Sediment Quality in Puget Sound: Changes in chemistry, toxicity, and benthic invertebrates at multiple geographic scales, 1989 – 2015

DEPARTMENT OF ECOLOGY
State of Washington

Monitoring Sediment Quality

The Washington State Department of Ecology (Ecology) monitors sediment condition throughout Puget Sound, including Puget Sound proper and the embayments within the southern Strait of Georgia, eastern Strait of Juan de Fuca, and San Juan Islands (Figure 1). Sediment condition is evaluated with calculated indices based on outcomes of laboratory analyses including:

- Chemistry - concentrations of potentially toxic chemicals
- Toxicity - sediment and porewater toxicity to test organisms
- Benthos - presence of sediment-dwelling invertebrates
- Triad - overall sediment quality; combination of the chemistry, toxicity, and benthic indices

This report covers the results from 2004-2014, referred to as the Second Round survey, and makes comparisons to results from 1997-2003, referred to as the Baseline, as well as results from 10 Long-term sites sampled for nearly three decades, 1989-2015.

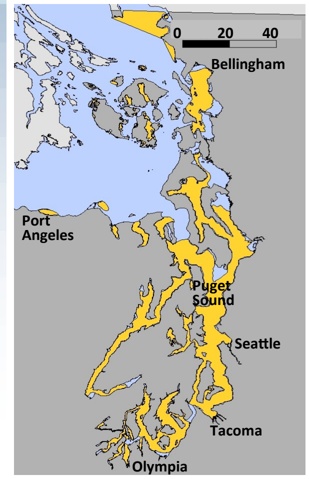


Figure 1. Puget Sound sediment monitoring study area.

Overall Results

Overall sediment quality, as measured with the Triad Index, decreased over the last decade (Figure 2). The Triad Index no longer meets the Puget Sound ecosystem recovery target value of 81 adopted by the Puget Sound Partnership (PSP). This was driven by both the Toxicity and Benthic Indices, which showed statistically significant declines from Baseline conditions. The Chemistry Index was statistically unchanged between the two sampling periods, and met the PSP ecosystem recovery target value.

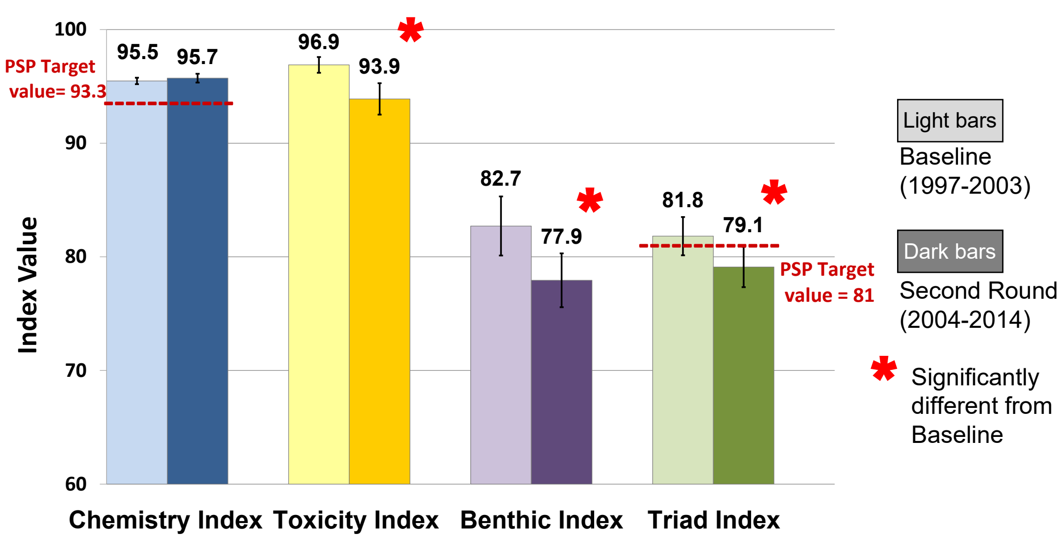


Figure 2. A comparison of weighted mean index values for Puget Sound, with 95% confidence intervals. PSP target values for the Chemistry and Triad Indices are shown as dashed red lines. Numerical values of the indices range from 0 (poor) to 100 (high quality).

Want more information?

Data and supporting information, including methods, are available for download.
Link to report:| [1803004]

Companion Report:
Information on annual monitoring of ten sentinel stations is provided by the Long-term program and is summarized in Partridge et al., 2018.

Ecology's website:
[Marine Water and Sediment Monitoring]

Sediment Monitoring in Puget Sound

Ecology sampled surface sediments throughout Puget Sound as part of the Puget Sound Ecosystem Monitoring Program (PSEMP). The Spatial monitoring program used a probabilistic survey design which balances the distribution of stations through a nested set of sampling frames. Sampling frames were developed at different spatial scales including: eight geographic regions; five strata based on geomorphology, waterbody characteristic and anthropogenic use; and the Puget Sound-wide study area (Figure 3). This survey design weights sample results by area. Ecology can then estimate the percent of area (spatial extent) of a sampling frame with given sediment conditions and compare results over multiple spatial scales and from multiple surveys.

Comparisons of the spatial extent of sediment conditions were made between the Baseline and Second Round surveys following Kincaid (2015). A similar sampling design, as well as similar field and laboratory methods were used in these surveys (Long et al., 2003), and changes over time could be examined.

Data from Ecology's Long-term sediment monitoring stations are also discussed in relation to the spatial sediment data. The Long-term program has characterized the condition of the benthos at ten sites annually, and sediment chemistry annually at first, then at five-year intervals, since 1989. Information from the more frequently assessed Long-term stations provides temporal context for the less frequently assessed regional, strata, and Puget Sound-wide sediment and benthos data. Detailed results for the Long-term program are provided in Partridge et al., 2018. The study design, sampling and analytical methods, and list of parameters for both programs are described in Dutch et al., 2009.

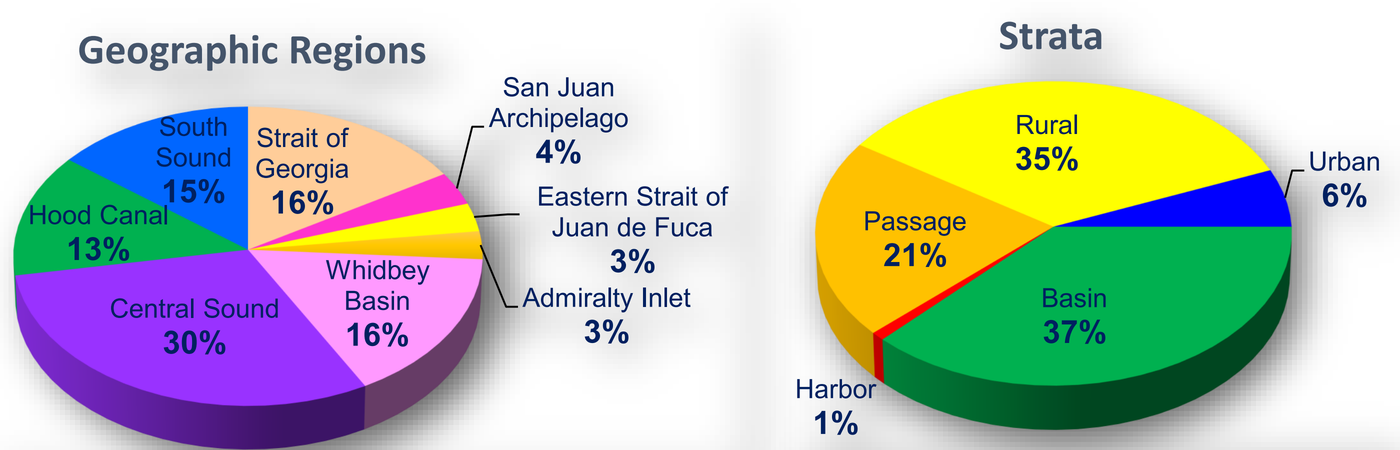


Figure 3. The 2004-2014 nested sampling frames: 8 geographic regions and 5 anthropogenic-use categories (strata), as percent of the total Puget Sound study area.

Physical Condition

Total organic carbon (TOC) content in Puget Sound sediments ranged from <0.1% to 7.2%, with a mean of 1.5%. Higher TOC content was found in the inner portions of the bays and inlets throughout all of the Puget Sound regions, especially in south Puget Sound. The Harbor stratum had the highest TOC concentrations, as well as the largest range in concentrations. Lowest TOC concentrations were found in the Passages of Puget Sound.

No statistically significant change in TOC concentrations was observed between the Baseline and Second Round surveys. Similarly, TOC was consistent over the years at six of the 10 Long-term stations. However, TOC increased at one station, decreased at two others, and had mixed trend at another.

A large portion (41%) of Puget Sound sediments was composed of silt and clay (Figure 4). This was true for all sampling strata and regions except Admiralty Inlet, where the majority of the area was sandy. Sediments with high silt and clay content were most often found in the inner portions of bays and inlets and near river mouths. The Strait of Georgia region had the highest silt and clay proportions.

Silt content in Puget Sound sediments was statistically significantly lower in the Second Round than in the Baseline survey. Percent fines (silt + clay) tended to vary within 5-10% over the 27 years at most of the Long-term stations, though silt content did decrease at one station and clay content decreased at two others. Percent fines showed a mixed trend, decreasing then increasing, at yet another station.

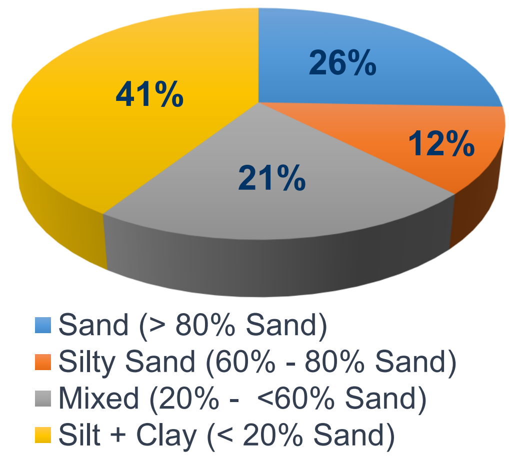


Figure 4. Sediment types and percent of total study area characterizing Puget Sound sediments in the 2004-2014 survey, from coarsest (sand) to finest (silt+clay) grain size.

Chemical Contamination

Many of the concentrations of individual chemicals measured were qualified as undetected, at or below the reporting limit of the analytical methods. Chemical classes that were most often detected included metals, polycyclic aromatic hydrocarbons (PAHs), polybrominated diphenylethers (PBDEs), and polychlorinated biphenyls (PCBs).

Several of these chemicals had concentrations higher than (not meeting) their respective WA State Sediment Quality Standards (SQS) (Ecology, 2013). Sites at which one or more of the SQSs were not met represented a relatively small portion (3.9%) of the Puget Sound study area. Most of that area was in the Central Puget Sound region. Other areas where SQSs were not met included the Whidbey Basin (0.4%), Admiralty Inlet (0.1%), and the Eastern Strait of Juan de Fuca (0.03%). The SQS for mercury was exceeded most often (at 11 sites), followed by total Aroclors, bis(2-ethylhexyl)phthalate, and hexachlorobenzene, at four, three, and two sites, respectively. Dibenzofuran and zinc did not meet their respective SQSs at one site each. Criteria were most often exceeded in the Harbor and Urban strata, which represented the smallest portions of the overall study area.

