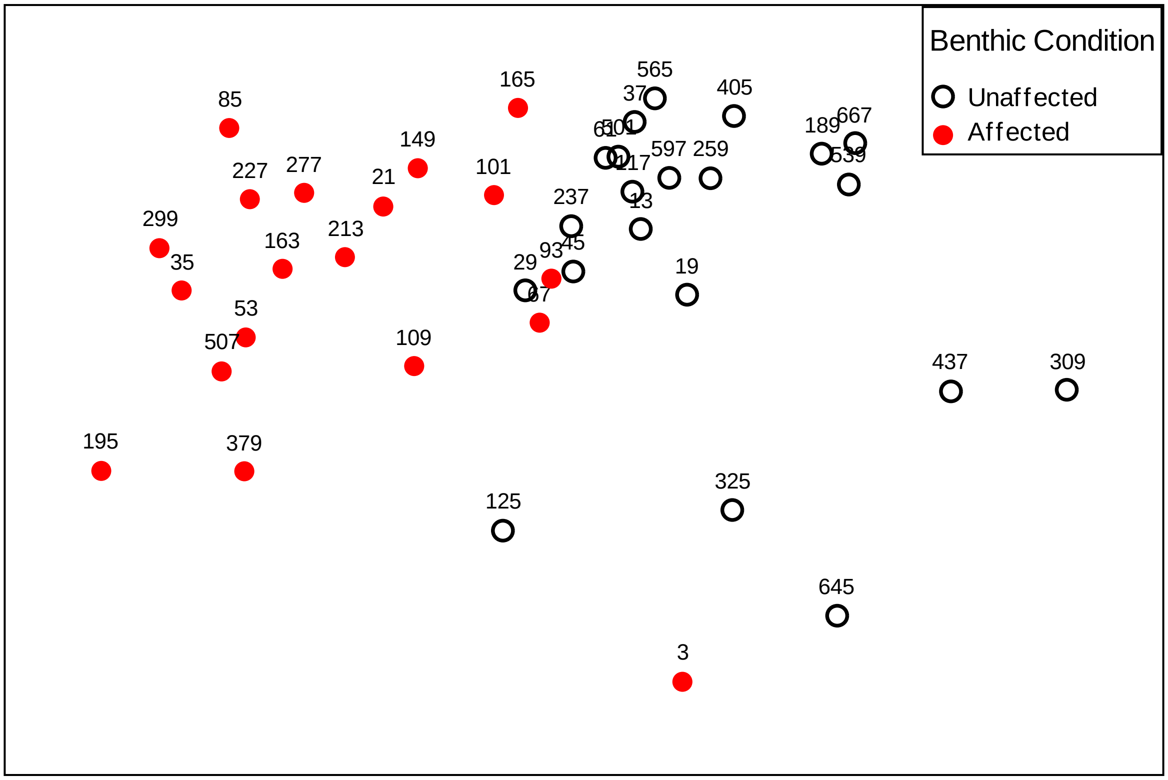


Figure 23. MDS diagram indicating relative similarities of adversely affected and unaffected benthic invertebrate assemblages in the 2006 PSAMP sediment survey.

(Bray-Curtis similarities of 4th-root-transformed abundances, all species; stress=0.13).
The closer the symbols are in the diagram, the more similar their assemblages are.
The numbers on the diagram are the station identifications.

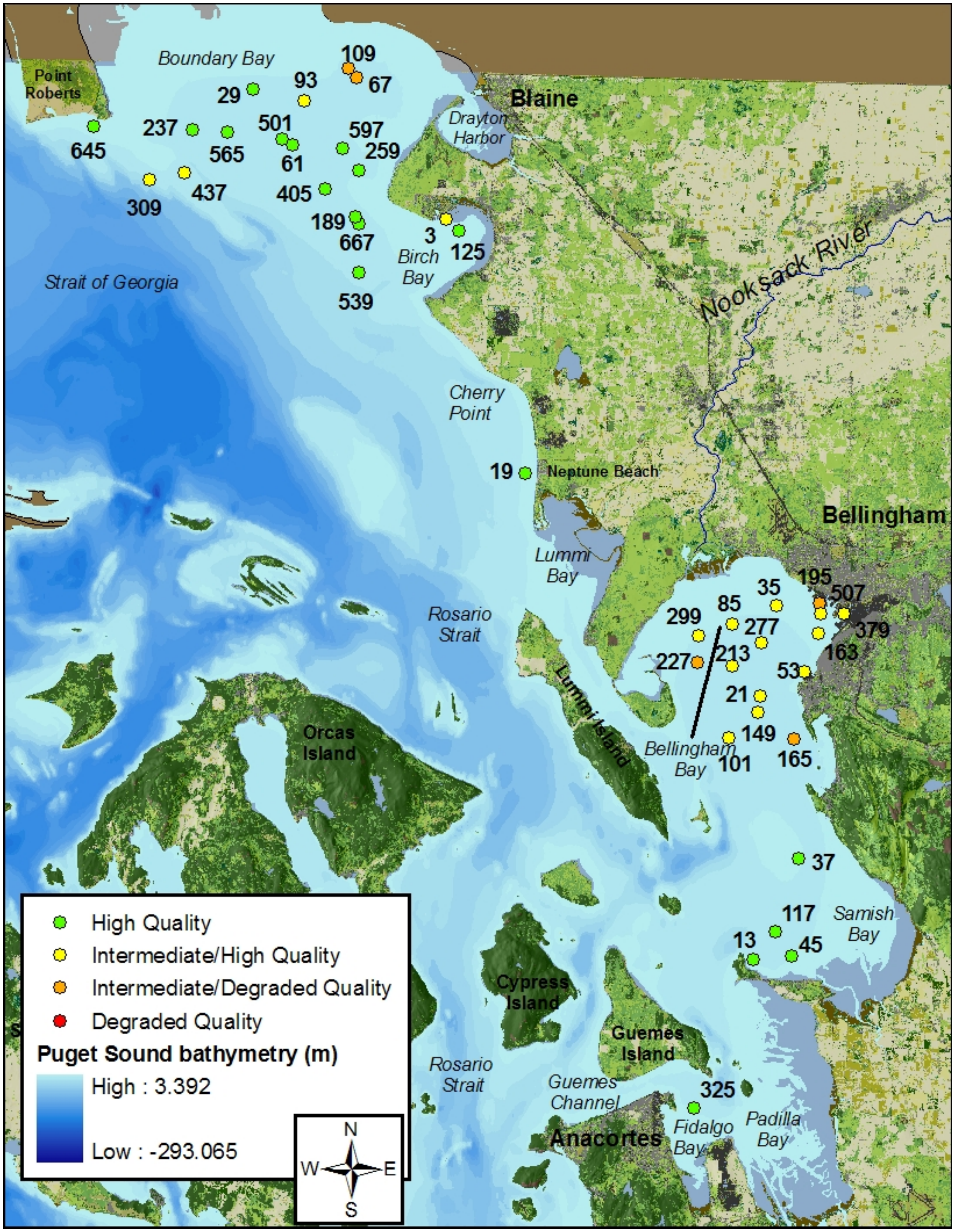


Figure 24. Spatial patterns in sediment quality based on the Sediment Quality Triad Index in the 2006 PSAMP sediment survey.

The numbers on the map are the station identifications.

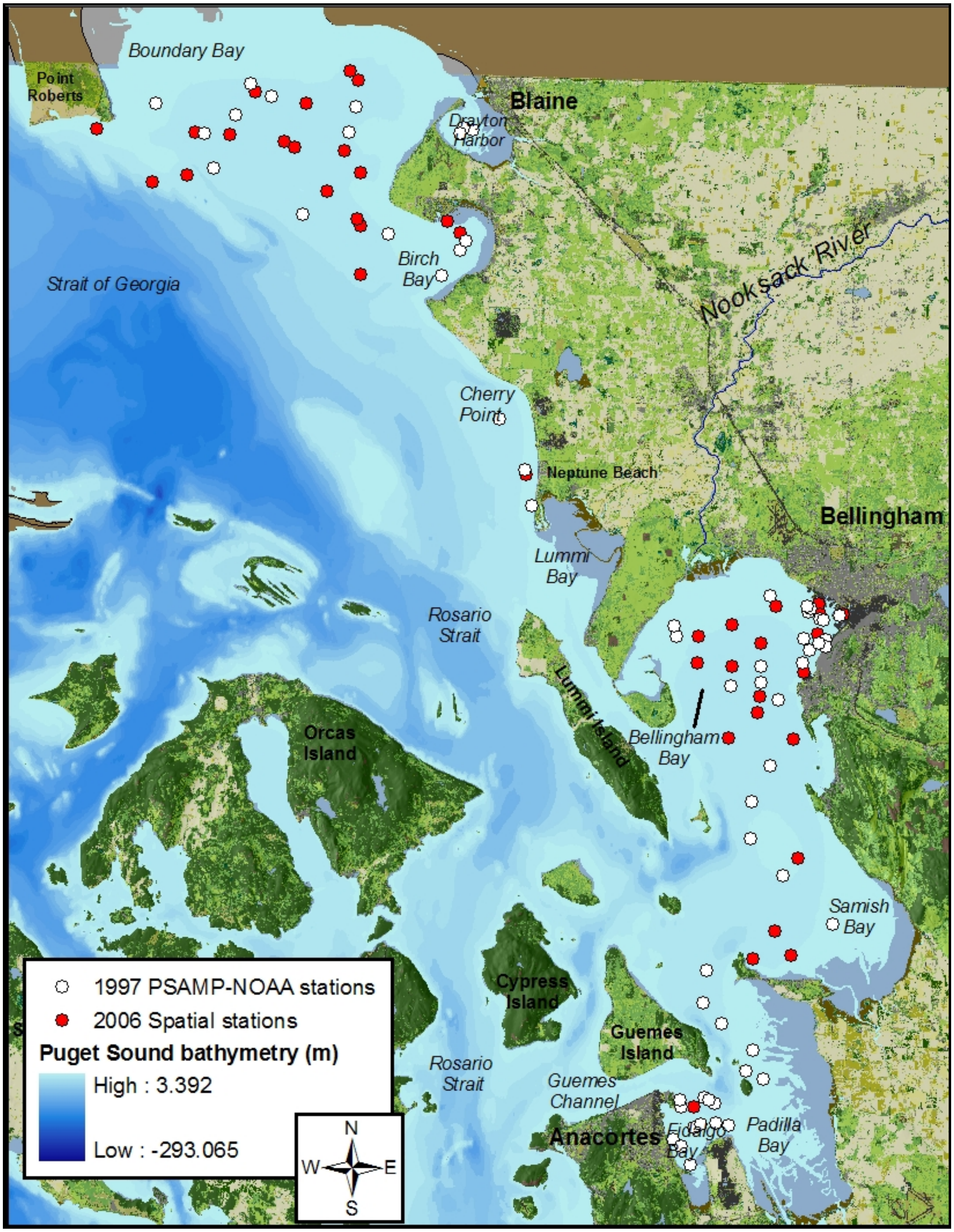


Figure 25. Locations of PSAMP sampling stations in 1997 and 2006 in the Strait of Georgia region.

