Sediment Quality in the Bainbridge Basin, Changes from 1998 to 2009

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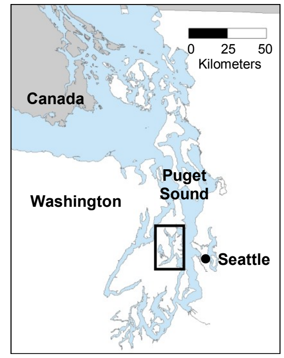

In 2009, the Washington State Department of Ecology (Ecology) surveyed surface sediment conditions throughout the Bainbridge Basin of Puget Sound (box in map at right) and compared them to those from a similar survey conducted with the same methods in 1998. Overall sediment quality in the Bainbridge Basin declined over this 11-year period, and significant changes (both positive and negative) in several individual parameters and indices were detected.

Sediment contaminant, toxicity, and sediment-dwelling (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 to enable estimation of percent of area (spatial extent) with given sediment conditions and comparison of results from the two surveys at a glance. The weighted mean sediment quality indices show a statistically significant deterioration in all but the Chemistry Index (Figure 1).

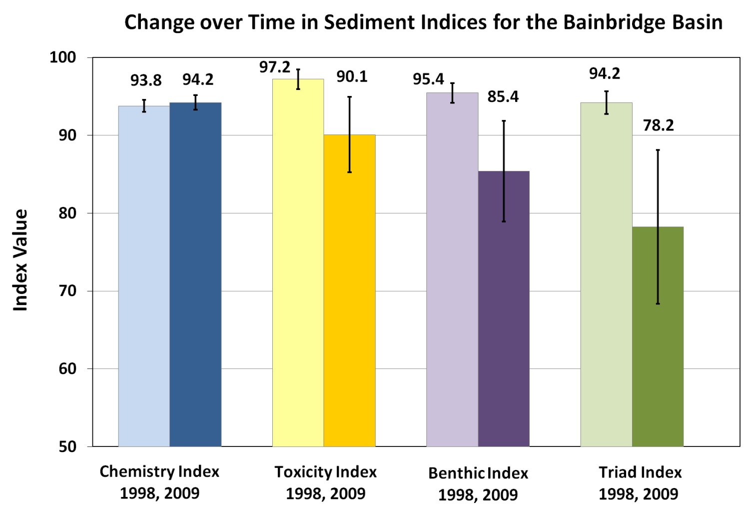

Figure 1. Weighted mean index values and 95% confidence intervals, indicating statistically significant deterioration in sediment toxicity, benthic invertebrate community structure, and overall quality from 1998 to 2009.

Overall sediment quality declined significantly from 1998 to 2009

Improvement

- Decreased concentrations of arsenic, lead, and some polycyclic aromatic hydrocarbons (PAHs)

Deterioration

- Increase in *adversely affected* benthic invertebrate communities
- Increased concentrations of several metals and multiple PAHs
- Increase in low-level sediment toxicity
- Decrease in *unimpacted* sediments and increase in *likely impacted* sediments

Sediment Monitoring of the Bainbridge Basin

Ecology surveyed the Bainbridge Basin as part of the Puget Sound Ecosystem Monitoring Program (PSEMP). The study area includes Port Madison and all of the bays, inlets, and passages west of Bainbridge Island. The basin is shallow (< 50 m deep) and includes industrial harbors (the naval shipyard in Sinclair Inlet), as well as urban and rural areas. The Bainbridge Basin previously had been characterized in a baseline survey conducted jointly by Ecology and the National Oceanic and Atmospheric Administration in 1998 (Long et al., 2005). The same field and laboratory methods were used, and the same station locations were sampled. Some analyses of the 1998 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.

Want more information?

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

Physical Conditions in the Bainbridge Basin

Sediments throughout the region were evenly divided between predominantly sandy (< 20% silt-clay) and finer-grained sediments. Total organic carbon (TOC) content outside Sinclair Inlet ranged from < 0.2% to 3.2%, averaging 1.3%. In Sinclair Inlet, TOC content ranged from 2.4% to 3.9%, averaging 3.0%.

Compared to 1998, TOC content in 2009 was slightly lower overall, but when weighted by area was not statistically significantly different (α=0.05, or 95% confidence). Similarly, there was a slight significant decrease in the percent fines (silt+clay), but not when weighted by area. However, there was a significant shift from silt to clay-sized particles.