Compared to the Baseline survey, chemical contamination decreased in surface sediments. The amount of area with chemical concentrations not meeting their respective SQSs decreased by 20%, from 106.9 km^2 to 85.8 km^2. Of the 39 SQSs evaluated, 26 were not met in the Baseline, while only 6 were not met in the Second Round. The percent of stations with at least one chemical not meeting the SQSs declined from 15.5% to 5.7%. Statistically significant decreases were observed in most metal and PAH concentrations. Only chromium concentrations statistically significantly increased from the Baseline survey.

The overall frequency at which chemicals were detected above reporting limits declined by 4.4%. Fewer chemicals were detected in every stratum type, most notably in the Harbor stratum, where detection rates declined by 5.8%.

The Long-term data show a similar spatial trend, with most of the contaminants which persistently exceeded the standards over time occurring in the urban areas, specifically Sinclair Inlet and the Thea Foss Waterway. Over the 27 years, silver and lead concentrations decreased, and chromium concentrations increased, at several Long-term stations. PAH patterns were mixed. Mercury increased at the Sinclair Inlet station. Since 2000, levels of arsenic, copper, and zinc have increased at several stations.

Chemistry Index

The Chemistry Index is a multi-chemical index that is used to estimate the potential exposure of benthic invertebrates to complex mixtures of potentially toxic chemicals that may accumulate in Puget Sound sediments. The values are based on the ratio of chemical concentrations to their respective SQSs . Index values are used to categorize sediments as having *minimum*, *low*, *moderate*, or *maximum exposure* to these chemicals (Long et al., 2012).

The Chemistry Index indicated that the vast majority of the Puget Sound study area (94%) had *minimum exposure* to the 39 chemicals incorporated into the index (Figure 6). Sediments with *low exposure* occurred in 5% of the area and were most often found near urban centers. Only one site, representing 0.7% of the study area, had sediments with *moderate exposure*. No sediments with *maximum exposure* were found in the Second Round.

When compared to the Baseline survey of Puget Sound, exposure to chemical contaminants did not change significantly overall. On a strata level, some changes were observed. In the Baseline survey, 22% of the Harbor stratum had *moderate* or *maximum exposure* sediments. Yet in the Second Round survey, only *minimum* and *low exposure* sediments were found in the Harbor, Urban, Passage, and Rural strata (Figure 5a).

Statistically significant decreases of chemical contamination occurred in the Harbor and Rural strata (Figure 5b). The majority of the decreases occurred in Everett Harbor, Elliott Bay, and Commencement Bay, within the urban growth areas of Everett, Seattle, and Tacoma, respectively. The Rural stratum had a significant decrease in *low* exposure sediments (from 7% to 2%) over the decade.

Similar to the spatial results, the majority of the sediments at eight of the ten Long-term stations were in the *minimum exposure* category. All but one of the sediment samples from Sinclair Inlet were in the *low exposure* category. Sediments in the Thea Foss Waterway of Commencement Bay were in the *high exposure* and *moderate exposure* categories the majority of the time, with no samples classified as *minimum exposure*.

Overall, the Chemistry Index indicated that the area of Puget Sound with *moderate* and *maximum exposure* sediments has decreased over time. The Chemistry Index indicated improvement in contamination at four of the 10 Long-term stations, deterioration at one, and no change at the remaining five.

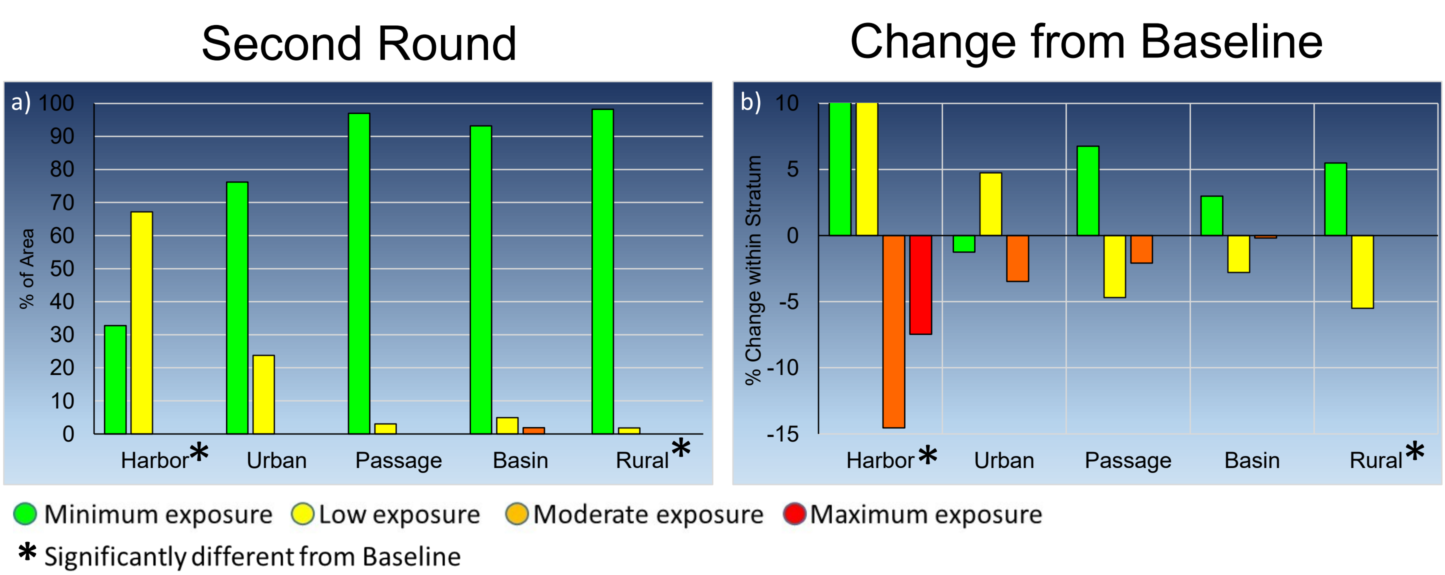


Figure 5. Chemistry Index categories within five strata, percent of area in Second Round (a) and percent change from Baseline (b).

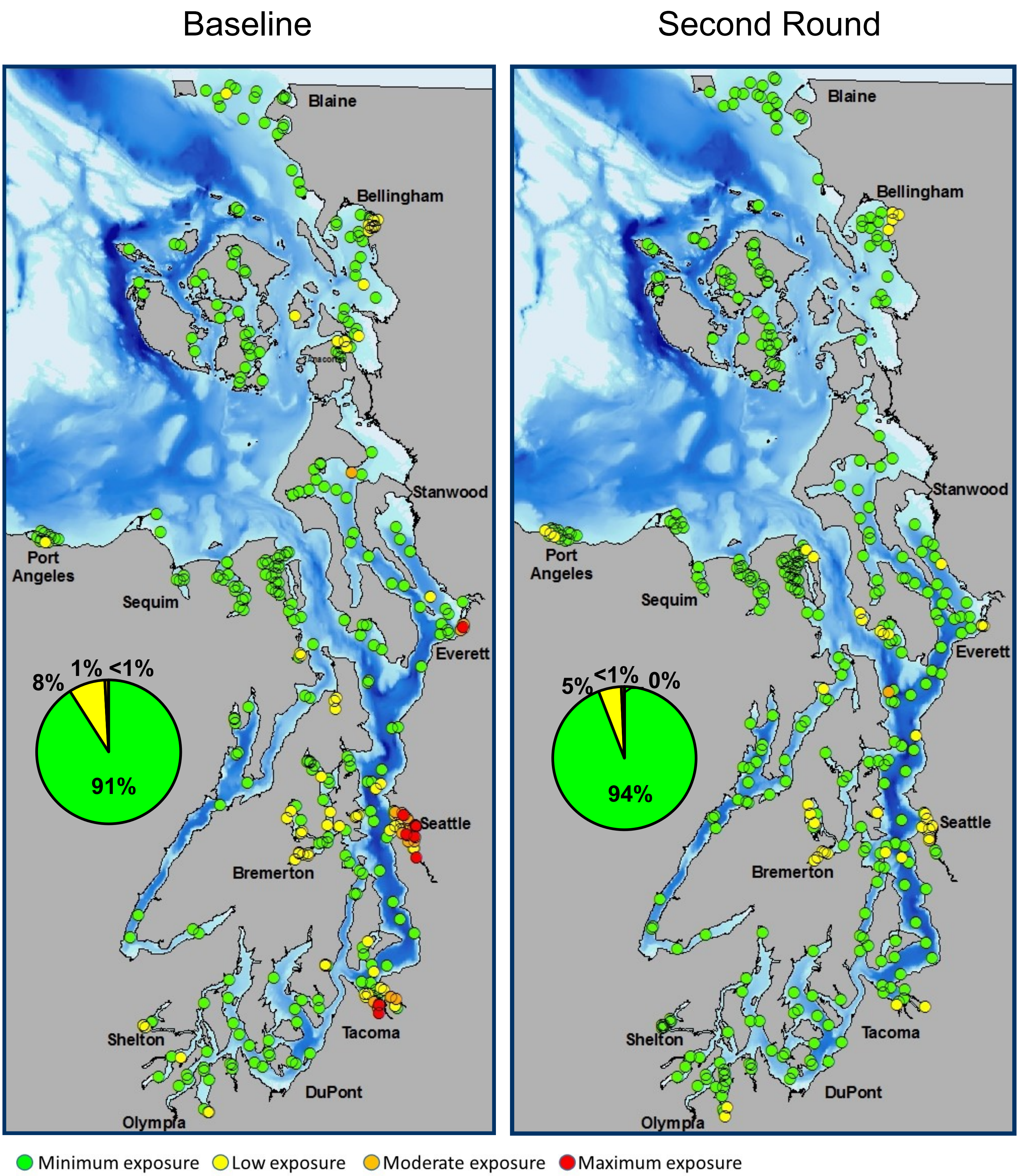


Figure 6. Comparison of spatial patterns at sampling stations (colored dots) and estimated spatial extent (percent of area, shown in pie charts) for the Chemistry Index categories calculated for the Baseline and the Second Round.

Toxicity Index

In the Second Round survey, each sediment sample was analyzed with two laboratory tests of acute toxicity: (1) 10-day survival of adult amphipods exposed to solid-phase sediments and (2) fertilization of sea urchin gametes exposed to sediment porewater. Test results were characterized into four toxicity ranges, from *non-toxic* to *high toxicity* (Table 1).

Table 1. Toxicity Index category descriptions.

Category	Description
Non-Toxic	Mean control-adjusted test results were not significantly lower than the controls **or** were ≥90% of controls
Low Toxicity	Mean control-adjusted test results were significantly lower than the controls **and** between <90-80% of controls
Moderate Toxicity	Mean control-adjusted test results were significantly lower than the controls **and** between <80-50% of controls
High Toxicity	Mean control-adjusted test results were significantly lower than the controls **and** <50% of controls

Amphipod survival tests indicated that 2.3% of the study area had *moderate* or *high toxicity* sediments, whereas the urchin fertilization test showed *moderate* or *high toxicity* in 6.7% of the area. The two tests were most often not in agreement in categorizing sediment as toxic, except at one location in Sinclair Inlet, near Bremerton.

The individual-test results were combined and characterized into the four toxicity categories as Ecology's Toxicity Index (Dutch et al., 2014).

