Sediment Quality in Central Puget Sound, Changes over a Ten-Year Period

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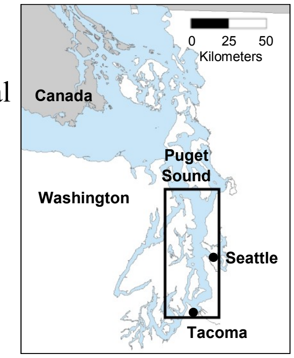
Overall sediment quality declined significantly from 1998-1999 to 2008-2009

Improvement

- Concentrations of lead, mercury, silver, and tin decreased
- Concentrations of some polycyclic aromatic hydrocarbons decreased

Deterioration

- Spatial extent of *adversely affected* benthic invertebrate communities increased
- Low-level toxicity increased slightly
- Spatial extent of *likely impacted* sediments increased, and spatial extent of *unimpacted* sediments decreased (Sediment Quality Triad Index categories)



In 2008 and 2009, the Washington State Department of Ecology (Ecology) surveyed surface sediment conditions throughout Central Puget Sound and compared them to conditions from a similar survey in 1998-1999 conducted with the same methods. The study area extends from Possession Sound to the Tacoma Narrows and includes the cities of Seattle and Tacoma (map at right).

Overall sediment quality in Central Sound declined over this 10-year period, driven primarily by increased spatial extent of *adversely affected* sediment-dwelling invertebrate communities (benthos). Low-level sediment toxicity also worsened slightly.

Sediment contaminant, toxicity, and benthic invertebrate data were summarized as Ecology's respective Chemistry, Toxicity, and Benthic Indices and combined Sediment Quality Triad Index (Dutch et al., 2012). These indices were developed to display the different types of information on a scale from 0 (poorest quality) to 100 (highest quality).

The survey design weights sample results by area, which enables Ecology to estimate percent of area (spatial extent) with given sediment conditions and to compare results from two surveys at a glance. For Central Sound, the weighted mean sediment quality indices show statistically significant deterioration in the Toxicity, Benthic, and Triad Indices (Figure 1).

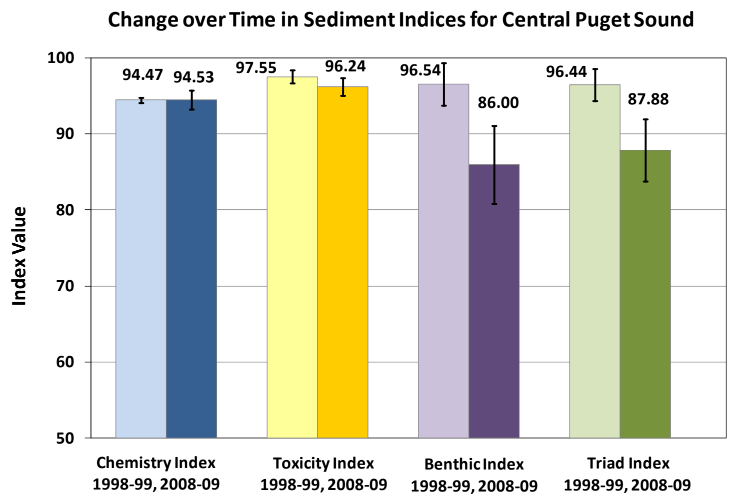


Figure 1. Weighted mean index values and 95% confidence intervals. Benthic invertebrate, toxicity, and overall sediment quality (Triad Index) scores decreased (worsened) significantly from 1998-1999 (light bars) to 2008-2009 (dark bars).

Sediment Monitoring of Central Puget Sound

Ecology surveyed the Central Puget Sound region as part of the Puget Sound Ecosystem Monitoring Program (PSEMP). This region was previously studied in a baseline survey conducted jointly in 1998-1999 by Ecology and the National Oceanic and Atmospheric Administration (Long et al., 2005). Most of the field and laboratory methods were the same. New sampling sites were selected for the 2008-2009 survey, and some analyses of the 1998-1999 data were updated for consistency with current statistical methods, for comparison. The study design, sampling and analytical methods, and list of parameters are described in Dutch et al. (2009) and on Ecology's website.

This report addresses the Central Sound *region as a whole*, not the individual urbanized and industrialized bays within.

Want more information?

The primary results of the 2008-2009 survey and comparisons to 1998-1999 results are given here. Data and supporting documentation, including methods, are on Ecology's website: **www.ecy.wa.gov/programs/eap/psamp.**

Physical Conditions

The study area consists of urban and rural embayments, industrial harbors, deep basins, and passages, from 3 m to 252 m deep. Except in passages, sediments throughout the region were largely finer-grained (> 80% silt-clay); sediments in passages were predominantly sandy. Total organic carbon (TOC) content in Central Sound ranged from 0.06% to 3.98%, averaging 1.28% across samples and 1.16% with stations weighted by amount of area represented. Highest TOC values were found at stations in the inner Elliott and Commencement Bays and west of Bainbridge Island. TOC content and percent fines in 2008-2009 were not statistically significantly different from those in 1998-1999.

Individual Contaminants

Samples were analyzed for the concentrations of 133 potentially toxic chemicals, including metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs, which are flame-retardants), and other organic compounds. Metals and PAHs were detected and measurable in about 92% of samples, PCBs in 16% of samples, and other target organic compounds (e.g., PBDEs, pesticides) in less than 9% of samples.