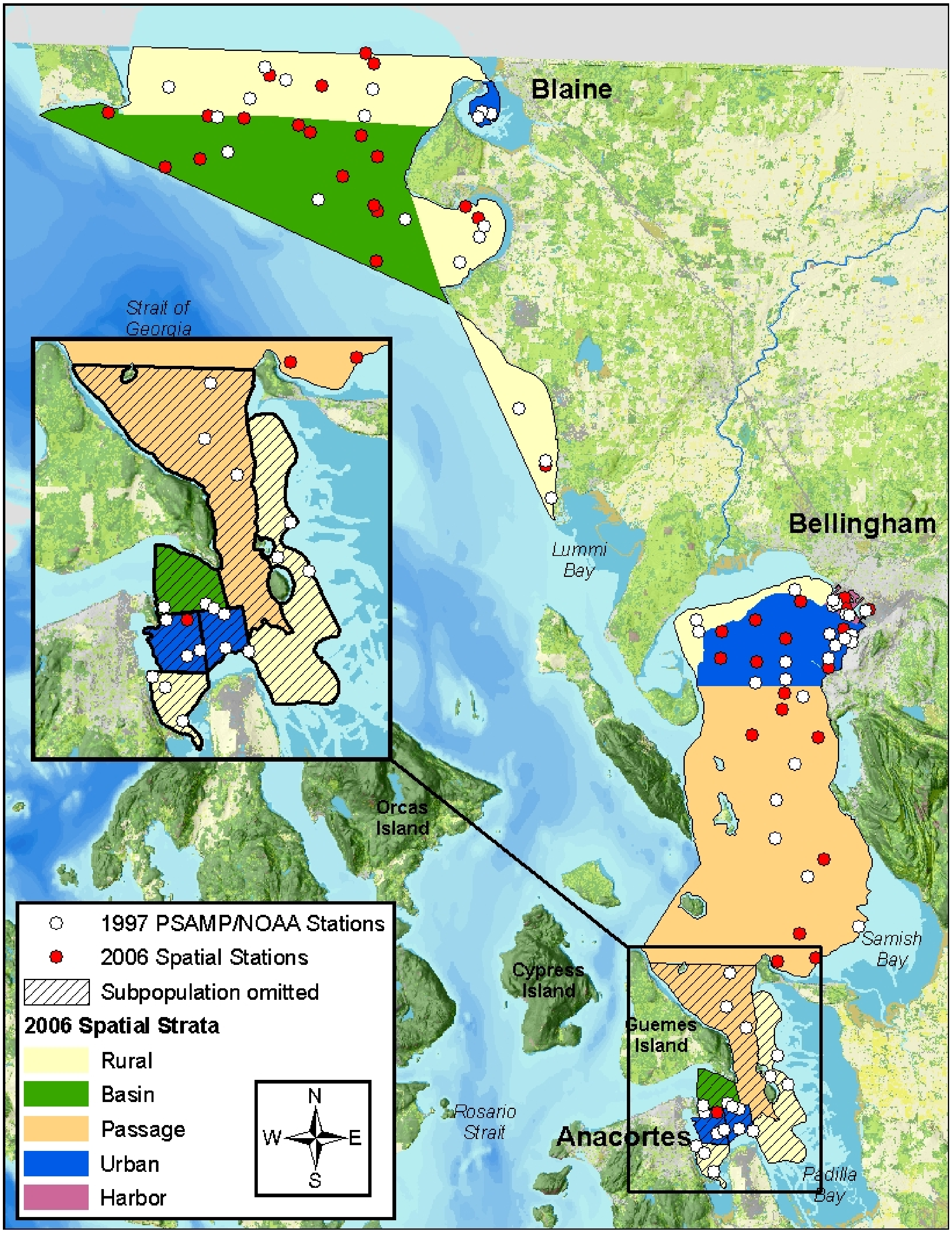


Figure 26. Map of the PSEMP Strait of Georgia region excluding the Padilla Bay and Fidalgo Bay subpopulation (enlarged in inset).

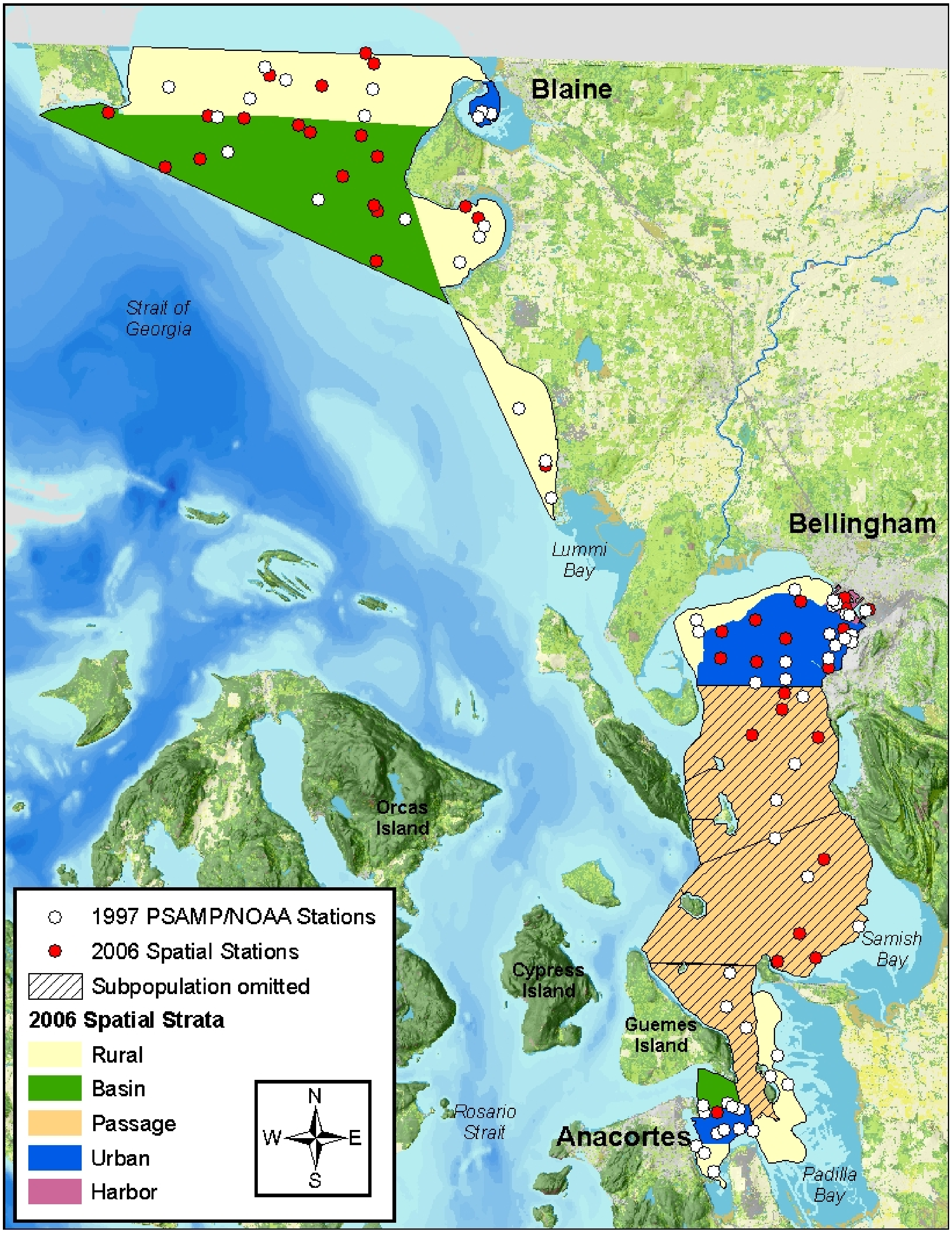
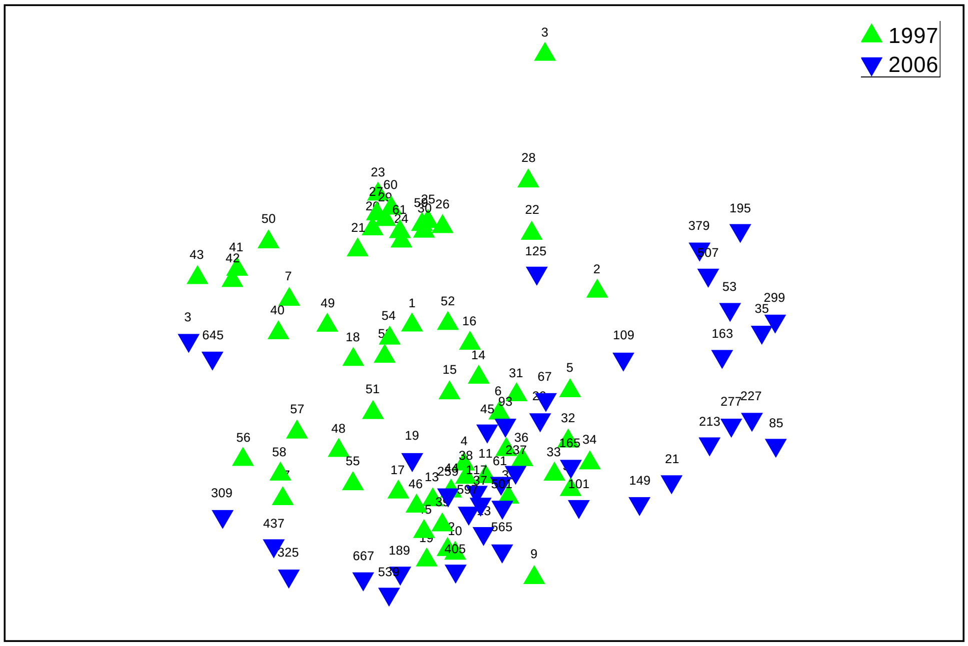
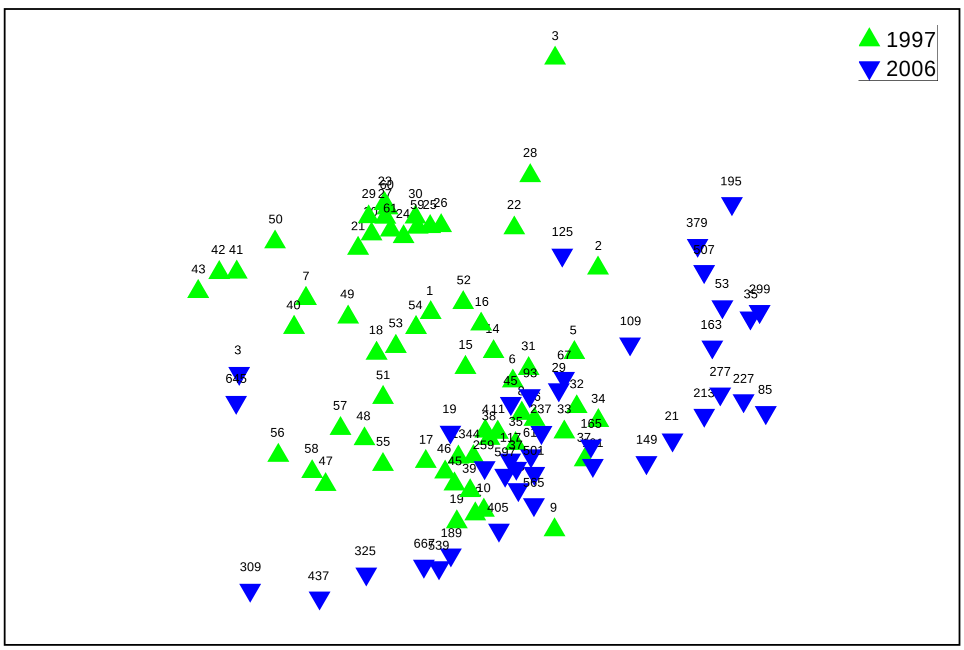