The Toxicity Index showed that the majority (80%) of the Puget Sound sediments were *non-toxic* (Figures 8). Sediments with *low toxicity* were found in 15% of the study area. Higher levels of toxicity, as indicated by the *moderate* and *high toxicity* categories of the index, were found in a relatively small portion of Puget Sound, 3% and 2% , respectively. Sites with *moderate* or *high toxicity* were located near the heads of terminal inlets and/or areas known to have poor circulation. *Non-toxic* sediments were most often found in the Passage and Basin strata. Sites with *low toxicity* sediments were found throughout the study area, with no apparent spatial pattern.

The Toxicity Index showed that sediment toxicity significantly increased in Puget Sound from the Baseline survey. Although non-toxic sediments occurred in all strata, in the Second Round, *moderate* and/or *high toxicity* sediments also occurred concurrently (Figure 7a). Statistically significant increases in toxicity were observed in the Urban, Basin, and Rural strata. A statistically significant decrease in *non-toxic* sediment was observed in all strata and Puget Sound as a whole, with related increases in areas with *low* and/or *moderate toxicity* (Figure 7b).

Toxicity testing was not conducted for the Long-term stations.

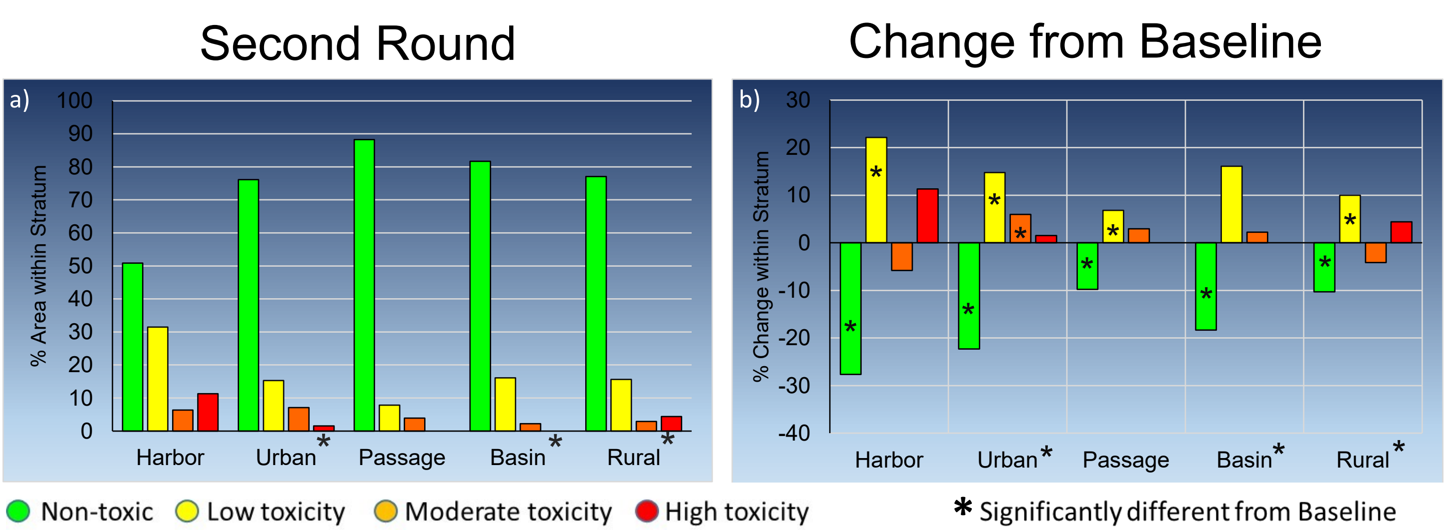


Figure 7. Toxicity Index categories within five strata, percent of area in Second Round (a) and percent change from Baseline (b).

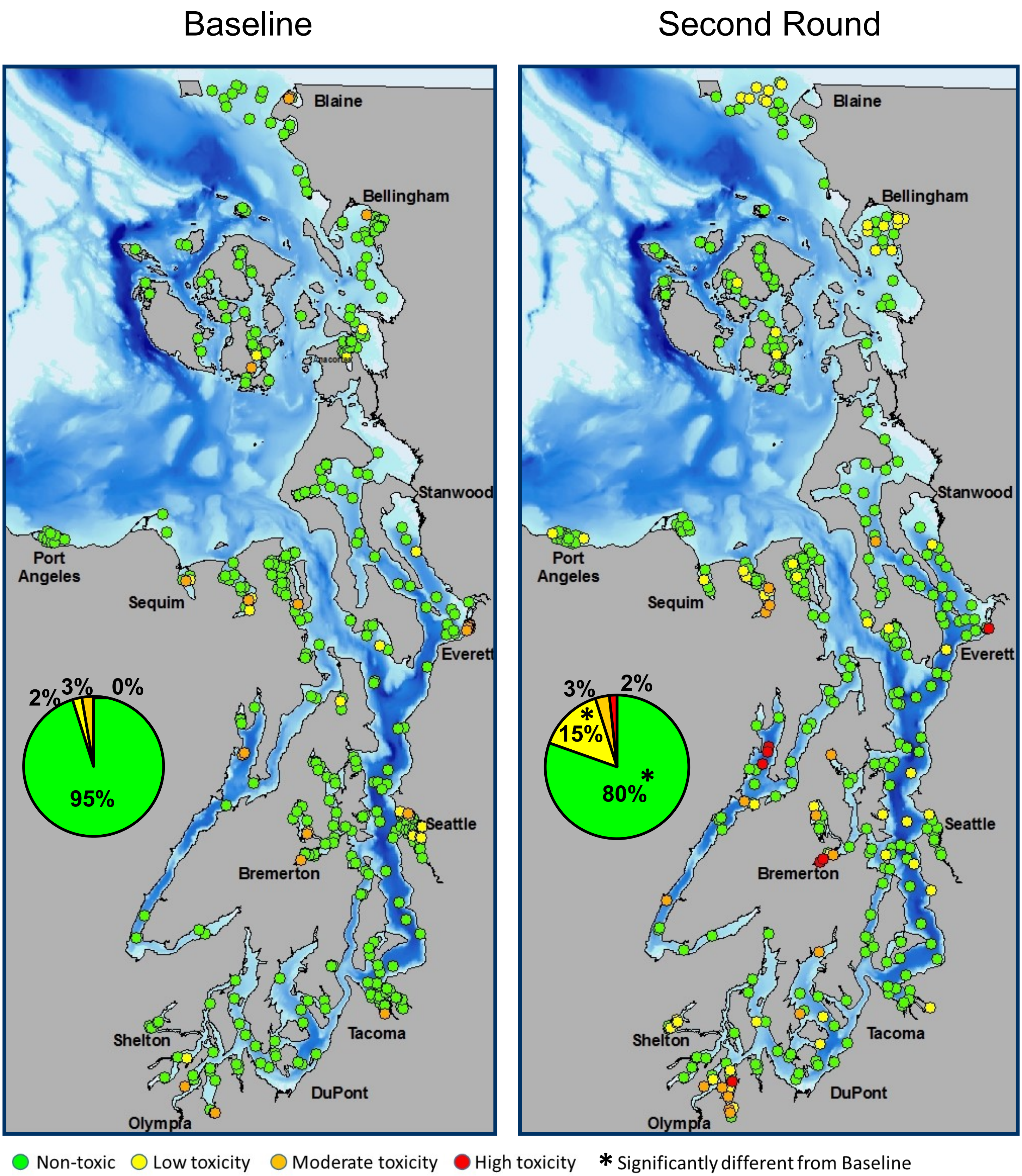


Figure 8. Comparison of spatial patterns at sampling stations (colored dots) and estimated spatial extent (percent of area, shown in pie charts) for the Toxicity Index categories calculated for the Baseline and the Second Round.

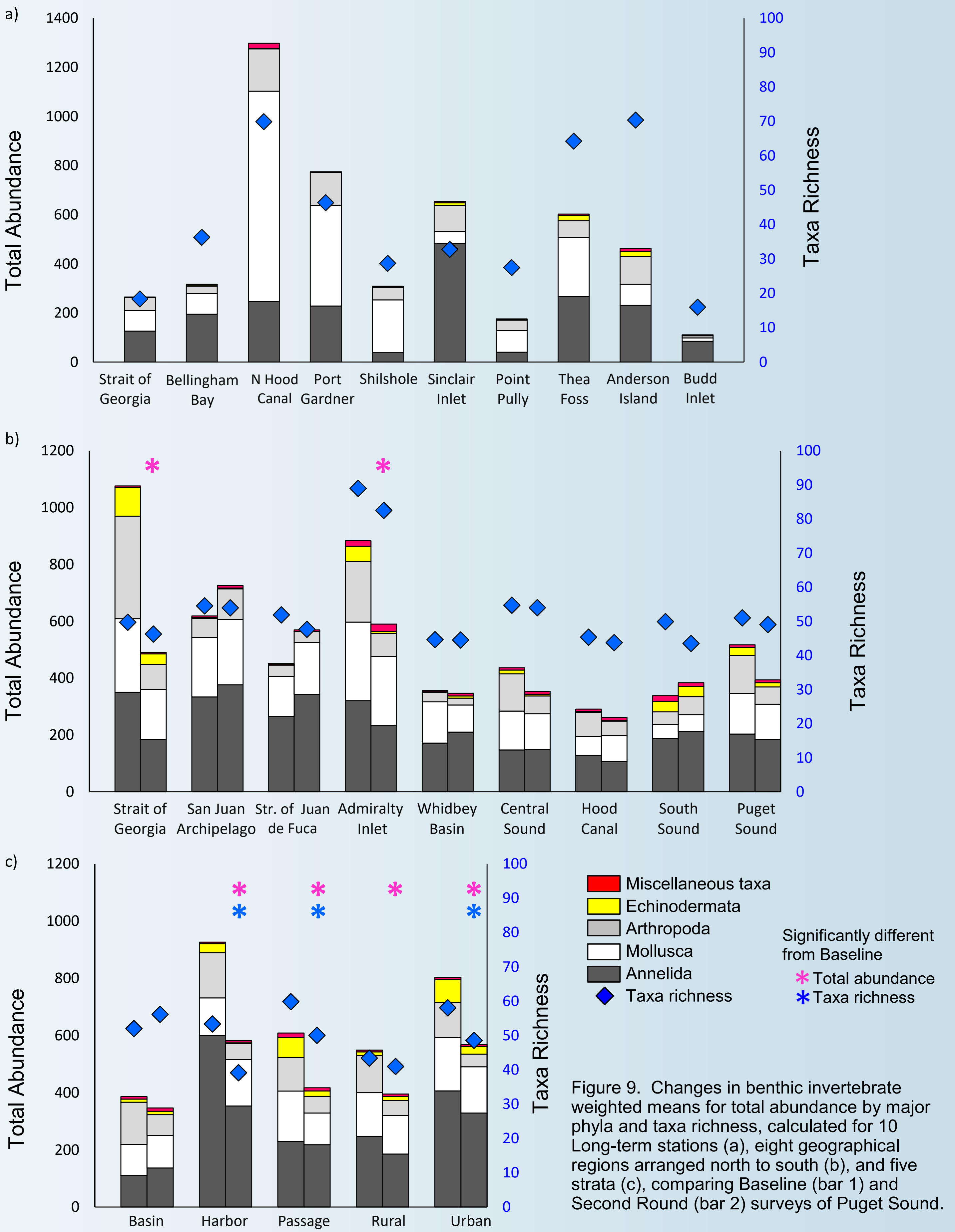


Figure 9. Changes in benthic invertebrate weighted means for total abundance by major phyla and taxa richness, calculated for 10 Long-term stations (a), eight geographical regions arranged north to south (b), and five strata (c), comparing Baseline (bar 1) and Second Round (bar 2) surveys of Puget Sound.