At 10 of the 80 stations sampled, mercury concentrations exceeded (did not meet) the Washington State Sediment Quality Standard (SQS) (Ecology, 1995), indicating levels which are likely to harm organisms. Concentrations also exceeded SQS for total PCB Aroclors (4 stations), bis(2-ethylhexyl)phthalate (2 stations), and hexachlorobenzene (1 station). The 17 stations at which SQS were exceeded represented 21% of the stations but 11% of the total study area. By contrast, in 1998-1999, 32% of the stations, representing only 4% of the study area, had contaminant concentrations above SQS. At most one chemical exceeded SQS at any station in 2008-2009, but some stations had up to 15 chemicals above the SQS in 1998-1999.

Concentrations of lead, mercury, silver, and tin decreased from 1998-1999 to 2008-2009, but chromium, nickel, and selenium increased. Some PAHs significantly decreased, while others remained unchanged over the 10-year period.

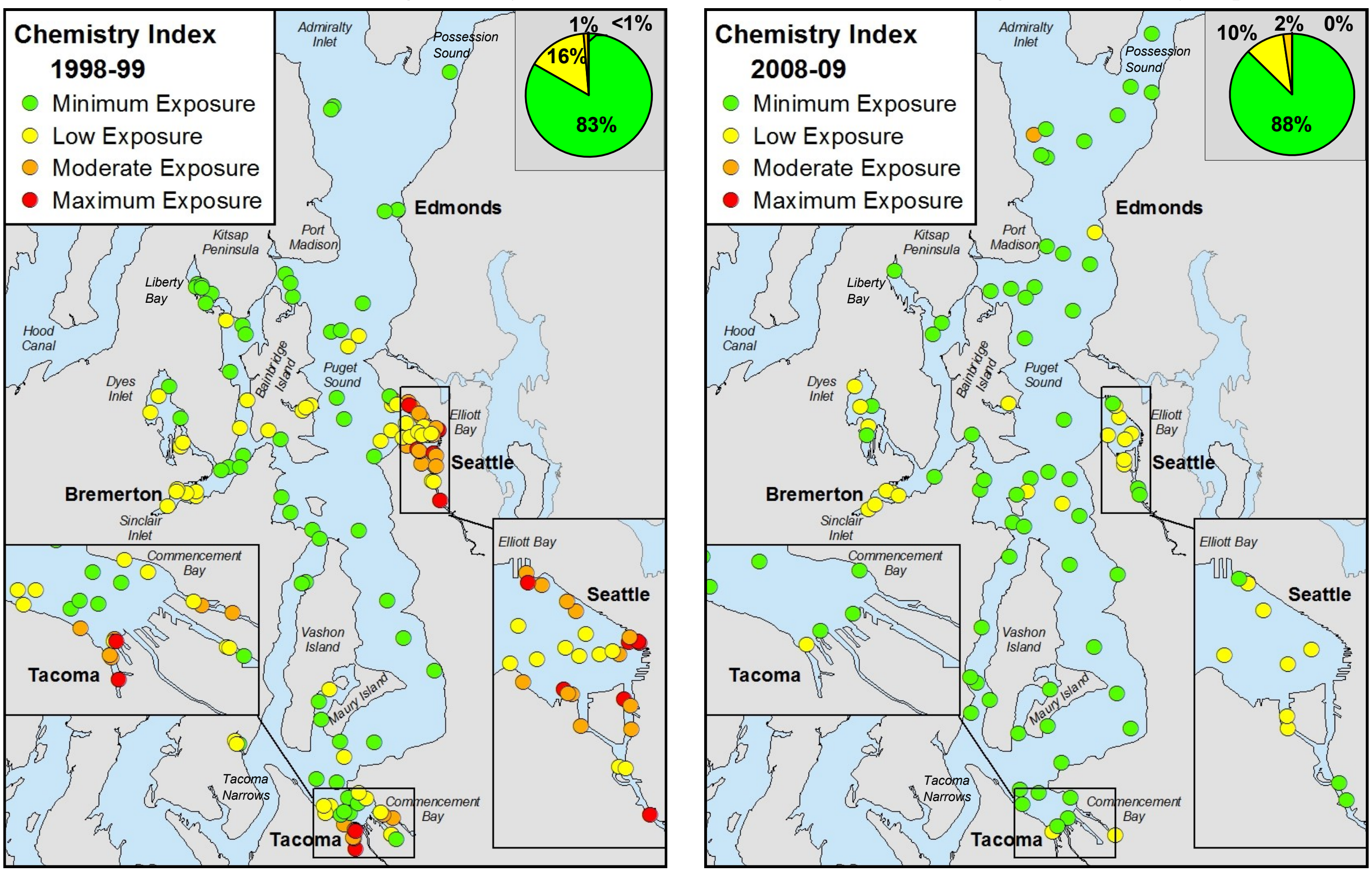


Figure 2. Spatial patterns at sampling stations and estimated spatial extent (percent of area, shown in pie chart) for the Sediment Chemistry Index categories for Central Puget Sound. There was no statistically significant change in spatial extent of the four Chemistry Index categories of exposure from 1998-1999 to 2008-2009 (α=0.05, or 95% confidence).

Sediment Chemistry Index

Ecology's Sediment Chemistry Index is an effects-based, multi-chemical index that accounts for the presence, concentrations, and potential toxicity of mixtures of chemicals (Long et al., 2013). It is used to categorize sediments as having *minimum, low, moderate,* or *maximum* levels of exposure to the chemicals for which SQS have been defined.