Figure 27. Map of the PSEMP Strait of Georgia region excluding the Passage stratum subpopulation.



a. All species included.



b. Common species only.

Figure 28. MDS diagrams indicating relative similarities of benthic invertebrate assemblages in the 1997 PSAMP/NOAA survey in the Strait of Georgia region and the 2006 PSAMP sediment survey with (a) all species and (b) only species common to both surveys.

The closer the symbols are in the diagram, the more similar their assemblages are (Bray-Curtis similarities of 4th-root-transformed abundances; stress=0.2).
The numbers on the diagram are the station identifications.

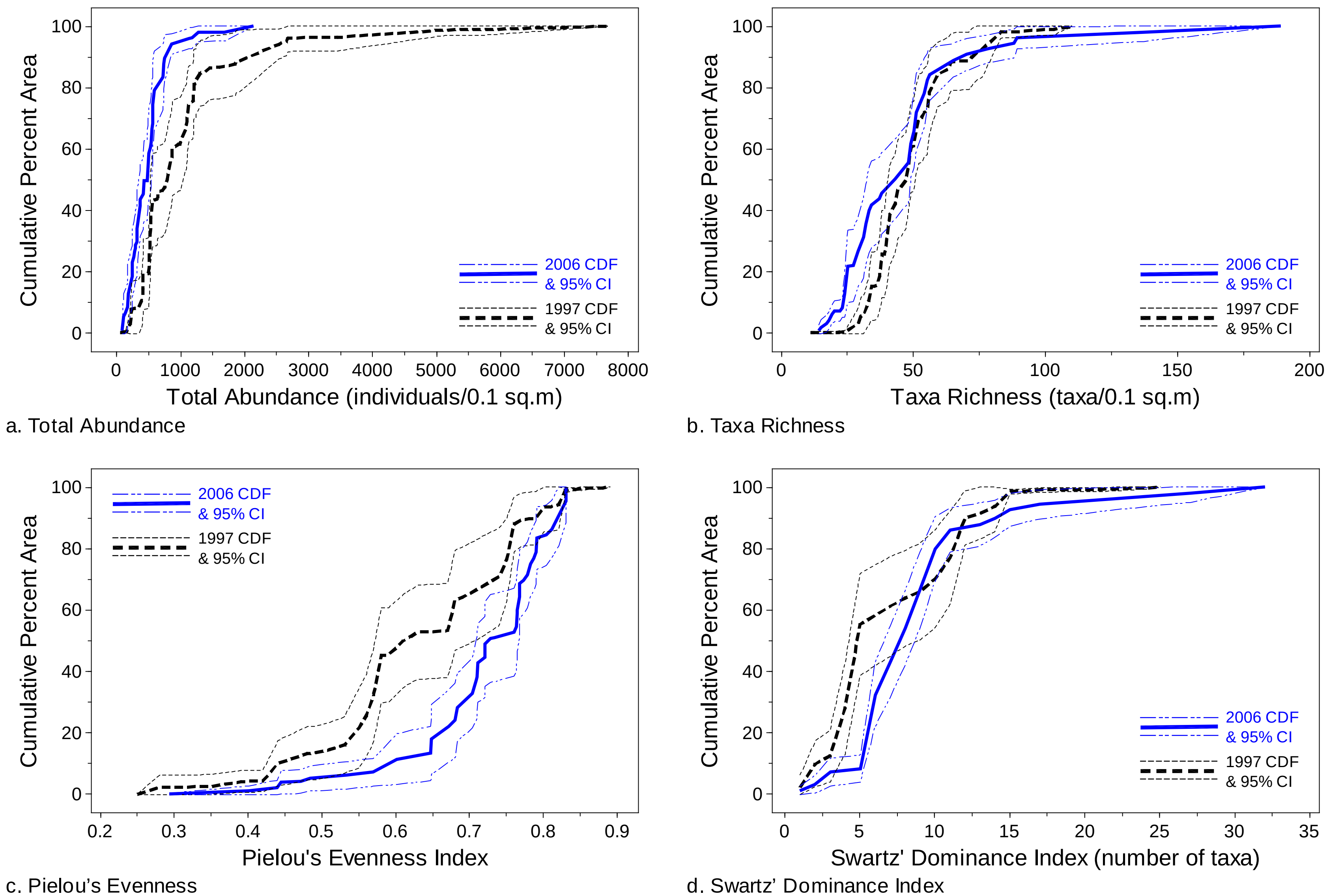


Figure 29. Cumulative distribution function (CDF) graphs for four benthic indices (weighted by sample area) in 1997 and 2006 in the PSEMP Strait of Georgia region. Nonoverlapping confidence bands indicates CDFs significantly different ($\alpha = 0.05$).

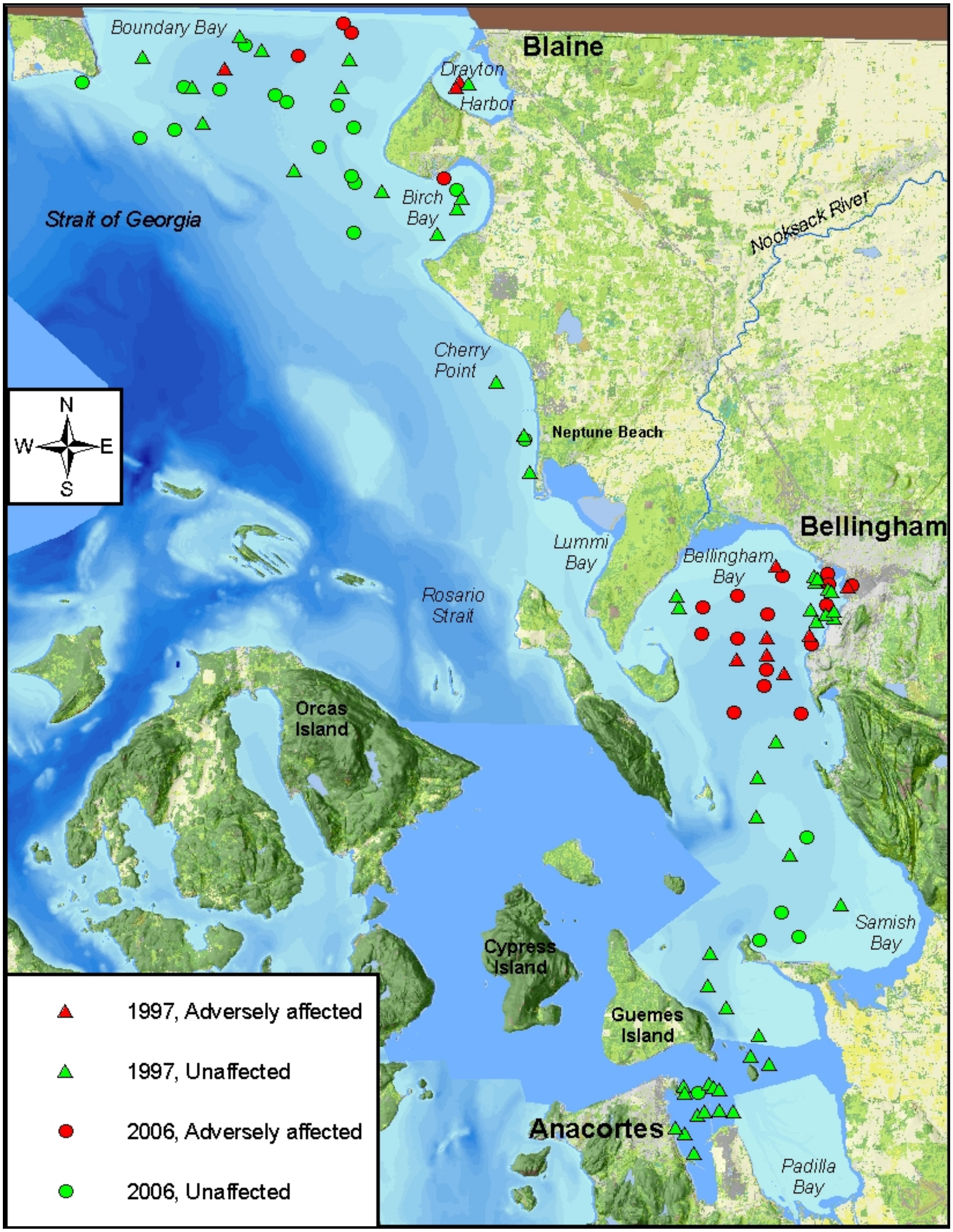


Figure 30. Spatial patterns in adversely affected benthic invertebrate assemblages in the 1997 PSAMP/NOAA survey and the 2006 PSAMP sediment survey.