Benthic Invertebrates

Benthic invertebrates (benthos) were identified and counted, and multiple community measures were calculated, including total abundance (number of organisms), taxa richness (number of species), and abundance of each of five major taxonomic groups. Total abundance was higher in the northern regions, with lower abundances in the Whidbey Basin and southward (Figure 9). Annelids made the largest contribution to the total abundance in most stations and sampling frames, followed by molluscs and arthropods. Sites in the deep Basin stratum had lower total abundance, and Harbor and Urban strata had higher numbers of individuals.

Taxa richness was similar in most of the regions, with an overall mean of 49 taxa (Figure 9b). Admiralty Inlet differed, having both the highest taxa richness and the largest representation of miscellaneous taxa. At the stratum level (Figure 9c), taxa richness was highest in the Basins, with a mean of 56 taxa, and lowest in the Rural and Harbor strata, with respective mean taxa richness of 41 and 39. Significant declines in total abundance occurred in all strata except the Basin stratum. Taxa richness significantly declined in the Harbor, Passage, and Urban strata.

Between the two surveys of Puget Sound, total abundance remained statistically similar throughout the regions, with the exceptions of the Strait of Georgia and Admiralty Inlet regions, where total abundance declined significantly.

Changes in the Strait of Georgia region were driven primarily by a few species. In the Baseline survey, one annelid, *Owenia fusiformis*, occurred at 56% of the sites, with a summed abundance of 20,722 individuals. In the second survey of the region, *O. fusiformis* occurred at only 1 site, with an abundance of 28. Similarly, one arthropod, *Euphilomedes carcharodonta,* occurred at 72% of the sites, with a summed abundance of 4,851 individuals in the Baseline, and declined to 13% of the sites, with a summed abundance of 81 in the Second Round. Two additional arthropod species, *Protomedeia grandimana* and *Protomedeia prudens,* had substantial reductions (>95%) in abundance.

The statistically significant change in total abundance for Admiralty Inlet between the Baseline and Second Round was due primarily to the significant drop in the numbers of three organisms: the brittle star *Amphiodia* spp. and two arthropod species, *Ericthonius rubricornis* and *Euphilomedes carcharodonta.*

Overall, 17% of the taxa identified showed significant change (8% decreased, 9% increased) between the two surveys. Of the taxa that decreased, 21% are thought or known to be sensitive to disturbance. The largest increases occurred in taxa that are known to be tolerant of pollution, hypoxia and/or nutrient enrichment: *Heteromastus filobranchus*, *Mediomastus* spp., *Parvilucina tenuisculpta*, and *Prionospio steenstrupi* (Gillett et al., 2015).

Collectively, PSEMP benthos data have identified a single benthos assemblage in sediments Puget Sound-wide, with low exclusivity and relatively small differences between sub-assemblages (Ranasinghe et al., 2013). However, a number of sub-assemblages can be distinguished, each associated with differing habitat characteristics. Benthos at the ten Long-term stations effectively represent these differing sub-assemblages and habitats. Characterized annually, benthos collected at these ten stations provide clues to changes in community structure on a more frequent time-scale than the Spatial program. The Long-term stations have a wide range in total abundance, richness, and major phyla composition (Figure 9a).

Although some declines were seen in the benthic communities at some of the Long-term stations, they did not correspond with those seen in regions or strata. Taxa richness declined over the years at the Sinclair Inlet and Anderson Island stations, and since 2000 at the North Hood Canal station. Arthropod abundance decreased significantly at four stations. *Parvilucina tenuisculpta* increased over the years at half the stations, as did the polychaete *Prionospio* spp. *Euphilomedes producta* decreased at four stations, and *E. carcharodonta* at two. All other taxa largely remained unchanged at the majority of stations, though some showed mixed trends or cycles.

The overall structure of Puget Sound benthos differs between the regions and presents a north-to-south distribution (Figure 10).

Regions tended to be similar to themselves over the two surveys, with the exception of Hood Canal, where the Baseline assemblage resembled that found in Central Puget Sound. At the stratum level, both temporal and spatial patterns emerged (Figure 10). The overall benthic assemblage structure shifted over the two surveys, yet the community structure, or the relative similarities of the strata types to each other, remained similar over time.

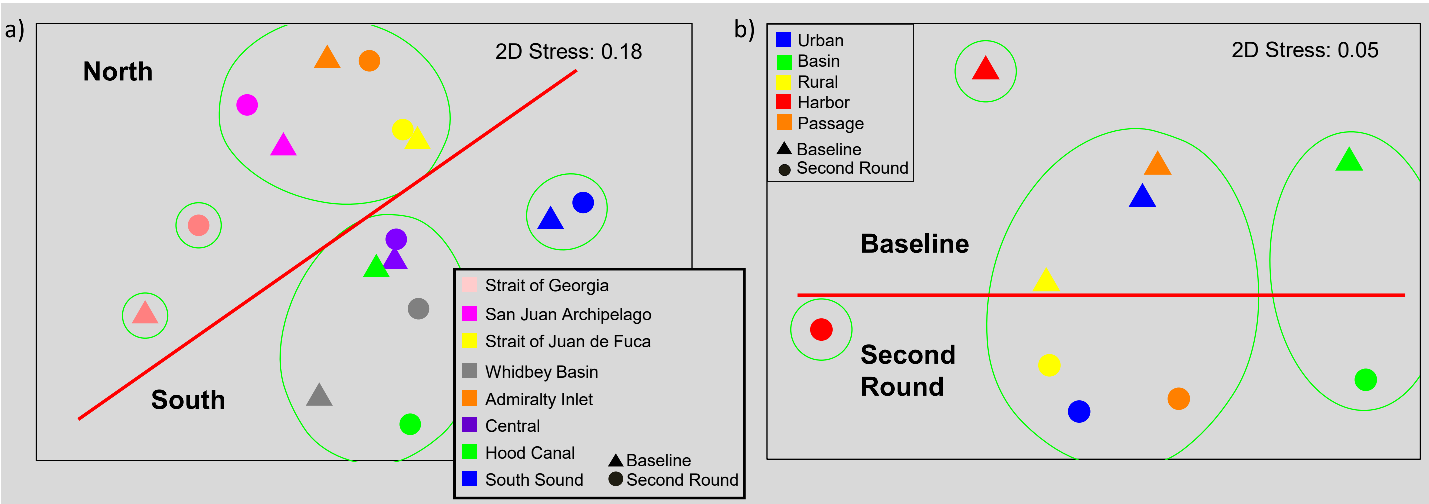


Figure 10. Nonmetric multidimensional scaling (MDS) diagram indicating relative similarities of benthic invertebrate assemblage centroids for eight geographic regions (a) and five strata (b) of Puget Sound (Bray-Curtis similarities of unweighted 4th-root-transformed abundances). The ellipses indicate assemblages with 20% (regions) and 30% (strata) or greater similarity. The closer the symbols are in the diagram, the more similar their assemblages are. The solid lines were added to draw attention to geographic (a) and temporal (b) divisions.

While there were some year-to-year changes in the benthic communities at the Long-term stations, the communities remained distinct from each other, i.e., the assemblages were more similar across years within stations than between stations within years (Figure 11). These similarities of the assemblages reflected the depth and grain size of the habitat. However, communities at individual stations changed over time. At eight of the stations, the changes were directional, i.e., years clustered in consecutive groups. The pattern was more mixed at the Strait of Georgia station. Budd Inlet is the only site where the benthic community did not change.

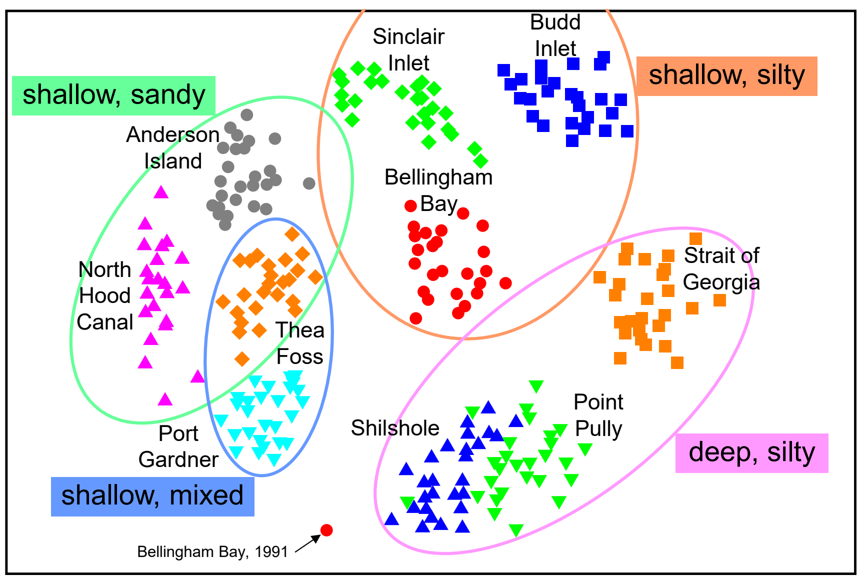
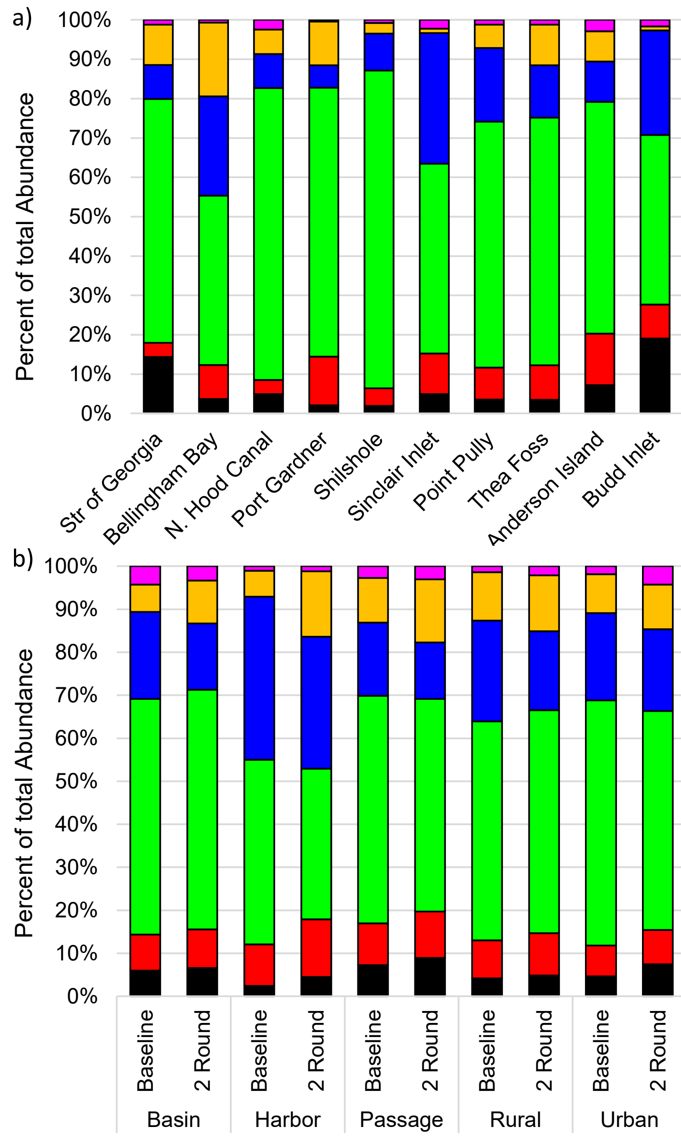


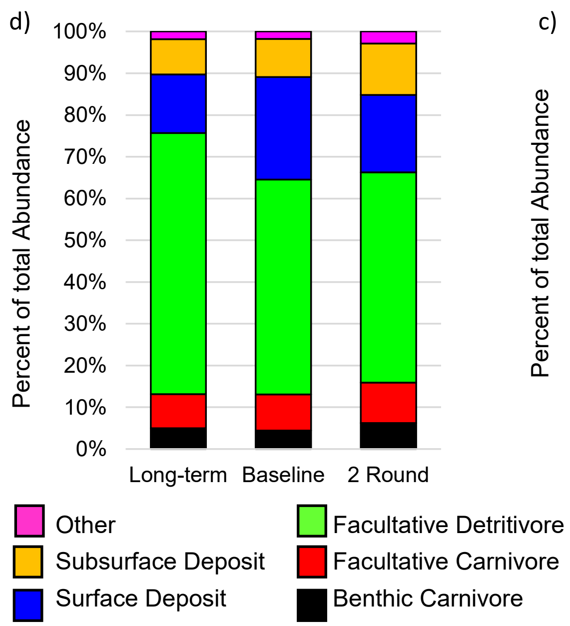
Figure 11. Nonmetric multidimensional scaling (MDS) diagram indicating relative similarities of benthic invertebrate assemblages.