The Chemistry Index indicated about 88% of the study area had *minimum exposure* to chemical contaminants in 2008-2009 (Figure 2). None of the study area was classified as having *maximum exposure* in 2008-2009, whereas nine stations (0.2% of area) had *maximum exposure* in 1998-1999. The spatial extent in the four Chemistry Index categories did not change significantly (Figure 2). Even though fewer samples were collected from the inner harbors in 2008-2009 than in the earlier survey, the later samples were weighted more heavily to represent the same area.

Sediment Toxicity Index

In the 2008-2009 survey, each sediment sample was analyzed with two laboratory toxicity tests: amphipod survival and sea urchin egg fertilization. The test results were combined into Ecology's Sediment Toxicity Index (Dutch et al., 2012) and characterized into four toxicity ranges, from *non-toxic* to *high toxicity* (Table 1).

Table 1. Toxicity Index category descriptions.

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

The Toxicity Index indicated that 54 of the 80 stations, representing 76% of the study area, had *non-toxic* sediments, and the remaining 24% of area (26 stations) had some degree of toxicity (Figure 3). By contrast, ten years earlier, 113 of 128 stations (99% of area), had *non-toxic* sediments. In the 2008-2009 survey, samples with the highest toxicity were located in Sinclair Inlet, Dyes Inlet, and Liberty Bay.

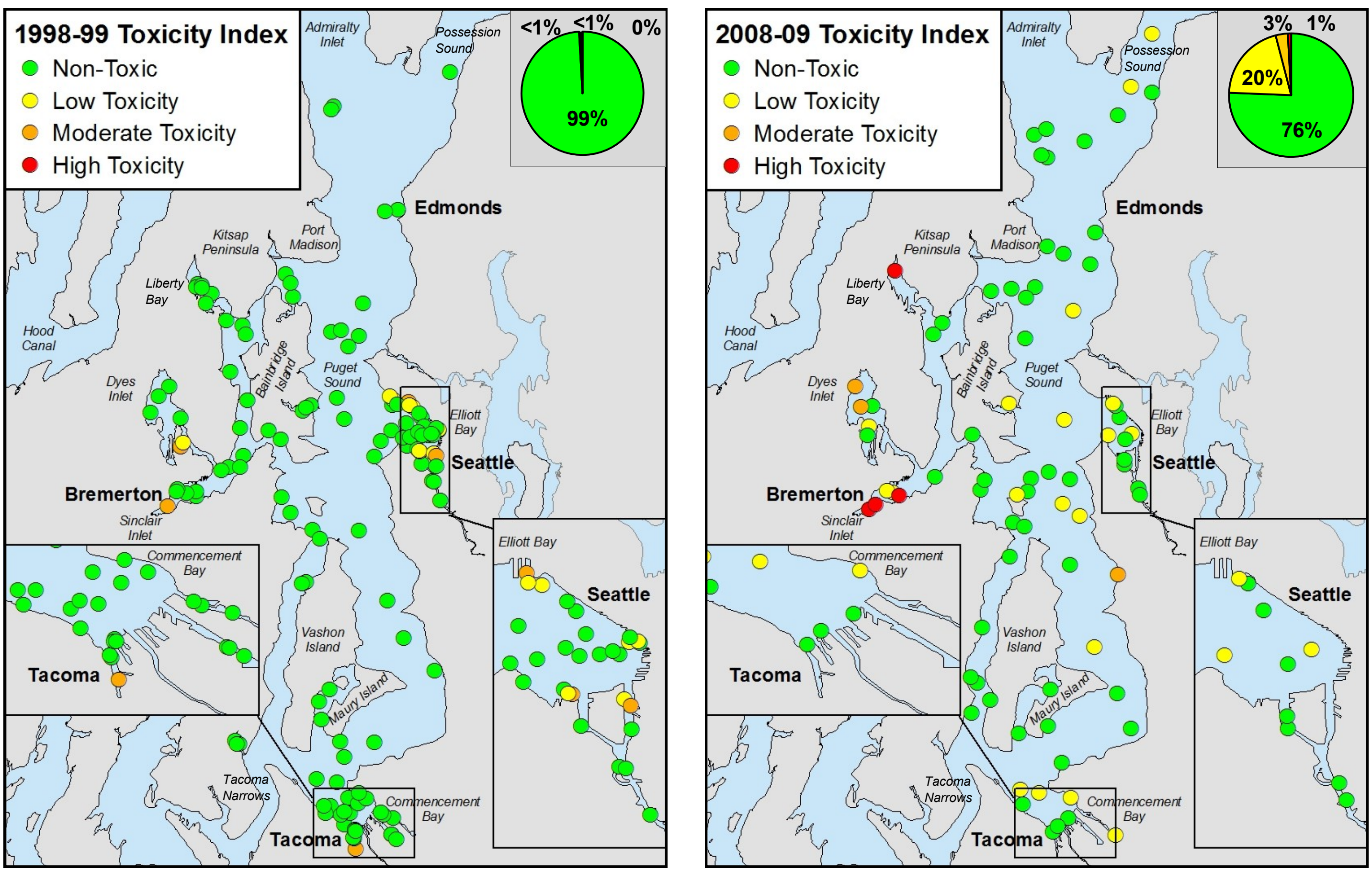


Figure 3. Spatial patterns at sampling stations and estimated spatial extent (percent of area, shown in pie chart) for the Sediment Toxicity Index categories for Central Puget Sound. Spatial extent of toxicity increased significantly from 1998-1999 to 2008-2009 (α=0.05, or 95% confidence).