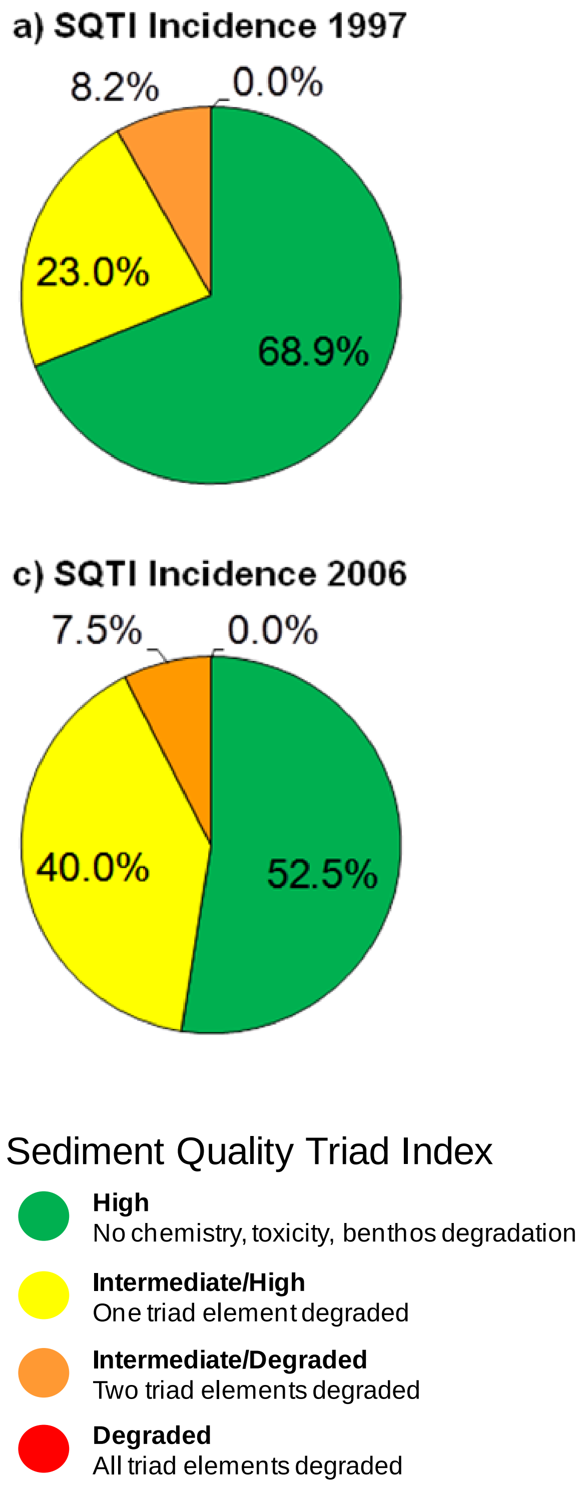


Figure 31. Incidence (% of stations) and spatial extent (% of area) of Sediment Quality Triad Index (SQTI) categories in the Strait of Georgia region in the 1997 PSAMP/NOAA and 2006 PSAMP sediment surveys.

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Tables

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Table 1. Station numbers, names, stratum types, and sample weights for the 2006 PSAMP survey of the Strait of Georgia region.

Station	Location
Basin (each station represents 6.63 km^2)	
61	Boundary Bay
189	Boundary Bay
237	Boundary Bay
259	Boundary Bay
309	Boundary Bay
405	Boundary Bay
437	Boundary Bay
501	Boundary Bay
539	Boundary Bay
565	Boundary Bay
597	Boundary Bay
645	Boundary Bay
667	Boundary Bay
Harbor (each station represents 0.47 km^2)	
195	Bellingham Bay
379	Bellingham Bay
507	Bellingham Bay
Passage (each station represents 15.51 km^2)	
13	Samish Bay/Bellingham Bay
21	Bellingham Bay
37	Samish Bay/Bellingham Bay
45	Samish Bay/Bellingham Bay
101	Bellingham Bay
117	Samish Bay/Bellingham Bay
149	Bellingham Bay
165	Bellingham Bay
Rural (each station represents 16.54 km^2)	
3	Birch Bay
19	Cherry Point
29	Boundary Bay
67	Semiahmoo Bay
93	Semiahmoo Bay
109	Semiahmoo Bay
125	Birch Bay
Urban (each station represents 3.68 km^2)	
35	Bellingham Bay (central)
53	Bellingham Bay
85	Bellingham Bay (central)
163	Bellingham Bay
213	Bellingham Bay (central)
227	Bellingham Bay (central)
277	Bellingham Bay (central)
299	Bellingham Bay (central)
325	Fidalgo Bay (outer)

Table 2. Number of stations and area represented in each stratum type for the 2006 PSAMP sediment survey in the Strait of Georgia region.

Sampling stratum	Number of stations successfully sampled	Area that was feasible to sample (km^2)	Total area (km^2)
Basin	13	86.21	92.84
Harbor	3	1.42	1.89
Passage	8	124.10	139.61
Rural	7	115.77	115.77
Urban	9	33.14	36.82
Total	**40**	**360.63**	**386.94**

Table 3. Chemical and physical parameters measured in sediments collected for the 2006 PSAMP sediment survey.

Physical Parameters
Grain Size
Total Organic Carbon

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

Trace Elements
Tin

Organics

Chlorinated Alkenes
Hexachlorobutadiene

Chlorinated and Nitro-Substituted Phenols
Pentachlorophenol

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

Chlorinated Pesticides
2,4'-DDD
2,4'-DDE
2,4'-DDT
4,4'-DDD
4,4'-DDE
4,4'-DDT
Aldrin
Cis-Chlordane
Dieldrin
Endosulfan I
Endosulfan II
Endosulfan Sulfate
Endrin
Endrin Aldehyde
Endrin Ketone
Gamma-BHC (Lindane)
Heptachlor
Heptachlor Epoxide
Mirex
Oxychlordane
Toxaphene
Trans-Chlordane (Gamma)

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

HPAHs
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

HPAHs (continued)
- Perylene
- Pyrene

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

Organonitrogen Compounds
- Caffeine
- N-Nitrosodiphenylamine

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

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

Polychlorinated Biphenyls (PCBs)
PCB Congeners
- PCB congener 8
- PCB congener 18
- PCB congener 28
- PCB congener 44
- PCB congener 52
- PCB congener 66
- PCB congener 77
- PCB congener 101
- PCB congener 105
- PCB congener 118
- PCB congener 126
- PCB congener 128
- PCB congener 138
- PCB congener 153
- PCB congener 169
- PCB congener 170
- PCB congener 180
- PCB congener 187
- PCB congener 195
- PCB congener 206
- PCB congener 209

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

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

Table 4. Laboratory analytical methods and reporting limits for the 2006 PSAMP sediment survey chemical variables.

Parameter	Extraction Method	Clean-Up Method	Analysis Method	Technique/ Instrument	Required Reporting Limit
Grain size	N/A	N/A	PSEP, 1986	Sieve-pipette method	>2000 to <3.9 microns
Total Organic Carbon	Drying sediment material	N/A	PSEP, 1986	Non-dispersive infrared detector	0.1%
Metals except mercury	EPA 3050B	N/A	EPA 200.8	ICP-MS	0.1 mg/kg dry weight (0.2 for Sn, 0.5 for Cr and Se, 5.0 for Zn)
Mercury	EPA 245.5	N/A	EPA 245.5	CVAA	0.005 mg/kg dry weight
Base/Neutral/ Acid Organic Compounds (BNAs)	EPA 3540B	No cleanup performed	EPA 8270	Capillary GC/MS	20 µg/kg dry weight (for ≥ 50% solids)
Polynuclear Aromatic Hydrocarbons (PAHs)	EPA 3545	EPA 3630C	EPA 8270 with isotopic dilution	Capillary GC/MS, GC/MS-SIM	0.5-2.0 µg/kg dry weight
Chlorinated Pesticides	EPA 3545B	EPA 3620 and EPA 3665	EPA 8081 and EPA 8082	GC-DDC/ECD	1 µg/kg dry weight (20 for Toxaphene)
PCB Aroclors	EPA 3545B	EPA 3620 and EPA 3665	EPA 8081 and EPA 8082	GC-DDC/ECD	10 µg/kg dry weight
PCB Congeners	EPA 3545B	EPA 3620 and EPA 3665	EPA 8081 and EPA 8082	GC-DDC/ECD	1 µg/kg dry weight
PBDE	EPA 3545B	EPA 3620 and EPA 3665	EPA 8081 and EPA 8082	GC-DDC/ECD	1 µg/kg dry weight

Table 5. Laboratory analytical methods and endpoints for the toxicity tests used in the 2006 PSAMP sediment survey.

Test	Species	Sediment phase	Test Duration	Endpoint	Protocol
Amphipod survival	*Eohaustorius estuarius*	solid bulk sediment	10 days	% survival	PSEP, 1995; ASTM, 2004a; Vizon/CANTEST 1603
Sea urchin fertilization	*Strongylocentrotus purpuratus*	sediment pore water	20 minutes	% fertilization	ASTM, 2004b; Carr et al., 1996; USGS F10.26
Sand dollar embryo development	*Dendraster excentricus*	sediment/ water elutriate	48-96 hours	% normal embryo development and survival	PSEP, 1995; ASTM, 2004b; Vizon/CANTEST 1608

Table 6. Indices calculated to characterize the benthic invertebrate assemblages identified for the 2006 PSAMP sediment survey.

Benthic 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, 1974)	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 $H' = -\sum^{s}_{i=1} p_i \log p_i$, 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., 1985)	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 7. Sediment types characterizing 40 samples collected in the 2006 PSAMP sediment survey.

Sediment type	Percent sand	Percent silt + clay (Percent fines)	Range of percent gravel for sediment type	Number of stations with this sediment type	Area (km^2)	Percent of total study area
Sand	>80	<20	0.1 – 15.6	4	33.48	9.28
Silty sand	60 – 80	20 – <40	0.1 – 30.8	4	26.53	7.36
Mixed	20 – <60	40 – 80	0.1 – 4.5	6	69.51	19.27
Silt + clay	<20	>80	0.1 – 0.95	26	231.11	64.09

Table 8. Chemical detection rates by chemical group in the 2006 PSAMP sediment survey.