Sediment Chemistry Index

Samples were analyzed for the concentrations of 129 potentially toxic chemicals, including metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and other organic compounds. Metals and PAHs were detected and measurable in about 97% of samples, PCBs in about 20% of samples, and other target organic compounds (e.g., flame-retardant polybrominated diphenyl ethers, or PBDEs; and pesticides) in less than 9% of samples.

Contaminant concentrations were higher in the terminal inlets than in the open passages. Generally, arsenic, copper, lead, mercury, and zinc concentrations were highest in Sinclair Inlet; whereas cadmium, chromium, and nickel were highest in Liberty Bay. PAH concentrations were highest in Dyes Inlet, followed by Sinclair Inlet. PCBs were found in Sinclair Inlet, sometimes detected in Dyes Inlet and Liberty Bay, and generally not detected elsewhere. Of 13 PBDE congeners, only four were detected (PBDE-47, -49, -99, and -209), all in Sinclair Inlet and occasionally in Liberty Bay. The few other organic compounds detected were located geographically like the metals.

Mercury concentrations exceeded (did not meet) the Washington State Sediment Quality Standards (SQS) (Ecology, 1995) at all stations in Sinclair Inlet and at two of the three stations in Dyes Inlet, largely the same conditions as in 1998.

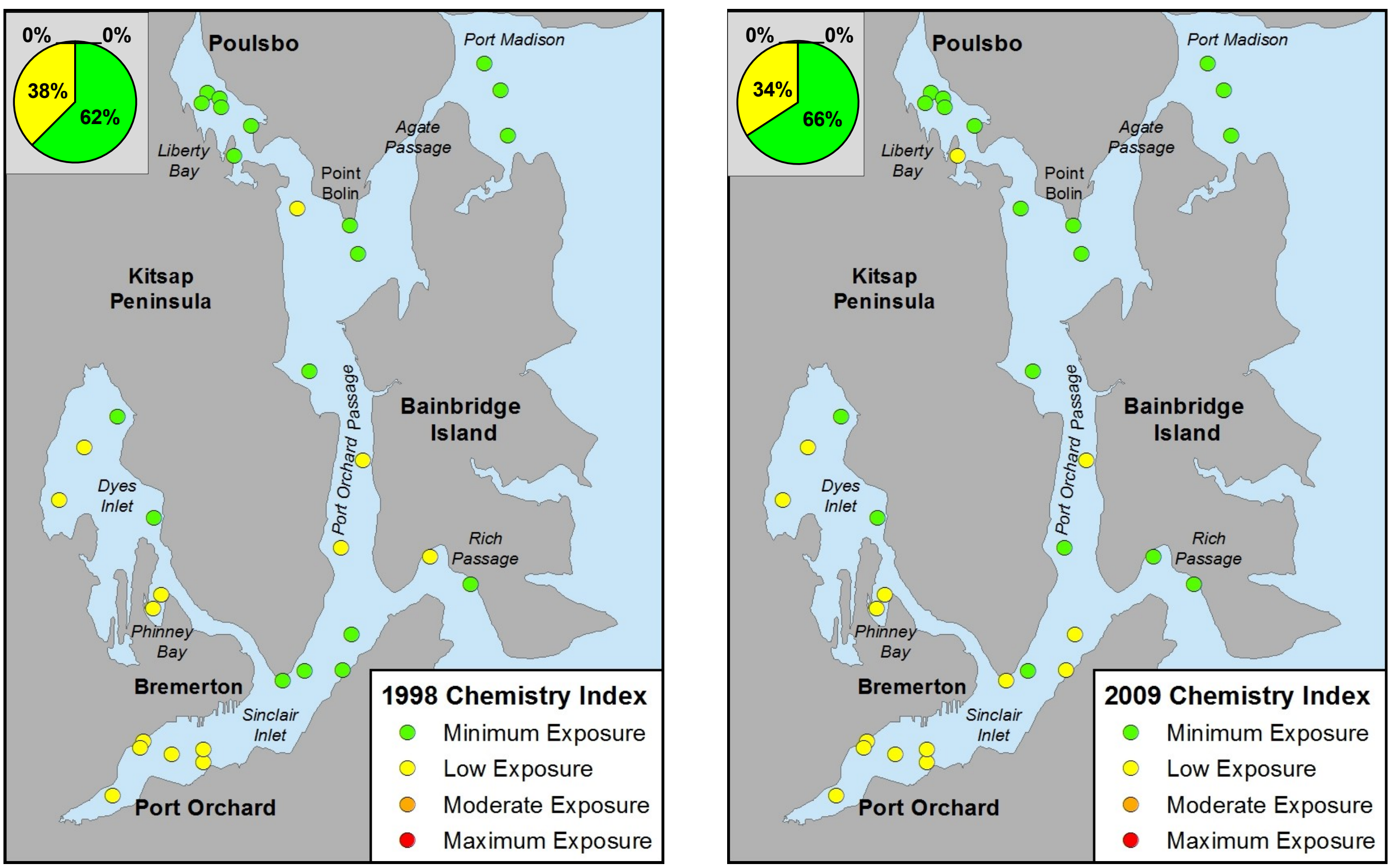