Sediment Benthic Index

Benthic invertebrate organisms (benthos) were identified and counted for all 80 locations sampled in 2008-2009, and several measures of benthic abundance and diversity were calculated. Geographically, total abundance and taxa richness (number of taxa, or species) were lower in Liberty Bay, Dyes Inlet, and Sinclair Inlet than in the rest of Central Sound. Annelid (marine worm) abundance was greatest in the Port Washington Narrows connecting Sinclair and Dyes Inlets. Mollusc abundance was low throughout most of the region but relatively high in Elliott and Commencement Bays. Arthropod abundance was also low throughout most of the region, with highest abundances found in Possession Sound, Elliott Bay, and Dyes Inlet. Echinoderms were relatively abundant at only a few scattered stations, primarily in the Bainbridge Basin (west of Bainbridge Island), west of Maury Island, and in Commencement Bay.

Ecology's Benthic Index was calculated by examining the data to determine whether the invertebrate assemblages appeared to be *adversely affected* or *unaffected* by natural and/or human-caused stressors. The determination was made by benthic experts based on assessment of a suite of calculated indices (total abundance, major taxa abundances, taxa richness, evenness, and species dominance). These indices were compared to median values for all of Puget Sound. Abundances of stress-sensitive and -tolerant species at each station were considered as well. The benthos data for all samples collected in Puget Sound since 1997 have been assessed by the same experts, using the same methods, with species standardized across the years, for consistency over all surveys.

In 2008-2009, the benthos were judged to have been *adversely affected* in 28% of the study area (Figure 4). By contrast, 7% of the study area in 1998-1999 had *adversely affected* benthos. This increase in spatial extent of *adversely affected* benthos was statistically significant. Although in 1998-1999 the *adversely affected* benthos were located primarily in Elliott Bay, Sinclair Inlet, and Commencement Bay, in 2008-2009, benthic conditions were somewhat improved in the industrial waterways of Elliott and Commencement Bays, but adversely affected benthic assemblages were scattered throughout the region (Figure 4). The reasons for the spread in adversely affected benthos are not known.

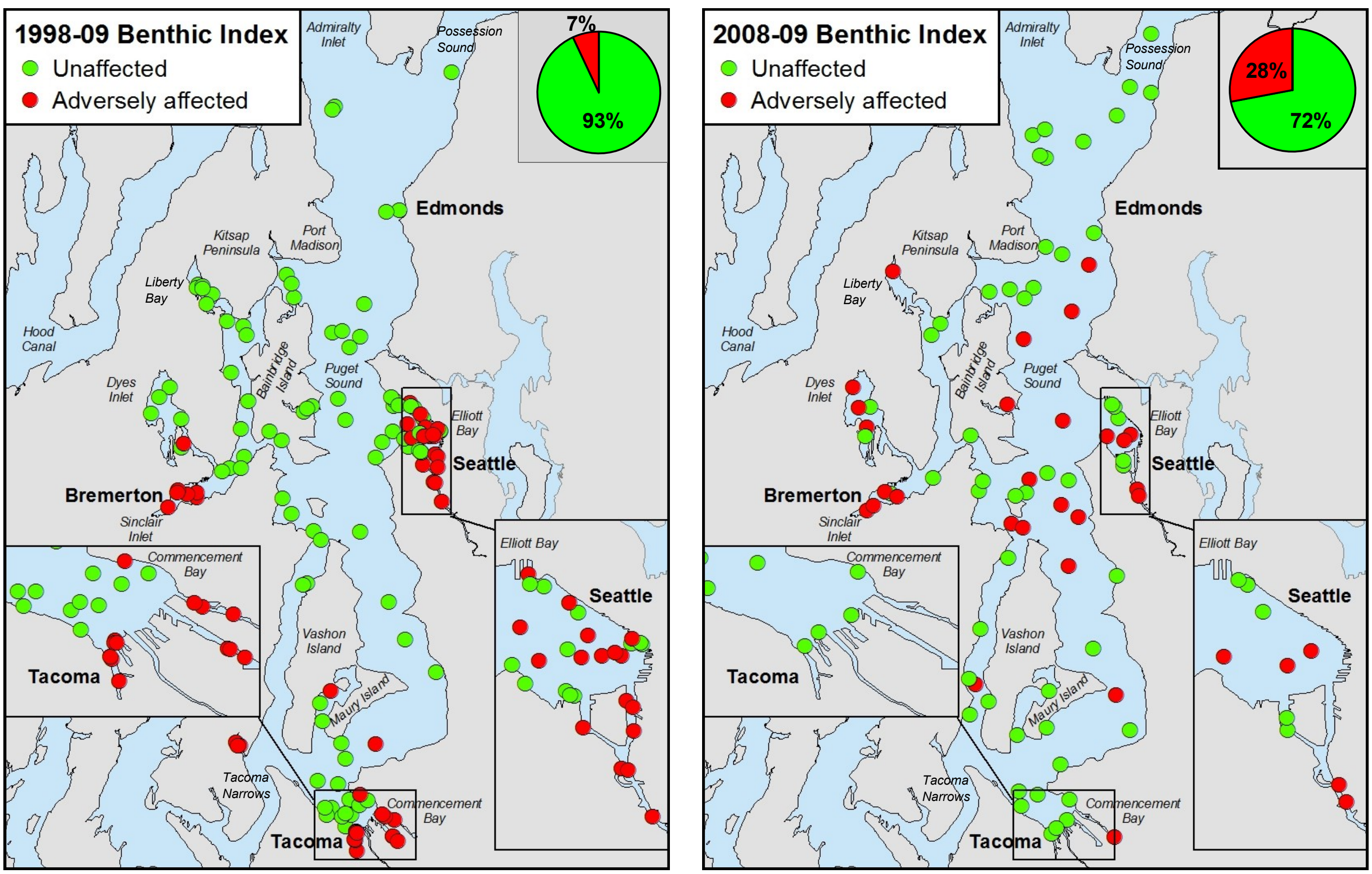


Figure 4. Spatial patterns at sampling stations and estimated spatial extent (percent of area, shown in pie chart) for the Sediment Benthic Index categories for Central Puget Sound. There was a statistically significant change in spatial extent of the two Benthic Index categories from 1998-1999 to 2008-2009 (α=0.05, or 95% confidence).