Feeding Guilds

Functional feeding guilds that integrate how, where, and what benthos eat have been defined for British Columbia (Macdonald et al., 2010, 2012). This work was applied to Puget Sound benthic communities, revealing that benthos in the Sound are dominated by facultative detritivores and surface deposit feeders, followed by subsurface deposit feeders, facultative carnivores and benthic carnivores (Figure 12).

Although the stations, regions, and strata vary considerably in total numbers of animals by feeding guild, the feeding guild proportions are generally similar over time and space. Among the Long-term stations that had experienced some type of disturbance, however, that disturbance was reflected in the feeding guilds, not just in a single year, but over multiple years.





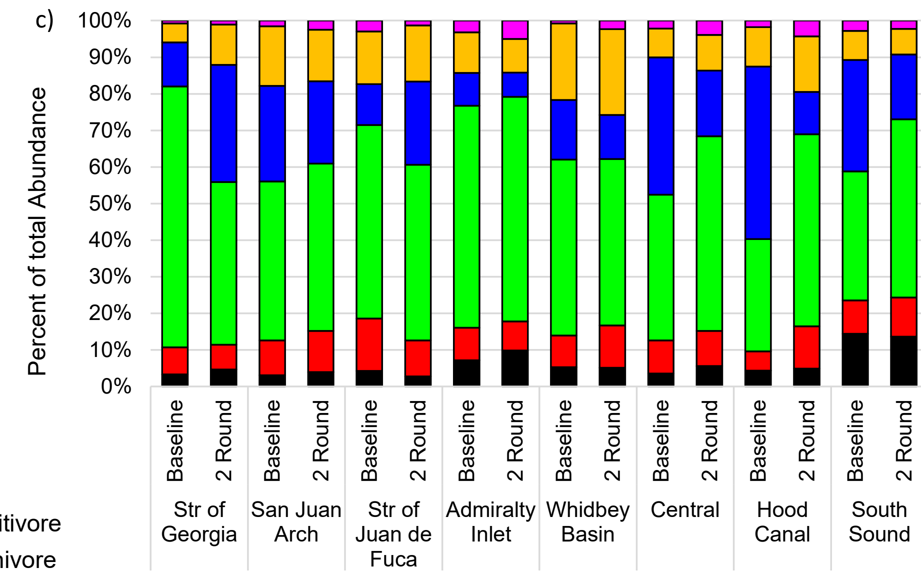


Figure 12. Percent of mean abundance by functional feeding guild for Long-term stations (a), strata (b), regions (c), and each sediment monitoring program (d).

Benthic Index

Ecology's Benthic Index is an assessment of whether the invertebrate assemblages at each station appear to be *adversely affected* or *unaffected* by natural and/or human-caused stressors. The determination is made by benthic experts, based on comparison of a suite of calculated indices, including total abundance, major taxa abundances, taxa richness, evenness, and species dominance, compared to median values for all of Puget Sound. Abundances of stress-sensitive and stress-tolerant species at each station are also considered.

Spatial and temporal patterns in the Benthic Index categories for Puget Sound are depicted in Figures 13 and 14. In the Second Round survey of Puget Sound, 56% of the study area had *unaffected* benthic communities (Figure 14). The remainder of the study area had *adversely affected* benthos. Many of the *adversely affected* communities were found in terminal inlets and bays throughout Puget Sound. The Harbor stratum had the greatest percentage of area with *adversely affected* benthic communities, whereas the Basin stratum had the largest percentage of *unaffected* benthos (Figure 13a).

Adversely affected communities were found in terminal inlets and bays throughout Puget Sound.

In comparison to the Baseline survey, there was a statistically significant decline in the overall area with *unaffected* benthic communities and a related increase in the areas with *adversely affected* benthos (Figure 14). These changes occurred in all strata except Rural, where the area with *unaffected* benthos increased, although not significantly (Figure 13b).

The benthos at the Long-term stations were not assessed with the Benthic Index.

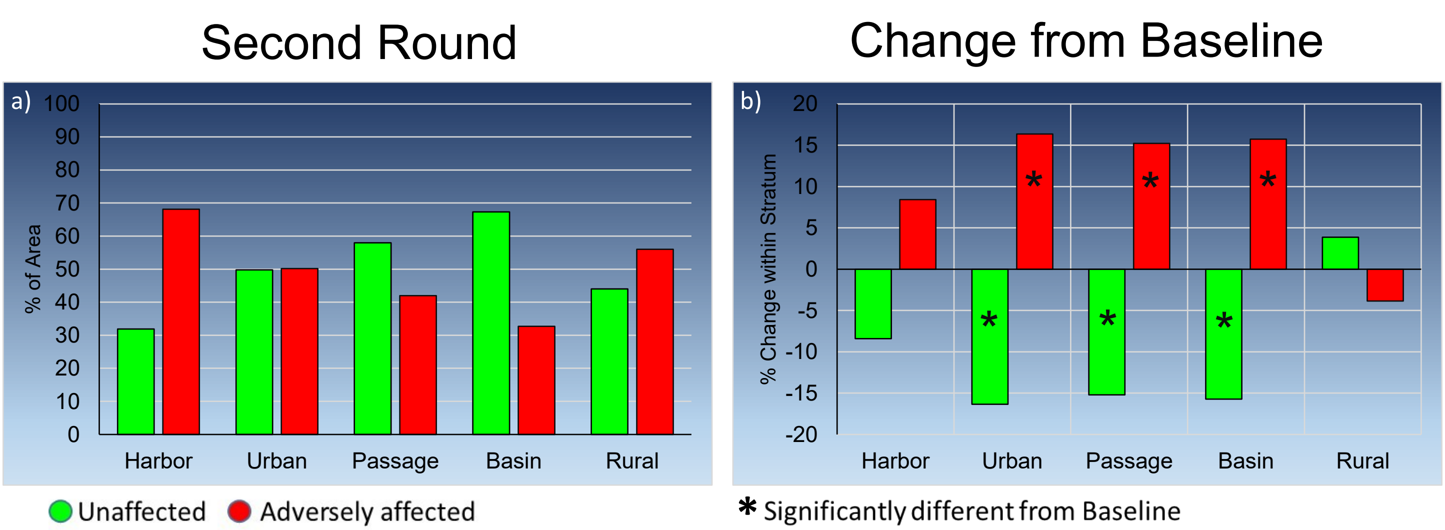


Figure 13. Benthic Index categories within five strata, percent of area in Second Round (a) and percent change from Baseline (b).

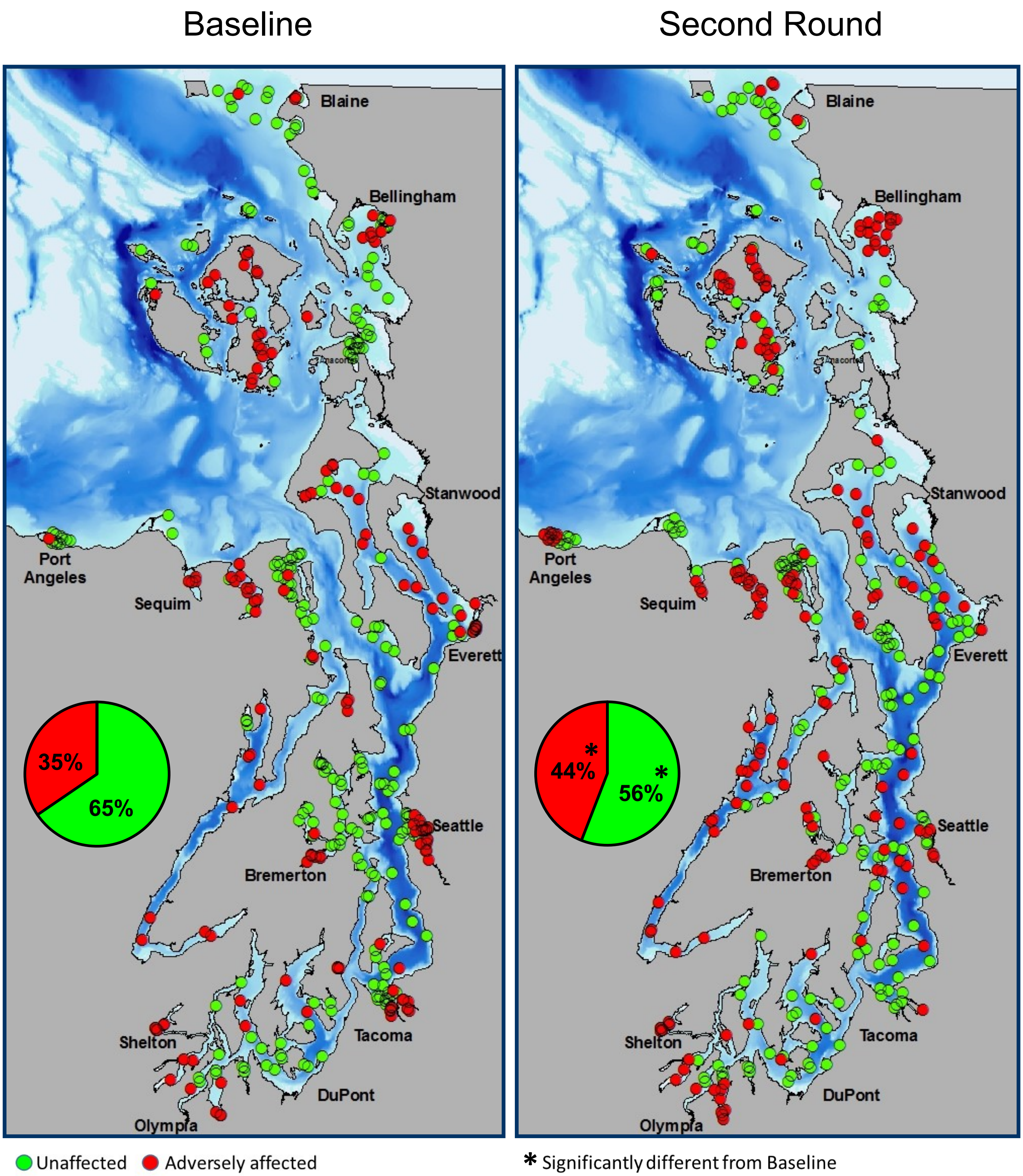


Figure 14. Comparison of spatial patterns at sampling stations (colored dots) and estimated spatial extent (percent of area, shown in pie charts) for the Benthic Index categories calculated for the Baseline and the Second Round.