Figure 2. Spatial patterns at sampling stations and estimated spatial extent (percent of area, shown in pie chart) for the Sediment Chemistry Index categories for the Bainbridge Basin. There was no statistically significant change (α=0.05) in spatial extent of the four Chemistry Index categories of exposure from 1998 to 2009.

Ecology's Sediment Chemistry Index (Long et al., 2013) indicated that 66% of the study area had *minimum exposure* to chemical contaminants in 2009 (Figure 2). The Chemistry Index is an effects-based, multi-chemical index that accounts for the presence, concentrations, and potential toxicity of mixtures of chemicals. 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. In 2009, none of the study area was classified as having *moderate* or *maximum exposure*. The spatial extent in each of the four Chemistry Index categories in 2009 was not significantly different than in 1998 (α=0.05).

Concentrations of a number of contaminants changed significantly (α=0.05) from 1998 to 2009, but when weighted by area, few contaminants changed significantly. Unweighted, levels of arsenic and most low-molecular-weight PAHs increased, whereas levels of other metals (including copper, lead, and silver) and a few high-molecular-weight PAHs decreased.

Sediment Toxicity Index

In the 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 66% of the study area in 2009 had *non-toxic* sediments (Figure 3). In addition, the weighted mean Toxicity Index value was significantly lower in 2009 than in 1998, indicating overall greater toxicity. Sediments in Liberty Bay which were not toxic in 1998 had *moderate*-*high* levels of toxicity in 2009 (Figure 3).