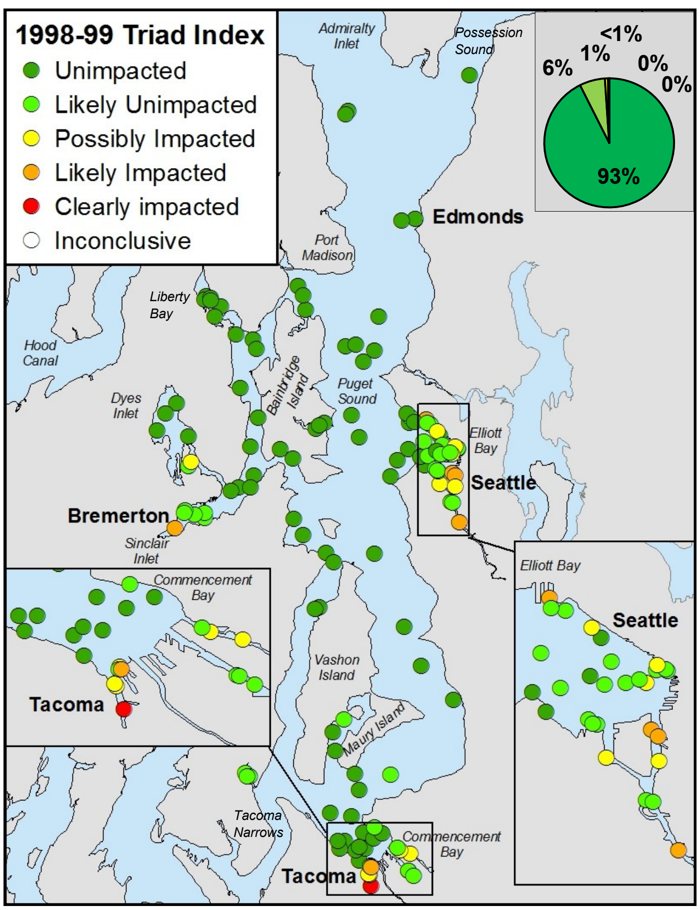
Sediment Quality Triad Index

Ecology's Sediment Quality Triad Index combines the evidence from the triad of measures (chemistry, toxicity, and benthos) to classify sediment quality into six categories of impact by chemical contamination and/or other enviromental stressors (Dutch et al., 2012). Categories range from *unimpacted* to *clearly impacted*, plus an *inconclusive* category for cases in which the three lines of evidence conflict. This multiple-lines-of-evidence approach was adapted from methods developed for the state of California to classify sediment quality (Bay and Weisberg, 2012).

In 2008-2009, 72% of the study area was classified as *unimpacted* (Figure 5; Table 2, next page). Another 15% of the area was determined to be *likely unimpacted*. Sediments *possibly impacted* and *likely impacted* by chemical contamination and/or other environmental stressors were found in 6% of the study area. None of the area was classified as *clearly impacted*. The remaining 7% of the area was classified as *inconclusive*, with conflicting Chemistry, Toxicity, and Benthos Index results (Table 2, next page).

Spatial extent of the *unimpacted* category was statistically significantly lower in 2008-2009 than in 1998-1999, and spatial extent of the *likely impacted* category was significantly higher. The overall decline in sediment quality throughout the region was driven by increased levels of toxicity and increased *adversely affected* benthos.

The primary changes in the geographical patterns of the Triad Index were possible deterioration in the terminal inlets of the Bainbridge Basin (Sinclair Inlet, Dyes Inlet, and Liberty Bay) and possible improvement in Elliott Bay and Commencement Bay (Figure 5).