Triad Index

The sediment triad concept of characterizing sediment condition is an empirical weight-of-evidence approach, originally conceived of and reported for Puget Sound by Long and Chapman, 1985.

Ecology's Triad Index combines evidence from three measures (chemistry, toxicity, and benthos) to classify sediment quality into six categories of impact by chemical contamination and/or other environmental stressors (Dutch et al., 2014). Categories range from *unimpacted* to *clearly impacted*, and *inconclusive* when lines of evidence are conflicting. This multiple-lines-of-evidence approach was adapted from methods developed for the State of California to classify sediment quality (Bay and Weisberg, 2012).

The Second Round assessment of Puget Sound sediment quality with the Triad Index indicated that the majority (86%) of the study area was classified as having *unimpacted* (56%) or *likely unimpacted* (30%) sediment quality (Figure 16). *Unimpacted* sediments were found throughout the study area and in all strata, but less often in the inner portions of bays and inlets or the Harbor stratum. *Possibly impacted* and *likely impacted* sediments were found in a relatively small portion of the study area: 3% and 2%, respectively. *Likely impacted* sediments were most often found in the Harbor stratum near Everett, Bremerton, and Olympia. Nine percent of the study area had *inconclusive* results. These sites were found in the center or outer portions of the bays and inlets and in the central basin. There were no *clearly impacted* sediments found in the Second Round survey (Figures 15 and 16). The Triad Index was not applied to the Long-term data.

Comparison of Triad Index categories between the Second Round and Baseline surveys shows a statistically significant decline in the area with *unimpacted* sediment quality and an associated increase in the areas with *likely impacted* or *inconclusive* sediment quality (Figure 16). In the Baseline, the majority of impacted sediments were found at 40 stations in the inner portions of bays and inlets near Everett, Seattle, Bremerton, Tacoma, and Olympia, representing 70 km^2, or 3% of the study area. In the Second Round, 31 stations were impacted, representing 114 km^2, or 5% of the study area. Changes in sediment quality were observed near Seattle and Tacoma, where the number of sites with impacted sediments dropped from 15 to 1, and in Quilcene Bay, where *likely impacted* sediments were found at 3 sites in the Second Round, representing 33.7 km^2. At the stratum level, the area with *unimpacted* sediments significantly declined in the Urban, Passage, and Basin strata (Figure 15b). Sediments classified as *inconclusive*, with conflicting Chemistry, Toxicity, and Benthic Index results occurred in all strata, but increased significantly in the Rural stratum in the Second Round.

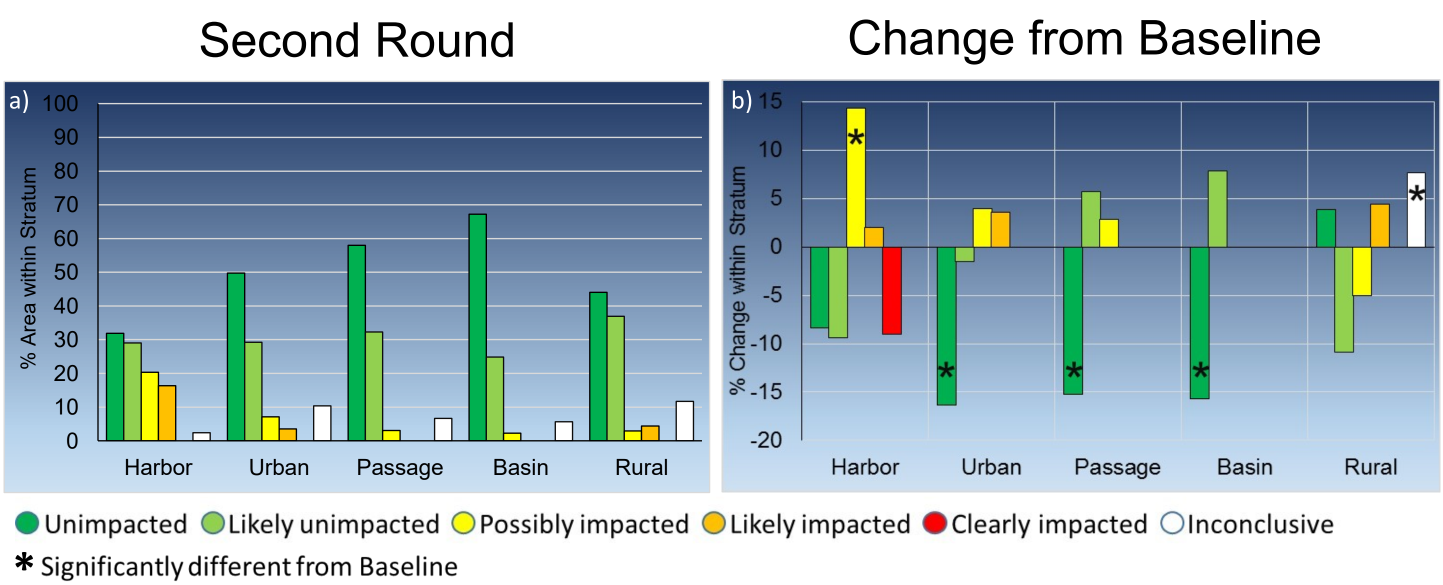


Figure 15. Triad Index categories within five strata, percent of area in Second Round (a) and percent change from Baseline (b).

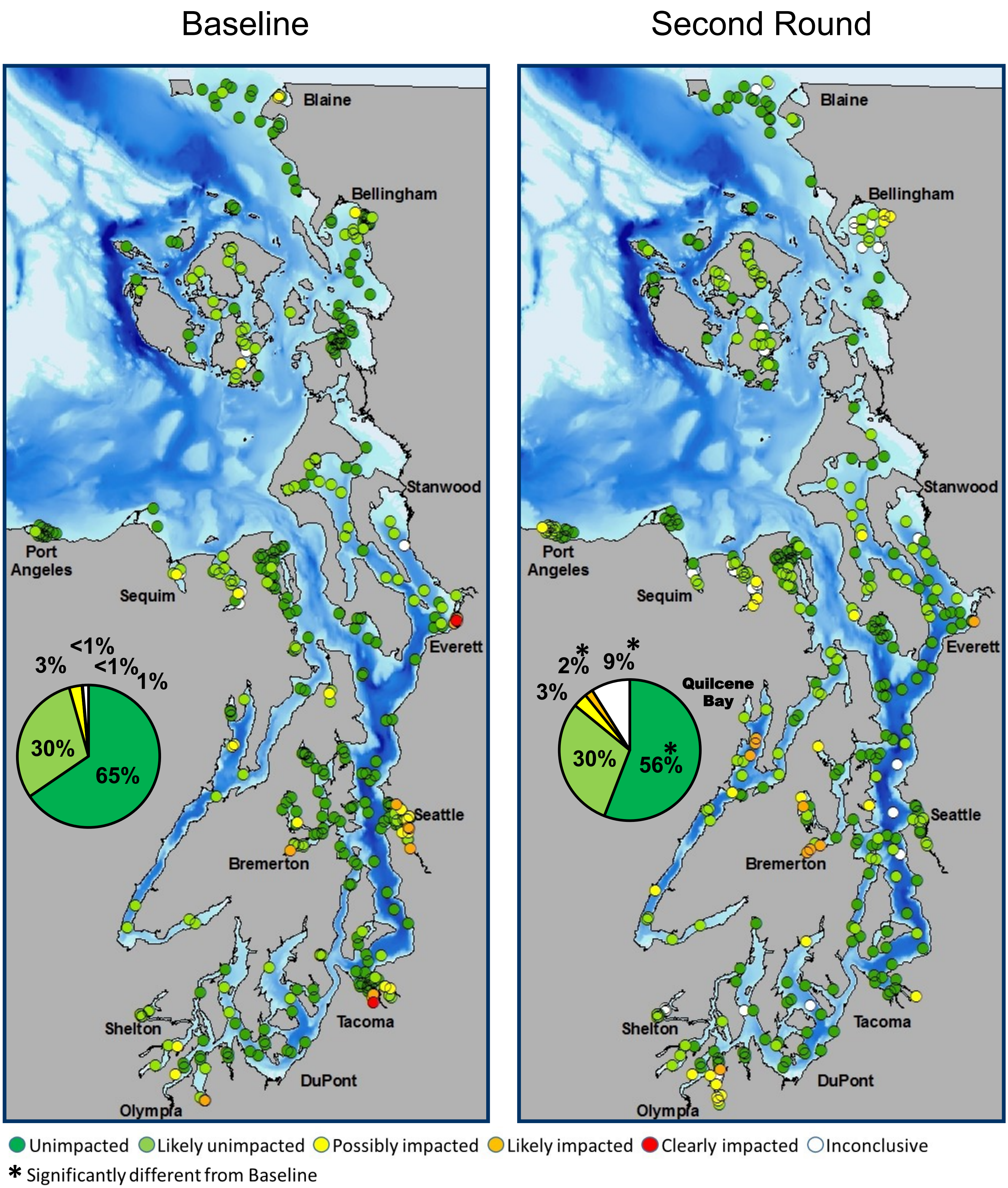


Figure 16. Comparison of spatial patterns at sampling stations (colored dots) and estimated spatial extent (percent of area, shown in pie charts) for the Triad Index categories calculated for the Baseline and the Second Round.

Puget Sound Partnership "Vital Signs" - Chemistry and Triad Indices

Ecology's Chemistry and Triad Indices, and also the percent of chemicals not meeting the Washington State Sediment Quality Standards (SQS), were adopted by the Puget Sound Partnership (PSP) to serve as "Vital Signs" indicators of the condition of Puget Sound sediments. Weighted mean Chemistry and Triad Index values are compared to target values for highest quality. The indices also are compared between years of repeated sampling to determine changes over time.

The weighted mean Chemistry Index value for Puget Sound was above the 2020 target value of 93.3. Chemistry Index values for the individual sampling regions of Puget Sound were similar to each other, all meeting the PSP target. Lowest values were found in Central Sound and Admiralty Inlet. For the strata, weighted mean Chemistry Index values were lowest in the Harbor stratum, where the PSP target was not met. While the PSP target was not met in the Harbor stratum, a statistically significant increase in index values was seen between the two surveys (Figure 17 b and c).