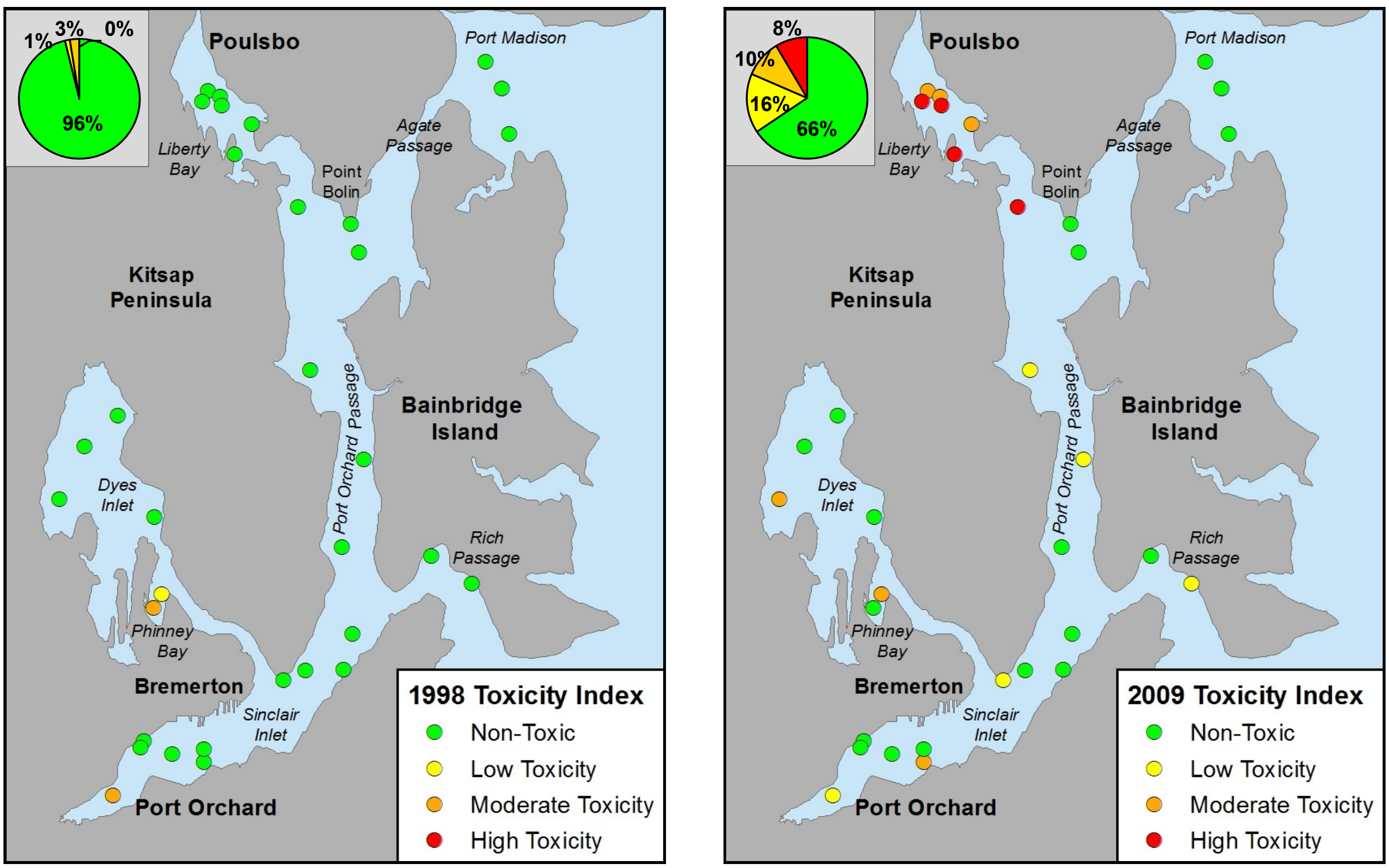

Figure 3. Spatial patterns at sampling stations and estimated spatial extent (percent of area, shown in pie chart) for the Sediment Toxicity Index categories for the Bainbridge Basin. Spatial extent of *low*-level toxicity increased significantly and spatial extent of *non-toxic* sediments decreased significantly from 1998 to 2009 (α=0.05). Changes in spatial extent of *moderate* and *high toxicity* were not statistically significant.

Sediment Benthic Index

Benthic invertebrate organisms (benthos) were identified and counted for all 33 locations sampled in 2009, and several measures of benthic abundance and diversity were calculated. Geographically, total abundance and taxa richness (number of taxa) were lowest in Liberty Bay, and lower in Sinclair Inlet than in the rest of the Bainbridge Basin. Annelid (marine worm) abundance was greatest in Phinney Bay. Mollusc abundance was low throughout most of the basin, but relatively high at Point Bolin and in Port Madison, Rich Passage, and southern Port Orchard Passage. Arthropod abundance was low in Liberty Bay and at two stations each in Sinclair Inlet and Port Orchard Passage. Echinoderms were relatively abundant at a few scattered stations, primarily in Port Madison.

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 anthropogenic stressors. The determination was made by benthic experts based on best professional judgment 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 2009 the benthos were judged to have been *adversely affected* in 29% of the study area, in contrast to 9% in 1998 (Figure 4). This increase in spatial extent of *adversely affected* benthos was statistically significant (α=0.05). Although in 1998 the *adversely affected* benthos were located primarily in Sinclair Inlet, in 2009, all of the benthic assemblages sampled in Liberty Bay also were *adversely affected*, as were the benthos at a few scattered other locations (Figure 4). Abundance of arthropods, molluscs, and echinoderms was significantly lower basin-wide in 2009 than in 1998 (α=0.05). Taxa richness also declined in general, though it increased in some individual locations.