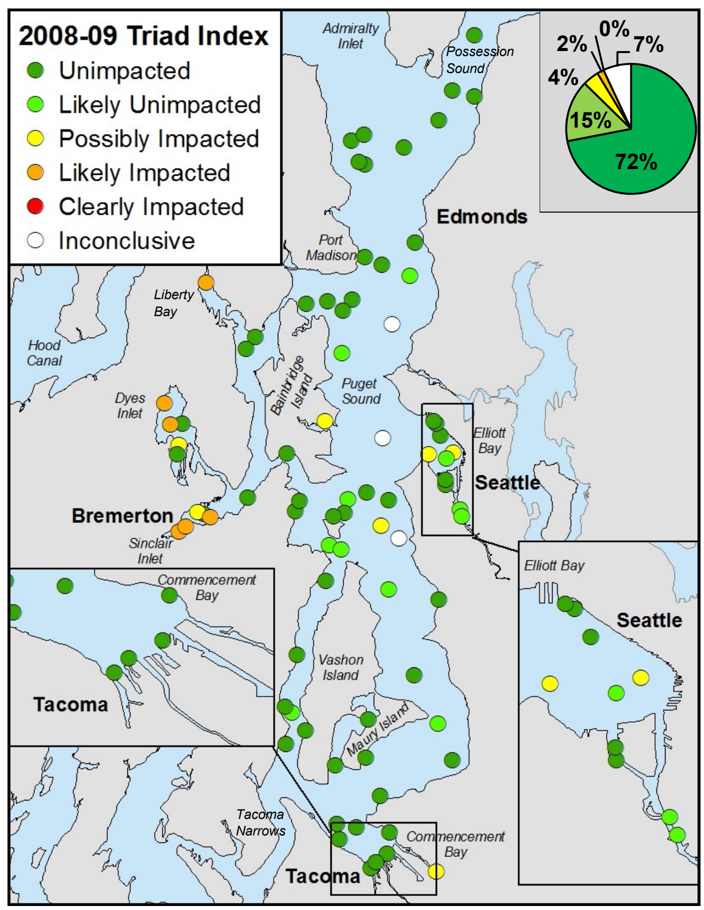


Figure 5. Spatial patterns at sampling stations and estimated spatial extent (percent of area, shown in pie chart) for the Sediment Quality Triad Index results in Central Puget Sound. There was a statistically significant increase in the spatial extent of *impacted* sediments from 1998-1999 to 2008-2009 (α=0.05, or 95% confidence).

Table 2. Specific combinations of index results (chemistry, toxicity, benthos) that led to Sediment Quality Triad Index categories for Central Puget Sound in 2008-2009. Spatial extent (% of study area) is given for each combination. For details on derivation of the index categories, see Dutch et al. (2012).

Triad Index =	Benthic Index +	Toxicity Index +	Chemistry Index	% of Area
Unimpacted	Unaffected	Non-Toxic	Minimum exposure	53.6
	Unaffected	Non-Toxic	Low exposure	4.4
	Unaffected	Non-Toxic	Moderate exposure	2.3
	Unaffected	Low toxicity	Minimum exposure	9.2
	Unaffected	Low toxicity	Low exposure	0.1
	Unaffected	Moderate toxicity	Minimum exposure	2.3
Likely unimpacted	Adversely affected	Non-Toxic	Minimum exposure	14.9
	Adversely affected	Non-Toxic	Low exposure	0.4
Possibly impacted	Adversely affected	Low toxicity	Low exposure	4.0
Likely impacted	Adversely affected	Moderate toxicity	Low exposure	0.8
	Adversely affected	High toxicity	Minimum exposure	0.4
	Adversely affected	High toxicity	Low exposure	0.4
Inconclusive	Adversely affected	Low toxicity	Minimum exposure	7.0

Central Region Sediment Quality Compared to All of Puget Sound

The Central Sound region comprises 30% of the area of Puget Sound. The nested sampling design of Ecology's sediment monitoring program is specifically intended to allow comparisons amongst nested areas, as well as across regions and times.

There are similar proportions of area in the *unimpacted* category in Central Sound Triad Index results, compared to those for the Puget Sound baseline (Figure 6). However, the Central region had a higher proportion of area in the *likely impacted* category and lower proportion of area in the *likely unimpacted* category than for the entire Puget Sound.

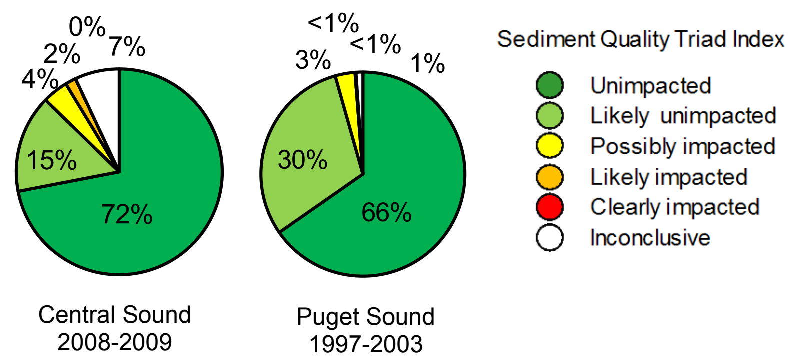


Figure 6. Spatial extent (percent of area) for the Sediment Quality Triad Index categories for Central Sound 2008-2009 (from Figure 5), compared to the Puget Sound 1997-2003 baseline.

Urban Bays in Central Puget Sound

The numbers of samples in urban bays in Central Puget Sound in the 2008-2009 survey are insufficient to make statements about sediment quality in the individual bays. However, Ecology also conducts separate, more intensive surveys of six urban bays in Puget Sound. Surveys of Elliott Bay, Commencement Bay, and the Bainbridge Basin (including Sinclair Inlet) were conducted during 2007-2009 (Partridge et al., 2009, 2010; Weakland et al., 2013).

Results, data summaries, and reports on sediment quality in the individual urban bays, including comparisons to 1998-1999 results, are available on Ecology's website:

Elliott Bay: www.ecy.wa.gov/programs/eap/psamp/DataSummaries/ElliottBay/ElliottBay.html

Commencement Bay:
www.ecy.wa.gov/programs/eap/psamp/DataSummaries/CommencementBay/CommencementBay.html

Bainbridge Basin: www.ecy.wa.gov/programs/eap/psamp/DataSummaries/BainbridgeBasin/Bainbridge.html

The Chemistry Index and the Triad Index as "Vital Signs" Indicators for the Puget Sound Partnership

Ecology's Chemistry and Triad Indices, and also the percent of chemicals exceeding (not meeting) SQS, were adopted by the Puget Sound Partnership (PSP) in 2010 to serve as one of the "Vital Signs" indicators of the condition of Puget Sound (www.psp.wa.gov/vitalsigns/index.php).