Chemical Group	Number of Chemicals in Group	≥85% Detected		≥50% Nondetect		>15% and <50% Nondetect	
		Number of Chemicals	Chemicals	Number of Chemicals	Chemicals	Number of Chemicals	Chemicals
BNA	28	5	2-Methylphenol; 4-Methylphenol; Carbazole; Cholesterol; Dibenzofuran	21	All but seven	2	2,4-Dimethylphenol; Isophorone
Metal	11	9	All but two	0	None	2	Selenium; Silver
PAH	26	25	All but one	0	None	1	Naphthalene
PBDE	13	0	None	12	All but one	1	PBDE- 47
PCB Congener	21	0	None	21	All	0	None
PCB Aroclor	9	0	None	9	All	0	None
Pesticide	23	0	None	23	All	0	None

Table 9. Mean SQS quotients (mSQSq) for 40 sediment samples from the 2006 PSAMP survey of the Strait of Georgia region.

The mSQSq is the average ratio of contaminant concentrations to respective SQS, i.e., $mSQSq = (1/n)\Sigma[\text{conc'n chemical}_i]/SQS_i$.

Station, location	Mean SQS Quotient	Station, location	Mean SQS Quotient
3, Birch Bay	0.040	189, Boundary Bay	0.060
13, Samish Bay/Bellingham Bay	0.057	195, Bellingham Bay	0.130
19, Cherry Point	0.052	213, Bellingham Bay (central)	0.080
21, Bellingham Bay	0.072	227, Bellingham Bay (central)	0.099
29, Boundary Bay	0.055	237, Boundary Bay	0.055
35, Bellingham Bay	0.062	259, Boundary Bay	0.063
37, Samish Bay/Bellingham Bay	0.058	277, Bellingham Bay (central)	0.093
45, Samish Bay/Bellingham Bay	0.053	299, Bellingham Bay	0.070
53, Bellingham Bay	0.277	309, Boundary Bay	0.051
61, Boundary Bay	0.049	325, Fidalgo Bay (outer)	0.050
67, Semiahmoo Bay	0.060	379, Bellingham Bay	0.224
85, Bellingham Bay	0.069	405, Boundary Bay	0.063
93, Semiahmoo Bay	0.056	437, Boundary Bay	0.047
101, Bellingham Bay	0.056	501, Boundary Bay	0.054
109, Semiahmoo Bay	0.056	507, Bellingham Bay	0.083
117, Samish Bay/Bellingham Bay	0.054	539, Boundary Bay	0.085
125, Birch Bay	0.052	565, Boundary Bay	0.052
149, Bellingham Bay	0.066	597, Boundary Bay	0.056
163, Bellingham Bay	0.110	645, Boundary Bay	0.033
165, Bellingham Bay	0.080	667, Boundary Bay	0.046

Table 10. Results of amphipod survival tests for 40 sediment samples from the 2006 PSAMP survey of the Strait of Georgia region.

Data are expressed as mean percent survival and as percentage of control response. Tests were performed with Eohaustorius estuarius.
** = Results statistically significant (t-test, α = 0.05).*
*** = Results statistically significant and mean survival <80% of control.*

Station, location	Mean amphipod survival (%)	Mean amphipod survival as % of control	Statistical significance
3, Birch Bay	91.0	93.8	
13, Samish Bay/Bellingham Bay	95.0	99.0	
19, Cherry Point	90.0	91.8	
21, Bellingham Bay	89.0	92.7	
29, Boundary Bay	83.0	83.0	*
35, Bellingham Bay	91.0	92.9	
37, Samish Bay/Bellingham Bay	90.0	93.8	
45, Samish Bay/Bellingham Bay	88.0	91.7	
53, Bellingham Bay	88.0	91.7	
61, Boundary Bay	86.0	88.7	*
67, Semiahmoo Bay	86.0	86.0	*
85, Bellingham Bay	92.0	93.9	
93, Semiahmoo Bay	87.0	87.0	*
101, Bellingham Bay	85.0	88.5	*
109, Semiahmoo Bay	93.0	93.0	*
117, Samish Bay/Bellingham Bay	86.0	89.6	
125, Birch Bay	95.0	97.9	
149, Bellingham Bay	86.0	89.6	
163, Bellingham Bay	88.0	89.8	*
165, Bellingham Bay	67.0	69.8	**
189, Boundary Bay	95.0	97.9	
195, Bellingham Bay	75.0	76.5	**
213, Bellingham Bay (central)	89.0	92.7	
227, Bellingham Bay (central)	78.0	79.6	**
237, Boundary Bay	82.0	82.0	*
259, Boundary Bay	91.0	92.9	
277, Bellingham Bay (central)	81.0	84.4	*
299, Bellingham Bay	81.5	83.2	*
309, Boundary Bay	97.0	97.0	
325, Fidalgo Bay (outer)	91.0	94.8	
379, Bellingham Bay	84.0	85.7	*

Station, location	Mean amphipod survival (%)	Mean amphipod survival as % of control	Statistical significance
405, Boundary Bay	88.0	90.7	
437, Boundary Bay	99.0	99.0	
501, Boundary Bay	87.0	87.0	*
507, Bellingham Bay	83.0	84.7	*
539, Boundary Bay	96.0	98.0	
565, Boundary Bay	87.0	89.7	*
597, Boundary Bay	90.0	92.8	
645, Boundary Bay	96.0	99.0	
667, Boundary Bay	95.0	97.9	

Table 11. Results of sea urchin fertilization tests in pore waters from 40 sediment samples from the 2006 PSAMP survey of the Strait of Georgia region.

Data are expressed as mean percent fertilization and as percentage of control response.
Tests were performed with Strongylocentrotus purpuratus.
** = Results statistically significant (t-test, α = 0.05).*
*** = Results statistically significant and mean percent fertilization <80% of control.*

Station, location	100% pore water			50% pore water			25% pore water		
	Mean fertilization (%)	Mean fertilization (% of control)	Statistical significance	Mean fertilization (%)	Mean fertilization (% of control)	Statistical significance	Mean fertilization (%)	Mean fertilization (% of control)	Statistical significance
3, Birch Bay	99.4	107.6		99.8	100.8		99.8	100.6	
13, Samish Bay/ Bellingham Bay	98.6	106.7		99.4	100.4		99.2	100.0	
19, Cherry Point	99.6	107.8		99.8	100.8		100.0	100.8	
21, Bellingham Bay	99.2	107.4		100.0	101.0		99.5	100.3	
29, Boundary Bay	99.6	107.8		99.6	100.6		99.8	100.6	
35, Bellingham Bay	98.8	106.9		99.6	100.6		100.0	100.8	
37, Samish Bay/ Bellingham Bay	100.0	108.2		99.6	100.6		99.6	100.4	
45, Samish Bay/ Bellingham Bay	99.4	107.6		100.0	101.0		99.4	100.2	
53, Bellingham Bay	99.2	107.4		99.4	100.4		99.4	100.2	
61, Boundary Bay	99.8	108.0		99.2	100.2		99.8	100.6	
67, Semiahmoo Bay	100.0	108.2		99.2	100.2		99.8	100.6	
85, Bellingham Bay	95.8	103.7		98.2	99.2		99.4	100.2	
93, Semiahmoo Bay	99.8	108.0		99.6	100.6		99.4	100.2	
101, Bellingham Bay	98.8	106.9		99.6	100.6		99.8	100.6	
109, Semiahmoo Bay	99.6	107.8		99.2	100.2		98.8	99.6	
117, Samish Bay/ Bellingham Bay	99.6	107.8		99.0	100.0		99.0	99.8	
125, Birch Bay	99.8	108.0		99.4	100.4		98.6	99.4	

Station, location	100% pore water			50% pore water			25% pore water		
	Mean fertilization (%)	Mean fertilization (% of control)	Statistical significance	Mean fertilization (%)	Mean fertilization (% of control)	Statistical significance	Mean fertilization (%)	Mean fertilization (% of control)	Statistical significance
149, Bellingham Bay	99.8	108.0		99.2	100.2		98.0	98.8	
163, Bellingham Bay	99.0	107.1		100.0	101.0		99.2	100.0	
165, Bellingham Bay	99.2	107.4		99.4	100.4		98.6	99.4	
189, Boundary Bay	99.2	110.5		99.6	100.0		99.8	101.0	
195, Bellingham Bay	80.4	89.6		99.4	99.8		99.0	100.2	
213, Bellingham Bay (central)	99.2	110.5		99.4	99.8		99.4	100.6	
227, Bellingham Bay (central)	98.2	109.4		100.0	100.4		99.5	100.7	
237, Boundary Bay	99.8	111.2		99.8	100.2		99.4	100.6	
259, Boundary Bay	100.0	111.4		99.6	100.0		99.6	100.8	
277, Bellingham Bay (central)	100.0	111.4		98.8	99.2		98.8	100.0	
299, Bellingham Bay	89.8	100.1		99.2	99.6		98.2	99.4	
309, Boundary Bay	99.8	111.2		99.6	100.0		100.0	101.2	
325, Fidalgo Bay (outer)	99.6	111.0		100.0	100.4		100.0	101.2	
379, Bellingham Bay	83.6	93.1		99.8	100.2		97.6	98.8	
405, Boundary Bay	99.4	110.8		100.0	100.4		100.0	101.2	
437, Boundary Bay	100.0	111.4		99.8	100.2		99.2	100.4	
501, Boundary Bay	100.0	111.4		99.6	100.0		99.2	100.4	
507, Bellingham Bay	97.2	108.3		99.6	100.0		99.0	100.2	
539, Boundary Bay	99.6	111.0		100.0	100.4		99.4	100.6	
565, Boundary Bay	99.2	110.5		99.8	100.2		98.6	99.8	
597, Boundary Bay	99.6	111.0		99.8	100.2		99.6	100.8	
645, Boundary Bay	99.8	111.2		99.8	100.2		99.6	100.8	
667, Boundary Bay	99.6	111.0		99.2	99.6		99.0	100.2	

Table 12. Results of sand dollar embryo tests for 40 sediment samples from the 2006 PSAMP survey of the Strait of Georgia region.