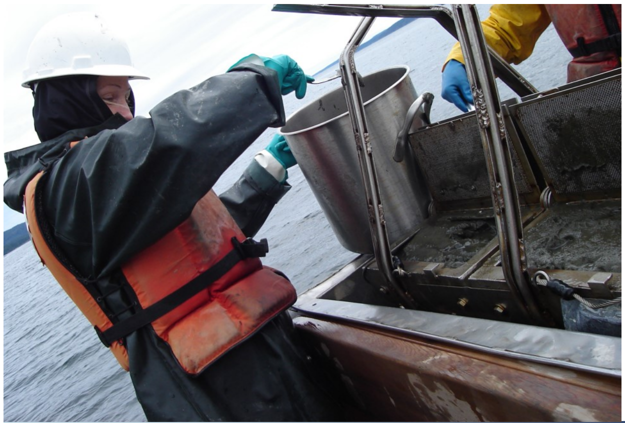
The Chemistry Index scores were above the target value for most Long-term stations and did not change significantly over time (Figure 17a). The exceptions were the more urban Thea Foss Waterway and Sinclair Inlet stations, which fall into the Harbor stratum, and had much lower index scores. The Thea Foss station had multiple years of poor scores with no consistent trend.

The percent of chemicals not meeting the SQSs has declined in all monitoring regions, strata, and Puget Sound as a whole, dropping to below 1% of the study area. The Harbor stratum, primarily in Central Puget Sound, saw the largest improvement, dropping from 4.2% to 0.9% (Figure 17 c).

Again, the Long-term stations showed a similar pattern, with percent of chemicals not meeting the SQSs being very low at most locations (<1%) and exceeding SQSs only in the more urban locations. Only the Sinclair Inlet and Thea Foss Waterway stations exceeded the SQSs more often over the years, with values of 2.8% and 11.5% respectively (Figure 17a).

Overall, the majority of Puget Sound sediments did not have elevated levels of chemical contaminants. The highest concentrations were found near population and/or industrial centers including Bellingham, Everett, Seattle, Tacoma, and Bremerton.

Overall, the majority of Puget Sound sediments did not have elevated levels of chemical contaminants.



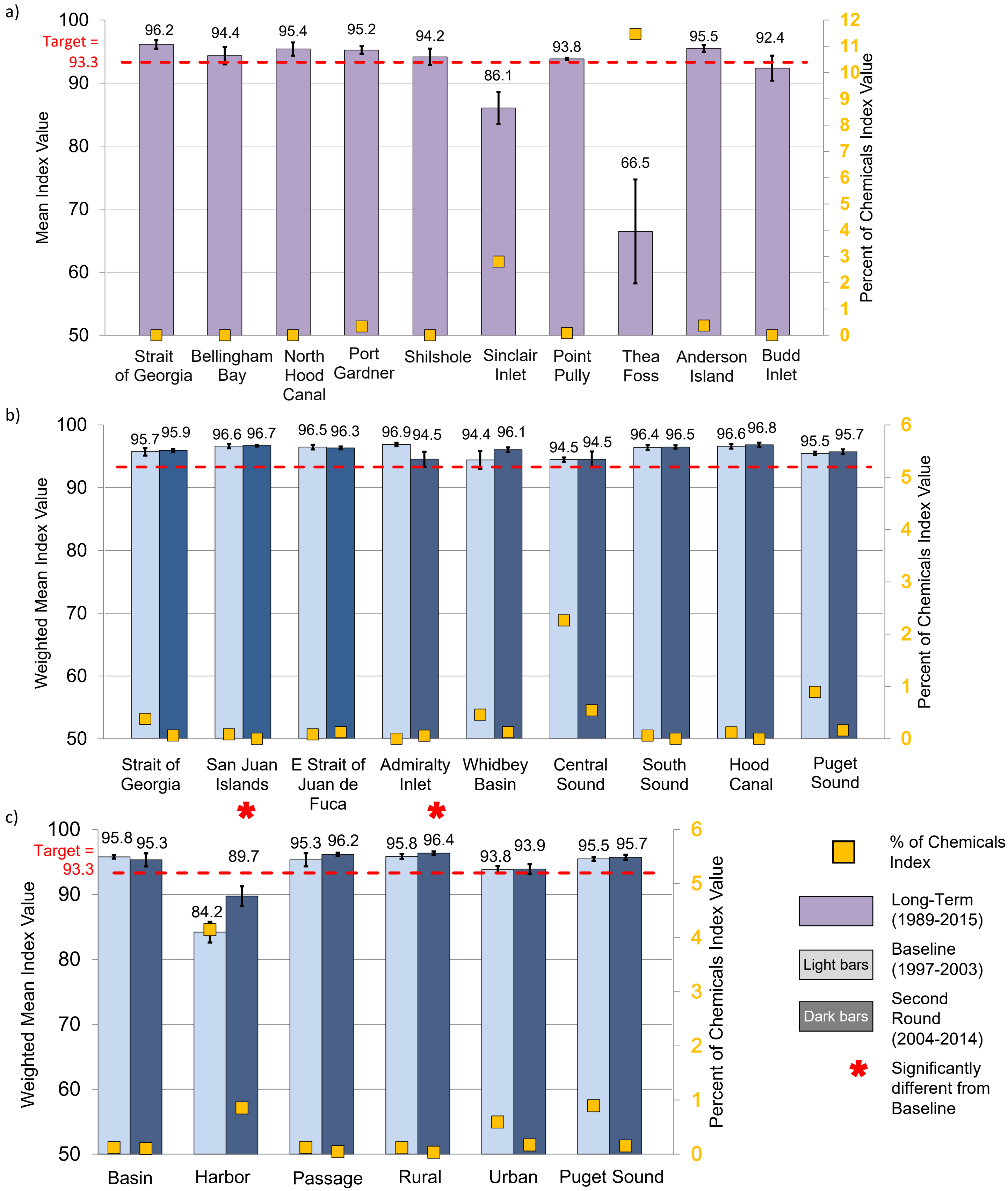
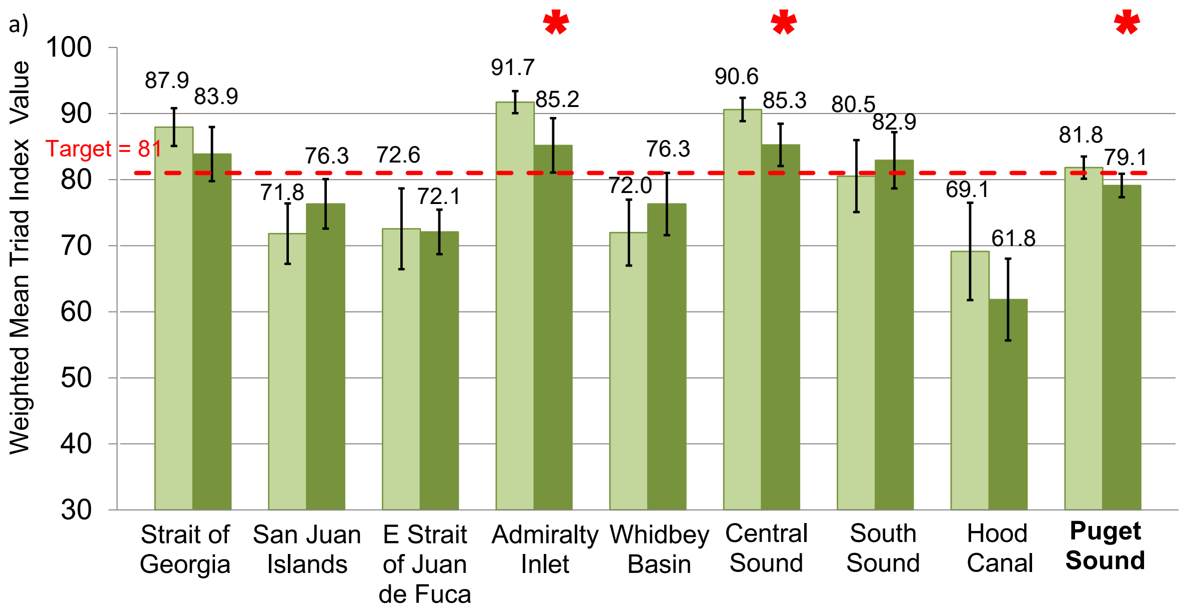


Figure 17. Change over time in Chemistry Index values for ten Long-term stations (a), eight geographical regions (b), and five strata (c) in Puget Sound. Weighted means from Baseline and Second Round surveys are displayed with 95% confidence intervals. The PSP's 2020 target value of 93.3 is shown as a dashed red line.

The percent of chemicals in Puget Sound not meeting their SQS criteria did not reach the PSP target of zero (Figure 17). Although the target was not met for Puget Sound as a whole, a statistically significant decline in number of chemicals not meeting the criteria was observed in the decade between surveys. The largest decline in number of chemicals not meeting their respective SQSs was observed in Central Sound and in the Harbor stratum.

The weighted mean Triad Index value for the Second Round survey was below the PSP target value of 81, which corresponds to the minimum value in the *unimpacted* Triad Index category (Figure 18). Weighted mean Triad Index values for the individual sampling regions of Puget Sound differed, ranging from 61.8 in Hood Canal to 85.3 in Central Sound. Statistically significant declines in index values from the Baseline were observed in Central Sound, Admiralty Inlet, and Puget Sound as a whole. Weighted mean Triad Index values for the strata met the PSP target only in the Basin and likely in the Passages. All strata except Rural areas had declines in index values between the two surveys (Figure 18). Statistically significant decreases in index values were seen for the Basin and Urban strata.



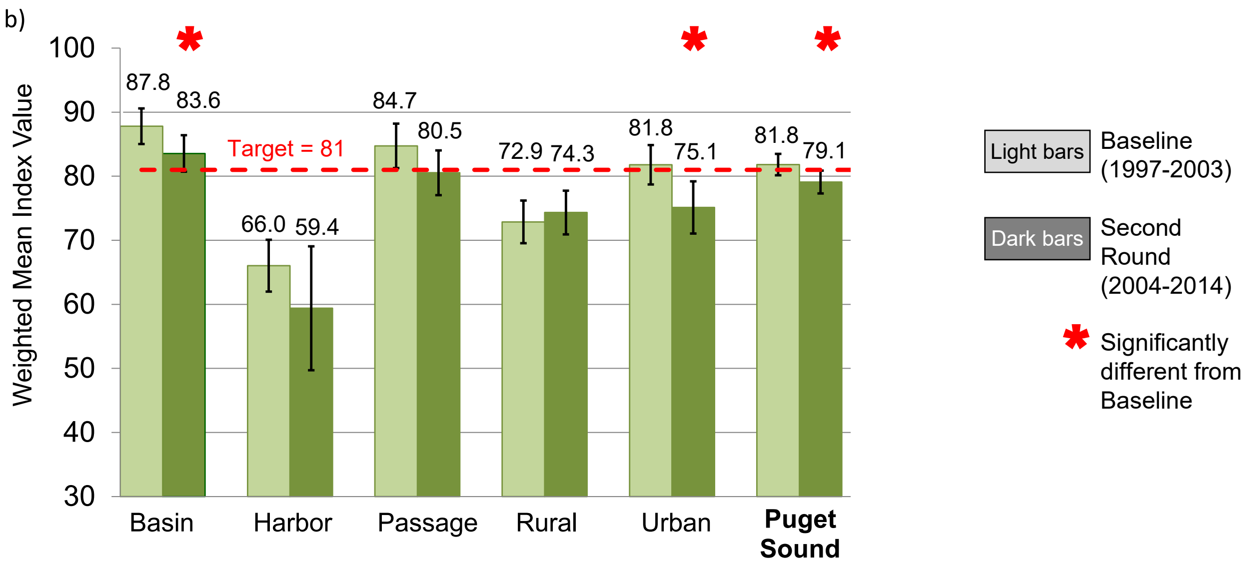
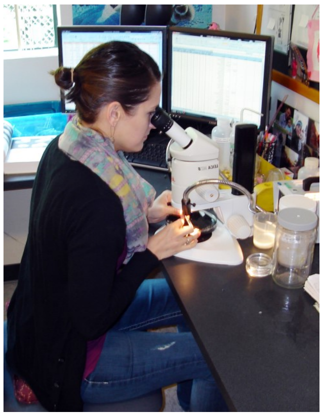
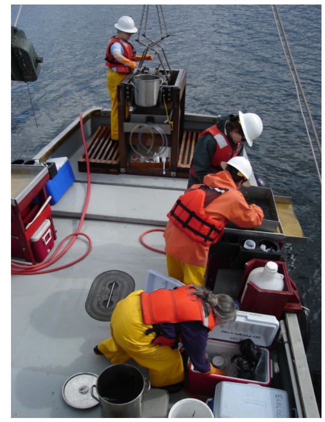
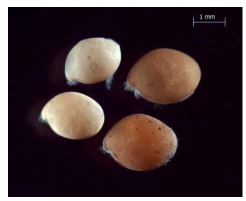


Figure 18. Change over time in Triad Index values for eight geographical regions (a) and five strata (b). Weighted means from Baseline (lighter bars) and Second Round (darker bars) surveys are displayed with 95% confidence intervals. Also shown is the PSP's 2020 target value of 81 (dashed red line).