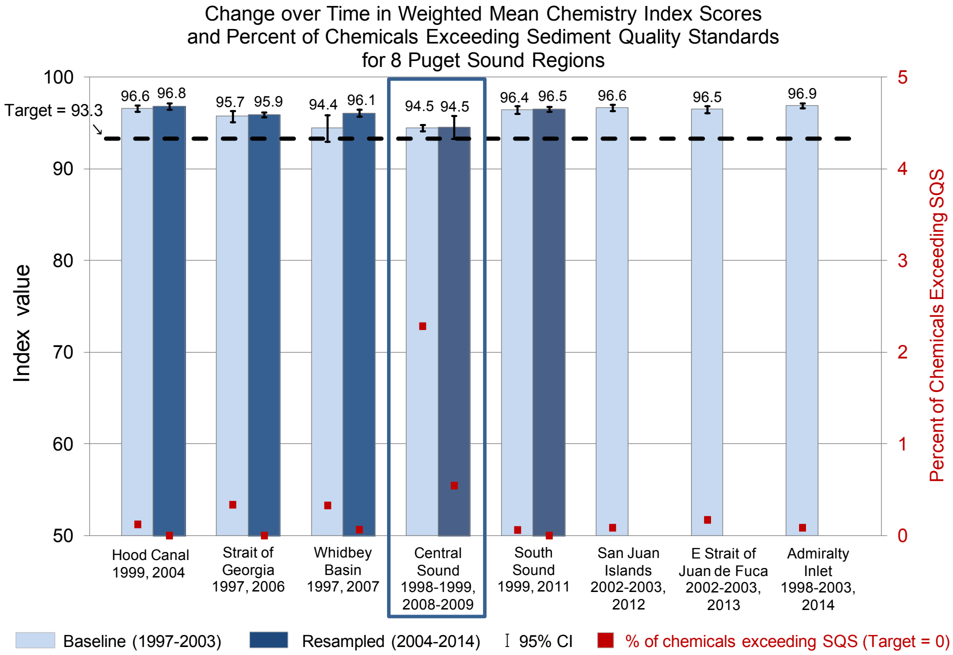


Figure 7. Weighted mean Sediment Chemistry Index values and 95% confidence intervals for all sediment monitoring regions sampled from 1997 to 2003 (Puget Sound baseline, light blue bars) and resampled from 2004 to 2009 (dark blue bars). The PSP target is shown. Also shown are the percent of chemicals exceeding SQS (red squares).

Weighted mean Chemistry and Triad Index values are compared among regions and between repeated years of sampling to determine changes over time (Figures 7 and 8). They are also compared with target values for 2020 adopted by the PSP.

There was no change in the Chemistry Index score for Central Sound over the 10-year period (Figure 7, outlined bars).

The Chemistry Index scores for Central Sound surpassed the PSP's 2020 target value of 93.3, indicating highest quality (Figure 7, dashed line).

The percent of chemicals exceeding SQS (Figure 7, red squares) declined significantly over the 10 years, but still did not meet the target of zero.

The Triad Index score for the 2008-2009 Central Sound survey was statistically significantly lower than that for 10 years prior (Figure 8, outlined bars).

However, the recent Triad score for Central region still was above the PSP target value of 81, indicating highest quality (Figure 8, dashed line).

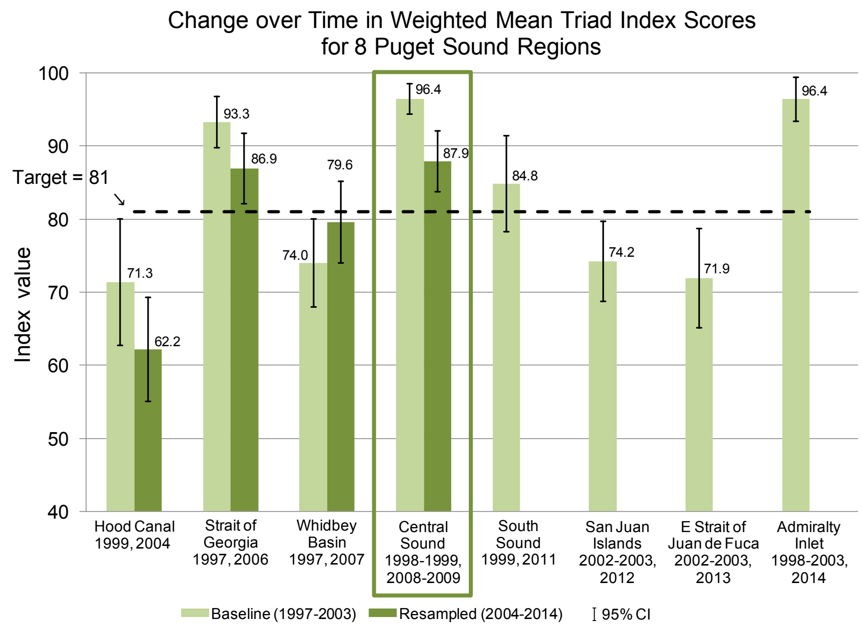


Figure 8. Weighted mean Sediment Quality Triad Index values and 95% confidence intervals for all sediment monitoring regions sampled from 1997 to 2003 (Puget Sound baseline, light green bars) and resampled from 2004 to 2009 (dark green bars). The PSP target value of 81 is shown.