Data are expressed as mean combined normal development and survival for each sample.
All results shown are saltwater-control-corrected. Tests were performed with Dendraster excentricus.
** = Results statistically significantly different from sediment reference (t-test, α=0.05).*
*** = Results statistically significantly different from sediment reference, and mean combined normal survival < 85% of reference.*

Station, location	Mean combined normal development and survival as % of saltwater control	Mean combined normal development and survival as % of sediment control	Mean combined normal development and survival as % of reference sediment	Statistical significance	Comments
3, Birch Bay	101.38	90.69	143.73		control sample failed
13, Samish Bay/Bellingham Bay	53.46	85.11	128.97		
19, Cherry Point	101.37	99.86	205.57		control sample failed
21, Bellingham Bay	46.77	74.45	112.81		
29, Boundary Bay	29.37	53.30	67.41		
35, Bellingham Bay	64.01	63.06	129.81		control sample failed
37, Samish Bay/Bellingham Bay	94.11	149.82	227.02		
45, Samish Bay/Bellingham Bay	54.27	86.40	130.92		
53, Bellingham Bay	31.29	49.82	75.49		
61, Boundary Bay	82.32	73.64	116.71		control sample failed
67, Semiahmoo Bay	29.85	54.19	68.52	**	
85, Bellingham Bay	95.33	93.91	193.31		control sample failed
93, Semiahmoo Bay	35.68	64.76	81.89		
101, Bellingham Bay	64.32	102.39	155.15		
109, Semiahmoo Bay	15.41	27.97	35.38	**	
117, Samish Bay/Bellingham Bay	72.40	115.26	174.65		
125, Birch Bay	70.53	63.09	100.00		control sample failed
149, Bellingham Bay	52.89	84.19	127.58		
163, Bellingham Bay	111.26	109.61	225.63		control sample failed

Station, location	Mean combined normal development and survival as % of saltwater control	Mean combined normal development and survival as % of sediment control	Mean combined normal development and survival as % of reference sediment	Statistical significance	Comments
165, Bellingham Bay	68.59	109.19	165.46		
189, Boundary Bay	63.06	56.41	89.42		control sample failed
195, Bellingham Bay	82.42	81.19	167.13		control sample failed
213, Bellingham Bay (central)	73.21	116.54	176.60		
227, Bellingham Bay (central)	87.77	86.47	177.99		control sample failed
237, Boundary Bay	33.98	61.67	77.99		
259, Boundary Bay	92.17	90.80	186.91		control sample failed
277, Bellingham Bay (central)	55.08	87.68	132.87		
299, Bellingham Bay	90.80	89.45	184.12		control sample failed
309, Boundary Bay	16.99	30.84	39.00	**	
325, Fidalgo Bay (outer)	90.18	143.57	217.55		
379, Bellingham Bay	77.75	76.59	157.66		control sample failed
405, Boundary Bay	80.16	71.70	113.65		control sample failed
437, Boundary Bay	6.55	11.89	15.04	**	
501, Boundary Bay	61.65	111.89	141.50		
507, Bellingham Bay	113.05	111.37	229.25		control sample failed
539, Boundary Bay	87.77	86.47	177.99		control sample failed
565, Boundary Bay	71.12	63.62	100.84		control sample failed
597, Boundary Bay	92.73	82.95	131.48		control sample failed
645, Boundary Bay	73.87	66.08	104.74		control sample failed
667, Boundary Bay	89.59	80.14	127.02		control sample failed

Table 13. Estimated incidence and spatial extent of toxicity in the 2006 PSAMP survey of the Strait of Georgia region.

The number and percent of stations and the size (km^2) and percent of the total study area are shown for significant responses.
The shaded area = total number of stations and total area sampled.

Critical Value Exceeded	Incidence		Spatial Extent	
	No. (%) of stations		km^2	(%) of total study area
Total Study Area	**40**	**(100.0)**	**360.6**	**(100.0)**
Amphipod survival (10-day)[1]	3	(7.5)	19.7	(5.5)
Echinoderm embryo (72-hr)[2]	4	(10.0)	46.3	(12.9)
Urchin fertilization (100% pore water)[3]	0	(0.0)	0.0	(0.0)
Total for any test	**7**	**(17.5)**	**66.0**	**(18.3)**

[1] Results statistically significant and mean percent survival <80% of control
[2] Results statistically significant and mean percent normal survival <85% of reference
[3] Results statistically significant and mean percent fertilization <80% of control

Table 14. Total benthos abundance, taxa richness, Pielou's evenness, and Swartz' Dominance Index calculated for the stations sampled in the 2006 PSAMP survey of the Strait of Georgia region.

Station, location	Total benthic abundance (# orgs/0.1 m^2)	Taxa richness (# taxa/0.1 m^2)	Pielou's evenness (J')	Swartz' Dominance Index (# taxa)
3, Birch Bay	581	43	0.65	6
13, Samish Bay/Bellingham Bay	478	54	0.72	10
19, Cherry Point	854	65	0.71	10
21, Bellingham Bay	170	25	0.76	7
29, Boundary Bay	355	25	0.83	8
35, Bellingham Bay	308	14	0.40	1
37, Samish Bay/Bellingham Bay	419	51	0.71	9
45, Samish Bay/Bellingham Bay	721	50	0.77	10
53, Bellingham Bay	233	19	0.53	2
61, Boundary Bay	277	49	0.79	14
67, Semiahmoo Bay	225	29	0.82	8
85, Bellingham Bay	159	17	0.57	3
93, Semiahmoo Bay	243	32	0.79	9
101, Bellingham Bay	734	49	0.60	6
109, Semiahmoo Bay	102	24	0.83	7
117, Samish Bay/Bellingham Bay	557	55	0.77	11
125, Birch Bay	500	31	0.70	6
149, Bellingham Bay	313	33	0.68	6
163, Bellingham Bay	355	20	0.48	3
165, Bellingham Bay	547	48	0.67	6
189, Boundary Bay	551	70	0.79	17
195, Bellingham Bay	1167	17	0.29	1
213, Bellingham Bay (central)	159	23	0.76	6
227, Bellingham Bay (central)	78	19	0.77	6
237, Boundary Bay	527	34	0.68	7
259, Boundary Bay	516	51	0.65	8
277, Bellingham Bay (central)	132	18	0.71	5
299, Bellingham Bay	292	15	0.44	2
309, Boundary Bay	1270	189	0.78	32
325, Fidalgo Bay (outer)	284	48	0.80	15
379, Bellingham Bay	1681	27	0.47	2
405, Boundary Bay	364	56	0.78	13
437, Boundary Bay	1129	137	0.78	27

Station, location	Total benthic abundance (# orgs/0.1 m^2)	Taxa richness (# taxa/0.1 m^2)	Pielou's evenness (J')	Swartz' Dominance Index (# taxa)
501, Boundary Bay	328	37	0.76	9
507, Bellingham Bay	472	22	0.73	5
539, Boundary Bay	741	89	0.81	22
565, Boundary Bay	261	38	0.73	9
597, Boundary Bay	405	54	0.72	11
645, Boundary Bay	2136	88	0.44	3
667, Boundary Bay	558	78	0.76	15
Mean	529.5	46.1	0.687	8.9
Standard Deviation	429.0	34.1	0.133	6.6
Median	412	37.5	0.725	7.5
Minimum	78	14	0.29	1
Maximum	2136	189	0.83	32

Table 15. Total abundance of the benthos, major taxa abundance, and major taxa percent abundance calculated for the stations sampled in the 2006 PSAMP survey of the Strait of Georgia region.

Station	Total benthic abundance (# orgs/ 0.1 m^2)	Annelida	Annelida % of total abundance	Arthro-poda	Arthropoda % of total abundance	Echino-dermata	Echino-dermata % of total abundance	Mollusca	Mollusca % of total abundance	Misc. taxa	Misc. taxa % of total abundance
3	581	121	20.83	52	8.95	0	0.00	403	69.36	5	0.86
13	478	81	16.95	59	12.34	2	0.42	332	69.46	4	0.84
19	854	160	18.74	86	10.07	4	0.47	591	69.20	13	1.52
21	170	83	48.82	14	8.24	1	0.59	72	42.35	0	0.00
29	355	52	14.65	135	38.03	42	11.83	126	35.49	0	0.00
35	308	300	97.40	3	0.97	0	0.00	4	1.30	1	0.32
37	419	127	30.31	113	26.97	114	27.21	56	13.37	9	2.15
45	721	227	31.48	124	17.20	49	6.80	320	44.38	1	0.14
53	233	213	91.42	9	3.86	0	0.00	11	4.72	0	0.00
61	277	77	27.80	63	22.74	74	26.71	56	20.22	7	2.53
67	225	67	29.78	74	32.89	25	11.11	56	24.89	3	1.33
85	159	137	86.16	3	1.89	0	0.00	18	11.32	1	0.63
93	243	36	14.81	96	39.51	34	13.99	76	31.28	1	0.41
101	734	498	67.85	39	5.31	0	0.00	193	26.29	4	0.54
109	102	38	37.25	18	17.65	12	11.76	33	32.35	1	0.98
117	557	178	31.96	113	20.29	43	7.72	218	39.14	5	0.90
125	500	183	36.60	225	45.00	3	0.60	80	16.00	9	1.80
149	313	182	58.15	5	1.60	0	0.00	123	39.30	3	0.96
163	355	332	93.52	15	4.23	0	0.00	7	1.97	1	0.28
165	547	267	48.81	79	14.44	183	33.46	13	2.38	5	0.91
189	551	268	48.64	139	25.23	93	16.88	32	5.81	19	3.45
195	1167	1161	99.49	0	0.00	0	0.00	6	0.51	0	0.00
213	159	88	55.35	14	8.81	0	0.00	56	35.22	1	0.63
227	78	67	85.90	3	3.85	0	0.00	7	8.97	1	1.28
237	527	107	20.30	238	45.16	35	6.64	144	27.32	3	0.57
259	516	90	17.44	286	55.43	99	19.19	39	7.56	2	0.39
277	132	106	80.30	5	3.79	1	0.76	19	14.39	1	0.76

Station	Total benthic abundance (# orgs/ 0.1 m^2)	Annelida	Annelida % of total abundance	Arthro-poda	Arthropoda % of total abundance	Echino-dermata	Echino-dermata % of total abundance	Mollusca	Mollusca % of total abundance	Misc. taxa	Misc. taxa % of total abundance
299	292	275	94.18	9	3.08	0	0.00	5	1.71	3	1.03
309	1270	903	71.10	139	10.94	22	1.73	137	10.79	69	5.43
325	284	176	61.97	30	10.56	14	4.93	54	19.01	10	3.52
379	1681	1647	97.98	9	0.54	0	0.00	24	1.43	1	0.06
405	364	104	28.57	76	20.88	70	19.23	100	27.47	14	3.85
437	1129	899	79.63	55	4.87	7	0.62	129	11.43	39	3.45
501	328	43	13.11	122	37.20	73	22.26	87	26.52	3	0.91
507	472	414	87.71	21	4.45	6	1.27	13	2.75	18	3.81
539	741	354	47.77	139	18.76	72	9.72	127	17.14	49	6.61
565	261	37	14.18	138	52.87	36	13.79	50	19.16	0	0.00
597	405	66	16.30	153	37.78	109	26.91	69	17.04	8	1.98
645	2136	157	7.35	132	6.18	10	0.47	1822	85.30	15	0.70
667	558	286	51.25	105	18.82	108	19.35	49	8.78	10	1.79
Mean	529.5	265.2	49.55	78.5	17.53	33.5	7.91	143.9	23.58	8.5	1.43
Std. Dev.	429.0	333.3	29.99	71.1	15.76	44.08	9.81	298.2	21.11	14.1	1.55
Median	412	158.5	48.2	68.5	11.64	11	1.5	56	18.08	3	0.91
Minimum	78	36	7.35	0	0	0	0	4	0.51	0	0
Maximum	2136	1647	99.49	286	55.43	183	33.46	1822	85.30	69	6.61

Table 16. Mean and median benthic indices at stations with adversely affected and unaffected benthos in the 2006 PSAMP survey of the Strait of Georgia region.