Summary and Discussion

Sediment quality in Puget Sound was *unimpacted* or *likely unimpacted* in the majority of the 2004-2014 study area, according to the Triad Index. However, sediment quality in Puget Sound declined significantly from the previous survey, having less area with *unimpacted* sediment quality and more area with *possibly* or *likely impacted* quality. These changes were due primarily to increases in sediment toxicity and degraded condition of the benthos, as reflected in declining Benthic and Toxicity indices. Chemical contamination has either decreased or remained unchanged.

Ecology’s sediment quality indices suggest a spatial gradient of improving sediment quality from inner to outer bay or inlet, and that impacted sites are primarily confined to the terminal inlets and bays of Puget Sound.

Potentially toxic chemicals monitored in sediments have declined in concentration and occurrence between the Baseline and Second Round surveys. This may be due to cleanup efforts, reduced use and release of toxic chemicals into the environment, and/or burial via natural sedimentation processes.

None of the chemical parameters measured in this survey corresponded with increases in *low* and *moderate toxicity* shown in the Toxicity Index. Parameters or factors not currently measured may be contributing to the increased toxicity. Additionally, the test species used in the Baseline survey, *Ampelisca abdita*, is less sensitive than the species used in the Second Round, *Eohaustorius estuarius*.

The area of Puget Sound with *unaffected* benthic communities has significantly declined since the 1997–2003 Baseline survey. The worsening condition of the benthic community is also reflected in significant decrease and increase in taxa recognized as either sensitive or tolerant, respectively, to environmental disturbance.

These declines do not appear to be strongly correlated to changes in measured chemical concentrations or toxicity test results. Although there was some correspondence between the spatial distribution of *adversely affected* benthic communities and sediment toxicity, it cannot be concluded that toxic conditions alone were impairing the community.

The rotational sampling of regions on a roughly 10-year cycle made it difficult to make inferences about changes to the benthic communities observed over time. While this time span is suitable to capture changes in sediment chemistry, sampling did not occur frequently enough in each region or collectively in each stratum or Puget Sound-wide to capture potential effects of more rapidly changing oceanographic or climatic stressors on the benthos. Furthermore, some of the changes observed between the Baseline and the Second Round surveys could potentially be due not resampling the same locations.

The Long-term program, while lacking extensive spatial coverage, provides annual information about sediment quality and condition of the benthos.

Together, results from both programs lead us to believe that chemical contamination and toxicity of the sediments are not the primary or sole drivers of changes observed in Puget Sound's benthos communities. Additional natural and anthropogenic factors not measured could also be affecting benthos, including: near-bottom dissolved oxygen, pH, nutrient input, water residence time, ocean acidification, and climate change, all of which need to be evaluated on appropriate temporal and spatial scales.

Moving Forward

The PSEMP sediment monitoring program was originally designed to establish baseline data for and monitor the spatial extent and effects of priority pollutant contamination and toxicity on Puget Sound benthic invertebrate communities. After nearly three decades of monitoring, those goals have been attained. However, the condition of the benthic invertebrate communities has worsened throughout Puget Sound over time, and no significant correlation was found between the chemistry, toxicity, and benthos parameters measured to date. For these reasons, we believe that additional environmental pressures are affecting the benthos.

In light of these findings, Ecology has reassessed the goals and objectives of the PSEMP Sediment Monitoring Program. Changes to the sampling design and parameters measured will be implemented to better address emerging environmental concerns for Puget Sound. A shift from the point-source discharge focus of the past to include a more comprehensive understanding of the biogeochemical attributes of the benthic ecosystem, particularly in light of climate change and ocean acidification, is needed.

Revisions to the study design, parameters monitored, and the rationale for these changes will be detailed in a revision of the Puget Sound Sediment Monitoring Quality Assurance Project Plan (Dutch et al., 2018.).

NOTE: Ambient vs. Regulatory Monitoring

It is important to distinguish between Ecology's ambient sediment monitoring activities, such as this study, and Ecology's Toxic Cleanup Program (TCP) Remedial Investigations and Feasibility Studies (RI/FS). This ambient study characterizes conditions for large geographic areas rather than targeted locations. The TCP is concerned primarily with the toxic legacy from past industrial practices and how those practices have impacted Puget Sound. The RI/FS process examines sediment contamination in the biologically active zone, whereas this ambient study assesses the most recently deposited sediments. As a result, these differences in approach could potentially lead to differing conclusions, even at similar locations. Results from this publication are not intended to supersede, revise, or replace the State's regulatory criteria under the Sediment Management Standards.

References

Bay, S.M. and S.B. Weisberg. 2012. Framework for interpreting sediment quality triad data. Integrated Environmental Assessment and Management 8:589-596. http://onlinelibrary.wiley.com/doi/10.1002/ieam.118/full (Erratum: http://onlinelibrary.wiley.com/doi/10.1002/ieam.1335/full).

Dutch, M., V. Partridge, S. Weakland, K. Welch, and E. Long. 2009. Quality Assurance Project Plan: The Puget Sound Assessment and Monitoring Program[1]: Sediment Monitoring Component. Washington State Department of Ecology, Olympia, WA. Publication 09-03-121. https://fortress.wa.gov/ecy/publications/summarypages/0903121.html.

Dutch, M., E.R. Long, S. Weakland, V. Partridge, and K. Welch. 2014. Sediment Quality Indicators for Puget Sound: Indicator Definitions, Derivations, and Graphic Displays. Unpublished report.

Dutch, M., S. Weakland, V. Partridge, D. Burgess, and A. Eagleston. 2018. Quality Assurance Monitoring Plan: Revisions to the Puget Sound Sediment Monitoring Program. Washington State Department of Ecology, Olympia, WA. Washington State Department of Ecology, Olympia, WA. Publication 18-03-109. https://fortress.wa.gov/ecy/publications/SummaryPages/1803109.html.

Ecology (Washington State Department of Ecology). 2013. Sediment Management Standards. Chapter 173-204, WAC. Washington State Department of Ecology, Olympia, WA. Publication No. 13-09-055. http://apps.leg.wa.gov/WAC/default.aspx?cite=173-204.

Gillett, D.J., S.B. Weisberg, T. Grayson, A. Hamilton, V. Hansen, E.W. Leppo, M.C. Pelletier, A. Borjà, D. Cadien, D. Dauer, R. Diaz, M. Dutch, J.L. Hyland, M. Kellogg, P.F. Larsen, J.S. Levinton, R. Llansó, L.L. Lovell, P.A. Montagna, D. Pasko, C.A. Phillips, C. Rakocinski, J.A. Ranasinghe, D.M. Sanger, H. Teixeira, R.F. Van Dolah, R.G. Velarde, and K.I. Welch. 2015. Effect of ecological group classification schemes on performance of the AMBI benthic index in US coastal waters. Ecological Indicators 50:99-107. Supplemental data. http://dx.doi.org/10.1016/j.ecolind.2014.11.005.

Kincaid, T. 2015. User guide for spsurvey, version 3.0 Probability Survey Design and Analysis Functions. U.S. Environmental Protection Agency, Office of Research and Development, Corvallis, OR. Available from the Comprehensive R Archive Network at https://cran.r-project.org/web/packages/spsurvey/index.html.

Long, E.R. and P.M. Chapman. 1985. A sediment quality triad-measures of sediment contamination, toxicity, and infaunal community composition in Puget Sound. Marine Pollution Bulletin 16:405-415.

Long, E.R., Dutch, S. Aasen, K. Welch, and M.J. Hameedi. 2003. Chemical Contamination, Acute Toxicity in Laboratory Tests, and Benthic Impacts in Sediments of Puget Sound: A summary of results of the joint 1997-1999 Ecology/NOAA survey. Washington State Dept. of Ecology Publication No. 03-03-049, Olympia, WA and National Oceanic and Atmospheric Administration, Technical Memo No. 163, Silver Spring, MD. 101 pp. + appendix. https://fortress.wa.gov/ecy/publications/SummaryPages/0303049.html.

Long, E.R., M. Dutch, V. Partridge, S. Weakland, and K. Welch. 2012. Revision of sediment quality triad indicators in Puget Sound (Washington, USA): I. A sediment chemistry index and targets for mixtures of toxicants. Integrated Environmental Assessment and Management 9(1):31-49. http://onlinelibrary.wiley.com/doi/10.1002/ieam.1309/full.

Macdonald, T., B. Burd, V. Macdonald, and A. van Roodselaar. 2010. Taxonomic and Feeding Guild Classification for the Marine Benthic Macroinvertebrates of the Strait of Georgia, British Columbia. Canadian Technical Report of Fisheries and Aquatic Sciences 2874. Fisheries and Ocean Canada, Sidney, BC.

Macdonald, T., B. Burd, and A. van Roodselaar. 2012. Facultative feeding and consistency of trophic structure in marine soft-bottom macrobenthic communities. Marine Ecology Progress Series 445:129-140.

Partridge, V., S. Weakland, M. Dutch, D. Burgess, and A. Eagleston. 2018. Sediment Quality in Puget Sound: Changes in chemical contaminants and invertebrate communities at ten sentinel stations, 1989 – 2015. Washington State Department of Ecology, Olympia WA. Publication 18-03-005. https://fortress.wa.gov/ecy/publications/SummaryPages/1803005.html.

Ranasinghe, J.A., E.D. Stein, M.R. Frazier, and D.J. Gillett. 2013. Development of Puget Sound Benthic Indicators. Washington State Department of Ecology, Olympia, WA. Publication No. 13-03-055. https://fortress.wa.gov/ecy/publications/SummaryPages/1303035.html

Additional Information

This report summarizes sediment quality for Puget Sound as a whole, for five strata, and for eight geographic regions. More detailed summaries of sediment quality for the eight regions, as well as for six urban bays, can be found in separate reports available on Ecology's website: https://www.ecology.wa.gov/Research-Data/Monitoring-assessment/Puget-Sound-and-marine-monitoring

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This report is available on the Department of Ecology's website at https://fortress.wa.gov/ecy/publications/SummaryPages/1803004.html.

Data for this project are available at Ecology's Environmental Information Management (EIM) website: EIM Database. Search Study ID, PSAMP_SP.

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