Summary and Conclusions

Resampling of the regions of Puget Sound continues each year; after the 2014 survey, the assessment of condition of the entire Sound will be updated based on the current round of surveys. In the meantime, the declining sediment quality trends, particularly in benthic invertebrate community health, seen almost everywhere throughout Puget Sound should be a concern for environmental managers.

Similar patterns are evident among the regions and urban bays which have been resampled since 2004, in comparison to the Puget Sound baseline (1997-2003). Except for the Whidbey Basin region in 2007, the patterns appear to be:

- Decreased concentrations of some SQS contaminants but increases in others, and no net change in the Chemistry Index.
- Increased levels or spread of toxicity (net decrease in the Toxicity Index).
- Large increases in the spatial extent of *adversely affected* benthic invertebrate communities.
- Deterioration in overall sediment quality, primarily reflecting the contribution of the Benthic Index to the Triad Index.

(See Ecology's sediment monitoring website for the regional and urban bay reports and data summaries: www.ecy.wa.gov/programs/eap/psamp.)

The majority (72%) of the area of Central Puget Sound in 2008-2009 had surface sediments categorized as *unimpacted*; however, that proportion represents a significant drop from the 93% of area with *unimpacted* sediments in 1998-1999. Spread of *adversely affected* benthos and increased levels of toxicity (primarily from the sea urchin fertilization test) drove the change in the Triad Index. The reasons for the deterioration in sediment quality are not known and would require further study to determine. It is possible that a combination of natural and human-caused factors was involved (e.g., dissolved oxygen levels or contaminants not measured in this survey).

On the other hand, although there was no net change in the Chemistry Index region-wide from 1998-1999 to 2008-2009, there were significant decreases in relative numbers and locations of chemical contaminants exceeding SQS, primarily in the heavily urbanized and industrialized portions of Elliott and Commencement Bays. This trend suggests positive results from collective cleanups and source control in those areas, but lingering contaminant concentrations above the SQS are still a problem.

Since conditions were assessed in the late 1990s, *adversely affected* benthos have spread away from heavily urbanized/ industrialized portions of Elliott and Commencement Bays and into areas which previously had *unaffected* benthos. That observation, combined with the large decrease in number of contaminant concentrations above the SQS, suggests that the SQS contaminants (i.e., chemicals for which the effects-based SQS were developed in 1995) may not be the major problem. Alternate possible mechanisms for the decline in benthic health include:

- Slow migration/transport of contaminants from nearshore to deeper zones.
- Exposure to SQS contaminants requiring a relatively long time to translate into observable detrimental effects at the benthic population/community level.
- Other contaminants not yet monitored.
- Low levels of dissolved oxygen in bottom waters.
- Changes in food availability.
- Large-scale oceanographic or climatic processes.

Note that the geographical observations mentioned above are descriptive only and that any conclusions drawn in this report are for the large scale of the Central Puget Sound region as a whole. This survey was not intended or designed for inferences about smaller areas, such as the individual urban bays. For bay-scale results, see Partridge et al. (2009, 2010) and Weakland et al. (2013).

Recommendations

- Continue annual PSEMP sediment quality monitoring to determine spatial status and temporal trends in Puget Sound regions and bays, maintaining the current sampling design and key parameters over time.
- Expand surveys to other environmentally important Puget Sound bays and the nearshore.
- Perform additional statistical analyses to examine relationships among the chemistry, toxicity, and benthos data.
- While maintaining the integrity of the existing monitoring program, continue to update, refine, and improve Puget Sound chemistry, toxicity, and benthic indicators by (1) quantifying new suites of chemicals of concern, (2) adopting more current and comprehensive methods of toxicity testing, including toxicity tests which are responsive to chemicals of emerging concern, and (3) continuing development and validation of a multivariate benthic index for Puget Sound.
- Determine additional environmental parameters to examine which may be affecting the benthos, such as (1) water quality measures, including near-bottom dissolved oxygen, pH, and nutrient levels, (2) rates of sediment deposition, mixing, and resuspension, and (3) patterns of sediment transport.
- Examine trophic connections between contaminants in sediments and resident biota through measurement of contaminants in infaunal and epifaunal invertebrates and also in benthic fish.

Technical Notes

- The sampling design differed slightly between the 1998-1999 and 2008-2009 surveys of Central Puget Sound. In the earlier survey, 128 stations had been selected at random from a stratified design, with generally three stations in each of several dozen strata of various dimensions and characteristics. In the later survey, 80 stations were selected from a probabilistic design with five strata representing different geographical, oceanographical, and human-use conditions. Because the amount of area remained the same, the more numerous samples in the inner bays in the 1998-1999 survey had smaller weights than the less numerous samples in the 2008-2009 survey. Both surveys were designed to estimate spatial extent of conditions for large areas.
- We explored whether the increase in toxicity seen in the later survey might have been a result of using a more sensitive species for the amphipod survival toxicity test in 2008-2009 than in 1998-1999. Comparison of the results separately for the two types of tests indicated no statistically significant increase in toxicity according to the amphipod survival test, but a significant increase in toxicity according to the urchin fertilization test, which was not changed.
- Aside from the more limited geographic focus, the bay-wide and regional surveys differ in sampling design. In the Urban Bays surveys, the original stations were resampled; in the Central Sound regional survey, all new sampling stations were chosen.
- A rigorous data quality review performed by Ecology's laboratory and Environmental Assessment Program staff resulted in no data being rejected. Even results that were qualified were still deemed usable for the purposes of the study.

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