Benthic index	Adversely affected benthos		Unaffected benthos	
	19 stations, representing 44.1% of study area		21 stations, representing 55.9% of study area	
	Mean	Median	Mean	Median
Total abundance (# orgs/0.1 m^2)	418.5	292.0	630.0	516.0
Taxa richness (# taxa/0.1 m^2)	26.0	23.0	64.2	54.0
Pielou's Evenness (J')	0.63	0.67	0.74	0.76
Swartz' Dominance Index (# taxa)	4.8	6.0	12.7	10.0
Annelid abundance	317.5	182.0	217.9	157.0
Arthropod abundance	24.6	14.0	127.1	124.0
Mollusc abundance	59.9	19.0	219.9	100.0
Echinoderm abundance	13.8	0.0	51.4	43.0
Abundance of misc. taxa	2.6	1.0	13.8	9.0

Table 17. Estimated incidence and spatial extent of degraded sediments in the 2006 PSAMP survey of the Strait of Georgia region, as measured with the Sediment Quality Triad Index.

Sediment Quality Triad Index Category	Incidence		Spatial extent	
	No. (%) of stations		km^2 (%) of study area	
Strait of Georgia monitoring region	**40**	**(100.0)**	**360.6**	**(100.0)**
High[1]	**19**	**(47.5)**	**188.3**	**(52.2)**
Intermediate/High[2]	**16**	**(40.0)**	**119.6**	**(33.2)**
Chemistry	0	(0.0)	0.0	(0.0)
Toxicity*	2	(5.0)	13.3	(3.7)
Benthos	14	(35.0)	106.33	(29.5)
Intermediate/Degraded[3]	**5**	**(12.5)**	**52.74**	**(14.6)**
Chemistry/toxicity*	0	(0.0)	0.0	(0.0)
Chemistry/benthos	0	(0.0)	0.0	(0.0)
Benthos/toxicity*	5	(12.5)	52.7	(14.6)
Degraded[4]	**0**	**(0.0)**	**0.0**	**(0.0)**

[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)
* All three toxicity tests

Table 18. Changes in sediment grain size, TOC, and contaminant concentrations bay-wide from 1997 to 2006, Strait of Georgia region (significant at α=0.05).

↑ = increase, ↓ = decrease, -- = no change, ? = significant only at α=0.10,
* = too few detects in 1997, ** = too few detects in 2006.

Contaminant	Results of CDF Comparisons [1] (Weighted)	Results of Unweighted Nonparametric Median Comparisons [2]
Percent Fines (Silt-Clay)	--	--
Total Organic Carbon	--	--
Metals		
Arsenic [3]	--	--
Cadmium [3]	*	↓
Chromium [3]	--	↑
Copper [3]	--	--
Lead [3]	*	↑
Mercury [3]	--	--
Nickel	--	--
Selenium	**	↑
Silver [3]	**	↓
Tin	*	↓
Zinc [3]	↑	↑
Polycyclic Aromatic Hydrocarbons (PAHs)		
1,6,7-Trimethylnaphthalene	↑	↑
1-Methylnaphthalene	↑	↑
1-Methylphenanthrene	↑	↑
2,6-Dimethylnaphthalene	↑	↑
2-Methylnaphthalene [3]	↑	↑
Acenaphthene [3,4]	*	--
Acenaphthylene [3,4]	↑	--
Anthracene [3,4]	--	--
Benzo(a)anthracene [3,5]	--	--
Benzo(a)pyrene [3,5]	--	--
Total Benzofluoranthenes [3,5]	--	--
Benzo(g,h,i)perylene [3,5]	--	--
Benzo[e]pyrene	--	--
Biphenyl	--	--
Chrysene [3,5]	--	--
Dibenzo(a,h)anthracene [3,5]	*	--
Dibenzothiophene	↑	↑
Fluoranthene [3,5]	--	--

Contaminant	Results of CDF Comparisons [1] (Weighted)	Results of Unweighted Nonparametric Median Comparisons [2]
PAHs (continued)		
Fluorene [3,4]	↑	↑?
Indeno(1,2, 3-c,d)pyrene [3,5]	↓	↓?
Naphthalene [3,4]	**	↑
Perylene	↑	↑
Phenanthrene [3,4]	↑	--
Pyrene [3,5]	--	--
Retene	--	--
Total LPAH [3]	↑	--
Total HPAH [3]	--	--
Base/Neutral/Acid (BNA) organic compounds		
Dibenzofuran [3]	↑	↑
Other organic compounds	**too few detects**	**too few detects**
Mean SQS quotient [6] (all)	--	--
Mean SQS quotient [6] (metals only)	--	--
Mean SQS quotient [6] (LPAHs only)	↑	↑
Mean SQS quotient [6] (HPAHs only)	--	--

[1] Wald F test.
[2] Generalized Wilcoxon test when nondetects present; Kruskal-Wallis test when no nondetects present.
[3] Subject to Sediment Quality Standard (SQS).
[4] Summed for Total LPAH SQS.
[5] Summed for Total HPAH SQS.
[6] Mean SQS quotient = $1/n \Sigma_i$ [sample concentration/SQS for $chemical_i$], i=1,...,n

Table 19. Changes in benthic invertebrate measures bay-wide from 1997 to 2006, Strait of Georgia region (significant at α=0.05).

↑ = increase, ↓ = decrease, -- = no change, ? = significant only at α = 0.10.

Benthic invertebrate measure	Results of CDF Comparisons [1] (Weighted)	Results of Unweighted Nonparametric Median Comparisons [2]
Total abundance	↓	↓
Taxa richness	↓	↓
Pielou's evenness (J')	↑	--
Swartz' dominance index (SDI)	↑	--
SDI standardized by taxa richness	↑	↑
Annelid abundance	↓	↓
Arthropod abundance	↓	↓
Echinoderm abundance	↓	↓
Mollusc abundance	--	↓?
Abundance of miscellaneous taxa	--	↓

[1] Wald F test.
[2] Kruskal-Wallis test.

Table 20. Summary statistics for benthic indices in the 1997 PSAMP/NOAA survey and the 2006 PSAMP survey of the Strait of Georgia region.

Benthic index	1997 (N=61)					2006 (N=40)				
	Mean	StDev	Median	Min	Max	Mean	StDev	Median	Min	Max
Total abundance (# orgs/0.1 m^2)	1354.7	1456.45	856	54	7685	529.6	429.0	412	78	2136
Taxa richness (# taxa/0.1 m^2)	51.1	20.69	46	11	112	45.7	34.06	37.5	13	188
Pielou's Evenness (J')	0.63	0.153	0.63	0.25	0.89	0.68	0.14	0.72	0.29	0.83
Swartz' Dominance (SDI) (# taxa)	8.0	5.80	6	1	27	8.75	6.65	7.5	1	32
SDI standardized by taxa richness (SDISTD) (%)	15.8	9.32	12.9	3.2	45.5	19.4	7.60	19.4	3.4	32
Annelid abundance	627.8	1030.31	272	37	5084	265.2	333.34	158.5	36	1647
Arthropod abundance	387	468.13	176	0	2062	78.5	71.11	68.5	0	286
Mollusc abundance	220.4	368.97	105	0	2581	143.9	298.25	56	4	1822
Echinoderm abundance	101.7	149.89	41	0	650	33.5	44.08	11	0	183
Abundance of misc. taxa	13.5	22.31	6	0	125	8.5	14.07	3	0	69

Table 21. Changes in incidence and spatial extent of Sediment Quality Triad Index results from 1997 to 2006, Strait of Georgia region (significant at α=0.05).

↑ = increase, ↓ = decrease, -- = no change, ? = significant only at α = 0.10.

SQTI Element	1997		2006			
	Incidence (% of stns)	Spatial Extent (% of area)	Incidence (% of stns)	Change? [1]	Spatial Extent (% of area)	Change? [2]
Chemistry	14.8	9.8	0.0	↓	0.0	↓
Toxicity*	8.2	2.5	7.5	--	5.5	↑
Benthos	16.4	15.4	47.5	↑	44.1	↑
SQTI Category						
High	68.9	76.0	52.5	↓?	55.9	↓
Intermediate/High	23.0	20.4	40.0	↑?	38.7	↑
Intermediate/Degraded	8.2	3.6	7.5	--	5.5	--
Degraded	0.0	0.0	0.0	--	0.0	--

*Amphipod mortality and sea urchin fertilization tests only.
[1] Two-proportion test, normal approximation.
[2] Chi-square test.

Table 22. Incidence and spatial extent of chemical contamination among eight PSEMP Sediment Component regions and all of Puget Sound.

Monitoring Region	Year(s) sampled	Numbers of Samples	Percent of samples > SQS	Percent of area > SQS
Strait of Georgia	1997	61	14.8	9.8
	2006	40	0.0	0.0
Whidbey Basin	1997	39	12.8	9.1
	2007	40	results in preparation	results in preparation
Central Puget Sound	1998-1999	128	32.0	4.0
	2008-2009	80	results in preparation	results in preparation
South Puget Sound	1999	42	2.4	1.7
Hood Canal	1999	21	4.8	0.5
	2004	30	0.0	0.0
San Juan Islands	2002-2003	30	3.3	3.3
Eastern Strait of Juan de Fuca	2002-2003	30	6.7	3.3
Admiralty Inlet	1998-2003	30	3.3	2.2
All of Puget Sound	1997-2003	381	15.7	4.8

Table 23. Incidence and spatial extent of toxicity from eight PSEMP Sediment Component regions and all of Puget Sound.

Monitoring Region	Year(s) sampled	Numbers of Samples	Sea Urchin Fertilization Test		Amphipod Survival Test		
			Incidence (% of stations)	Spatial Extent (% of area)	Test Species	Incidence (% of stations)	Spatial Extent (% of area)
Strait of Georgia	1997	61	8.2	2.5	*Ampelisca abdita*	0.0	0.0
	2006	40	0.0	0.0	*Eohaustorius estuarius*	7.5	5.5
Whidbey Basin	1997	39	25.6	6.0	*Ampelisca abdita*	0.0	0.0
	2007	40	results in preparation		No amphipod test results for 2007.		
Central Puget Sound	1998-1999	128	7.8	0.6	*Ampelisca abdita*	0.8	0.2
	2008-2009	80	results in preparation		*Eohaustorius estuarius*	results in preparation	
South Puget Sound	1999	42	9.5	3.0	*Ampelisca abdita*	0.0	0.0
Hood Canal	1999	21	14.3	11.7	*Ampelisca abdita*	0.0	0.0
	2004	30	16.7	17.7	No amphipod test performed in 2004.		
San Juan Islands	2002-2003	30	3.3	3.3	*Eohaustorius estuarius*	3.3	3.3
Eastern Strait of Juan de Fuca	2002-2003	30	17.7	13.3	*Eohaustorius estuarius*	0.0	0.0
Admiralty Inlet	1998-2003	30	6.7	11.1	*Ampelisca abdita*, *Eohaustorius estuarius*	0.0	0.0
All of Puget Sound	1997-2003	381	10.2	4.5	*Ampelisca abdita*, *Eohaustorius estuarius*	0.3	0.05

Table 24. Incidence and spatial extent of adversely affected benthos from eight PSEMP Sediment Component regions and all of Puget Sound.

Monitoring Region	Year(s) sampled	Numbers of Samples	Percent of Stations with Adversely Affected Benthos	Percent of Area with Adversely Affected Benthos
Strait of Georgia	1997	61	16.4	15.4
	2006	40	47.5	44.1
Whidbey Basin	1997	39	74.4	69.0
	2007	40	results in preparation	results in preparation
Central Puget Sound	1998-1999	128	32.8	6.9
	2008-2009	80	results in preparation	results in preparation
South Puget Sound	1999	42	42.9	38.2
Hood Canal	1999	21	66.7	68.0
	2004	30	76.7	78.1
San Juan Islands	2002-2003	30	66.7	66.7
Eastern Strait of Juan de Fuca	2002-2003	30	50.0	63.8
Admiralty Inlet	1998-2003	30	6.7	4.5
All of Puget Sound	1997-2003	381	39.4	34.5

Table 25. Incidence and spatial extent of four categories of relative sediment quality for eight PSEMP Sediment Component regions and all of Puget Sound, based on the Sediment Quality Triad Index (SQTI).

Monitoring region	Year(s) sampled	Incidence (% of stations) in each category				Spatial extent (% of study area) in each category			
		High	Intermediate/ High	Intermediate/ Degraded	Degraded	High	Intermediate/ High	Intermediate/ Degraded	Degraded
Strait of Georgia	1997	68.9	23.0	8.2	0.0	76.0	20.4	3.6	0.0
	2006	52.5	40.0	7.5	0.0	55.9	38.7	5.5	0.0
Whidbey Basin	1997	23.1	48.7	20.5	7.7	28.0	60.0	11.9	0.1
	2007	results in preparation				results in preparation			
Central Puget Sound	1998-99	53.9	22.7	19.5	3.9	90.9	6.8	2.0	0.3
	2008-09	results in preparation				results in preparation			
South Puget Sound	1999	57.1	33.3	7.1	2.4	61.8	35.2	1.3	1.7
Hood Canal	1999	33.3	47.6	19.1	0	32.0	55.8	12.2	0
	2004	23.3	60.0	16.7	0	21.9	60.4	17.7	0
San Juan Islands	2002-03	30.0	63.3	6.7	0.0	30.0	63.3	6.7	0.0
Eastern Strait of Juan de Fuca	2002-03	46.7	36.7	16.7	0.0	34.8	45.7	19.5	0.0
Admiralty Inlet	1998-2003	83.3	16.7	0.0	0.0	82.2	17.8	0.0	0.0
All of Puget Sound	1997-2003	52.5	31.5	13.4	2.6	62.4	31.6	5.7	0.4

Appendices

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Appendix A. Glossary, Acronyms, and Abbreviations

Glossary

Amphipod: a type of small crustacean.

Anthropogenic: human-caused.

Assemblage: a group of organisms collected from the same location.

Benthic: bottom.

Benthic infauna (or **benthos**)**:** tiny sediment-dwelling invertebrates, including a wide variety of organisms that live on or in marine sediments.

Biota: living organisms.

Degree of response: in toxicity testing, the magnitude of the response, e.g., the percent normal in a sample or group of samples, percent survival, percent fertilization, or the Microtox EC50 photic response.

Demersal: living near the bottom.

Echinoderm: a group of invertebrates including brittle stars, sea urchins, and sea cucumbers.

EC50: Median Effective Concentration (concentration required to induce a toxic response in 50% of the test population)

ERL: Effects Range Low, NOAA sediment quality guideline established by the 10th percentile of chemical concentrations associated with adverse effects in the benthos

ERM: Effects Range Median, NOAA sediment quality guideline established by the 50th percentile of chemical concentrations associated with adverse effects in the benthos

Geomorphological: dealing with the nature of the surface of the Earth.

Incidence: for chemical contamination, toxicity, or the Sediment Quality Triad, the number and percentage of samples indicating a response.

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

Pore water: the water filling the spaces between grains of sediment.

Spatial extent: for chemical contamination, toxicity, or the Sediment Quality Triad, the areal extent, in km^2, and percentage of total study area affected.

Surficial: relating to or occurring on a surface.

Taxon: lowest level of identification for organisms.

Taxa: plural of taxon.

Taxa richness: number of different taxa.

Toxicant: Any chemical that has the potential of causing acute or chronic adverse effects in organisms.

Clean Water Act: A federal act passed in 1972 that contains provisions to restore and maintain the quality of the nation's waters.

Dissolved oxygen (DO): A measure of the amount of oxygen dissolved in water.

Parameter: Environmental constituent being measured. A physical, chemical, or biological property whose values determine environmental characteristics or behavior.

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.

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

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

10th percentile: A statistical number obtained from a distribution of a data set, below which 10% of the data exists and above which 90% of the data exists.

50th percentile: A statistical number obtained from a distribution of a data set, below which 50% of the data exists and above which 50% of the data exists; also known as the **median**.

90th percentile: A statistical number obtained from a distribution of a data set, below which 90% of the data exists and above which 10% of the data exists.

Acronyms and Abbreviations

ASTM	American Society for Testing Materials
BNA	Base/neutral/acid organic compounds
CI	Confidence interval
CL	Confidence limit
CSL	Cleanup Screening Level
EC50	Median Effective Concentration (see glossary)

Ecology	Washington State Department of Ecology
EIM	Environmental Information Management database
EPA	U.S. Environmental Protection Agency
ERL	Effects Range Low (see glossary)
ERM	Effects Range Median (see glossary)
GC/MS	Gas chromatography/mass spectrometry
GFAA	Graphite furnace atomic absorption
GIS	Geographic Information System software
GRTS	Generalized random tessellation stratified ICP-AES Inductively coupled plasma atomic emission spectroscopy
ICP-MS	Inductively coupled plasma mass spectroscopy
MEL	Manchester Environmental Laboratory
NCCR	National Coastal Condition Report (EPA)
NEPCCR	National Estuary Program Coastal Condition Report (EPA)
NOAA	The National Oceanic and Atmospheric Administration within the U.S. Department of Commerce
NOEC	No observed effect concentration
NS&T	NOAA's National Status and Trends Program
PAH	Polycyclic aromatic hydrocarbon, also known as polynuclear aromatic hydrocarbon
PBDE	Polybrominated diphenyl ether
PCB	Polychlorinated biphenyl
PSAMP	Puget Sound Assessment and Monitoring Program
PSEMP	Puget Sound Ecosystem Monitoring Program
PSEP	Puget Sound Estuary Program
QAPP	Quality assurance project plan
SIM	Selected ion monitoring
SMS	Sediment Management Standard
SOP	Standard operating procedure
SQS	Sediment Quality Standard
SQT	Sediment quality triad, a weight-of-evidence approach to sediment quality evaluations
SQTI	Ecology's Sediment Quality Triad Index
USGS	U.S. Geological Survey
WAC	Washington Administrative Code

Units of Measurement

°C	degrees Celsius
cm	centimeter, a unit of length equal to one-hundredth of a meter

dw	dry weight
ft	feet
g	gram, a unit of mass
kg or Kg	kilogram, a unit of mass equal to 1,000 grams
km	kilometer, a unit of length equal to 1,000 meters
l or L	liter, a unit of volume
m	meter, a unit of length
mg	milligram, a unit of mass equal to one-thousandth of a gram
mg/Kg	milligrams per kilogram (parts per million)
ml or mL	milliliter, a unit of volume equal to one-thousandth of a liter
mm	millimeter, a unit of length equal to one-thousandth of a meter
ng	nanogram, a unit of mass equal to one-billionth of a gram
ng/g	nanograms per gram (parts per billion)
ng/Kg	nanograms per kilogram (parts per trillion)
psu	practical salinity unit
µg or ug	microgram, a unit of mass equal to one-millionth of a gram
µg/g or ug/g	micrograms per gram (parts per million)
µg/Kg or ug/Kg	micrograms per kilogram (parts per billion)
µg/L or ug/L	micrograms per liter (parts per billion)
ww	wet weight

Appendices B through I are available on the Internet as a data supplement (zip file).

Appendix B. Activities in the Strait of Georgia Region

Appendix C. Navigation report

Appendix D. Field notes

Appendix E. Grain size data, graphical summaries, and QA

Appendix F. TOC and chemistry data, graphical summaries, and QA

Appendix G. Toxicity lab reports (including QA) and data

G-1. Amphipod survival and sand dollar larval development toxicity tests

G-2. Sea urchin fertilization toxicity test

Appendix H. Benthic invertebrates data, graphical summaries, and QA

Appendix I. Selected results for chemistry, toxicity, and infaunal analyses