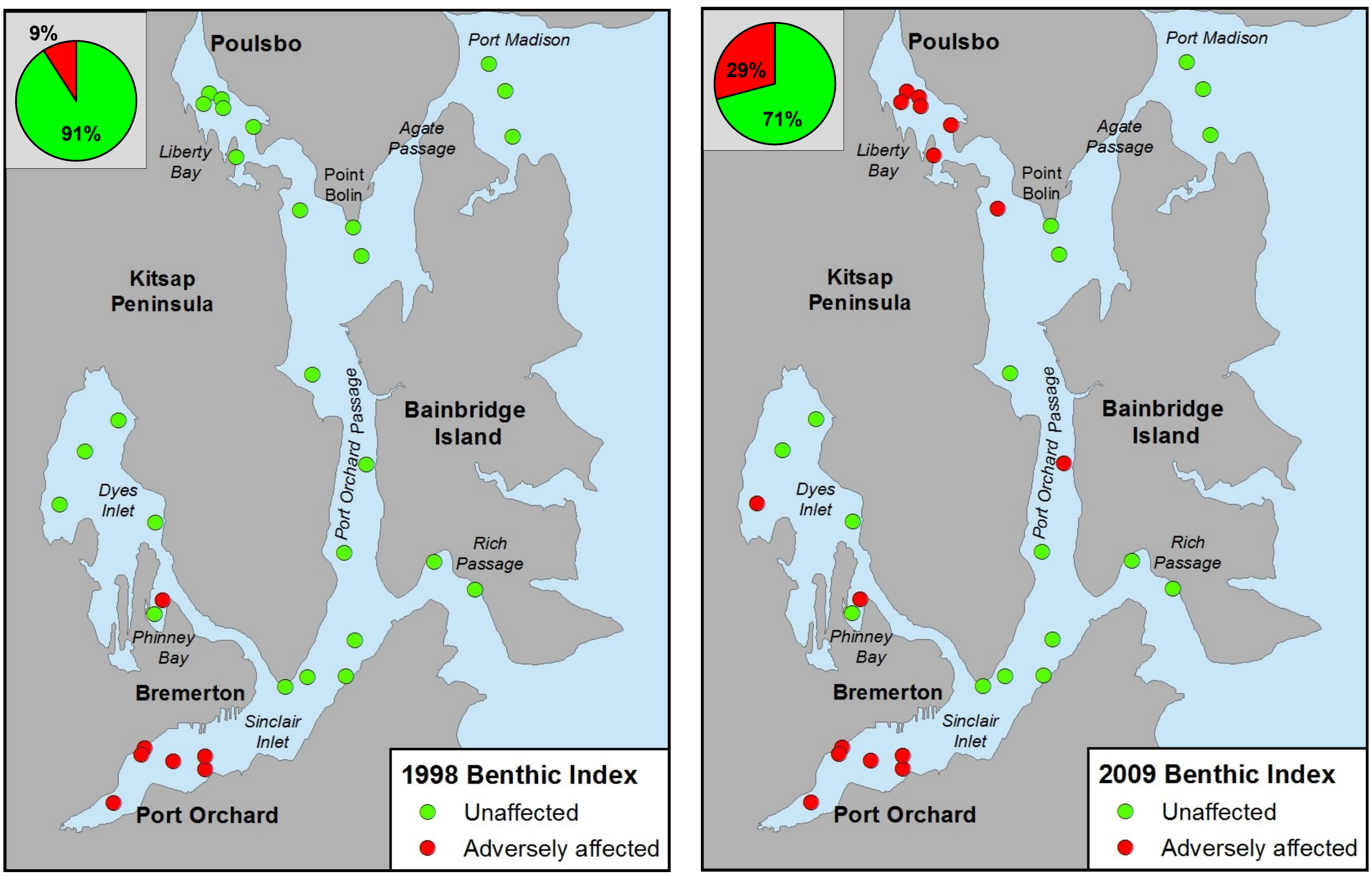

Figure 4. Spatial patterns at sampling stations and estimated spatial extent (percent of area, shown in pie chart) for the Sediment Benthic Index categories for the Bainbridge Basin. There were a statistically significant decrease (α=0.05) in spatial extent of the *unaffected* Benthic Index category from 1998 to 2009 and corresponding significant increase in spatial extent of the *adversely affected* category.

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 environmental stressors (Dutch et al., 2012). 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).

In 2009, 71% of the study area was classified as *unimpacted* (Table 2; Figure 5). Another 5% 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 24% of the study area. None of the area was classified as *clearly impacted* or *inconclusive*.

Spatial extent of the *unimpacted* Triad Index category was statistically significantly lower in 2009 than in 1998 (α=0.05), and spatial extent of the *likely impacted* category was significantly higher. The primary change in the geographical patterns of the Triad Index was in Liberty Bay (Figure 5).

Table 2. Specific combinations of index results (chemistry, toxicity, benthos) that lead to Sediment Quality Triad Index categories for the Bainbridge Basin in 2009. Spatial extent (percent of study area) is given for each combination.

Triad Index =	Benthic Index +	Toxicity Index +	Chemistry Index	% of Area
Unimpacted	Unaffected	Non-Toxic	Minimum exposure	47.6
	Unaffected	Low toxicity	Minimum exposure	8.2
	Unaffected	Non-Toxic	Low exposure	12.5
	Unaffected	Low toxicity	Low exposure	2.4
Likely unimpacted	Adversely affected	Non-Toxic	Low exposure	5.4
Possibly impacted	Adversely affected	Low toxicity	Low exposure	5.4
	Adversely affected	Moderate toxicity	Minimum exposure	2.7
Likely impacted	Adversely affected	High toxicity	Minimum exposure	7.2
	Adversely affected	Moderate toxicity	Low exposure	7.3
	Adversely affected	High toxicity	Low exposure	1.2

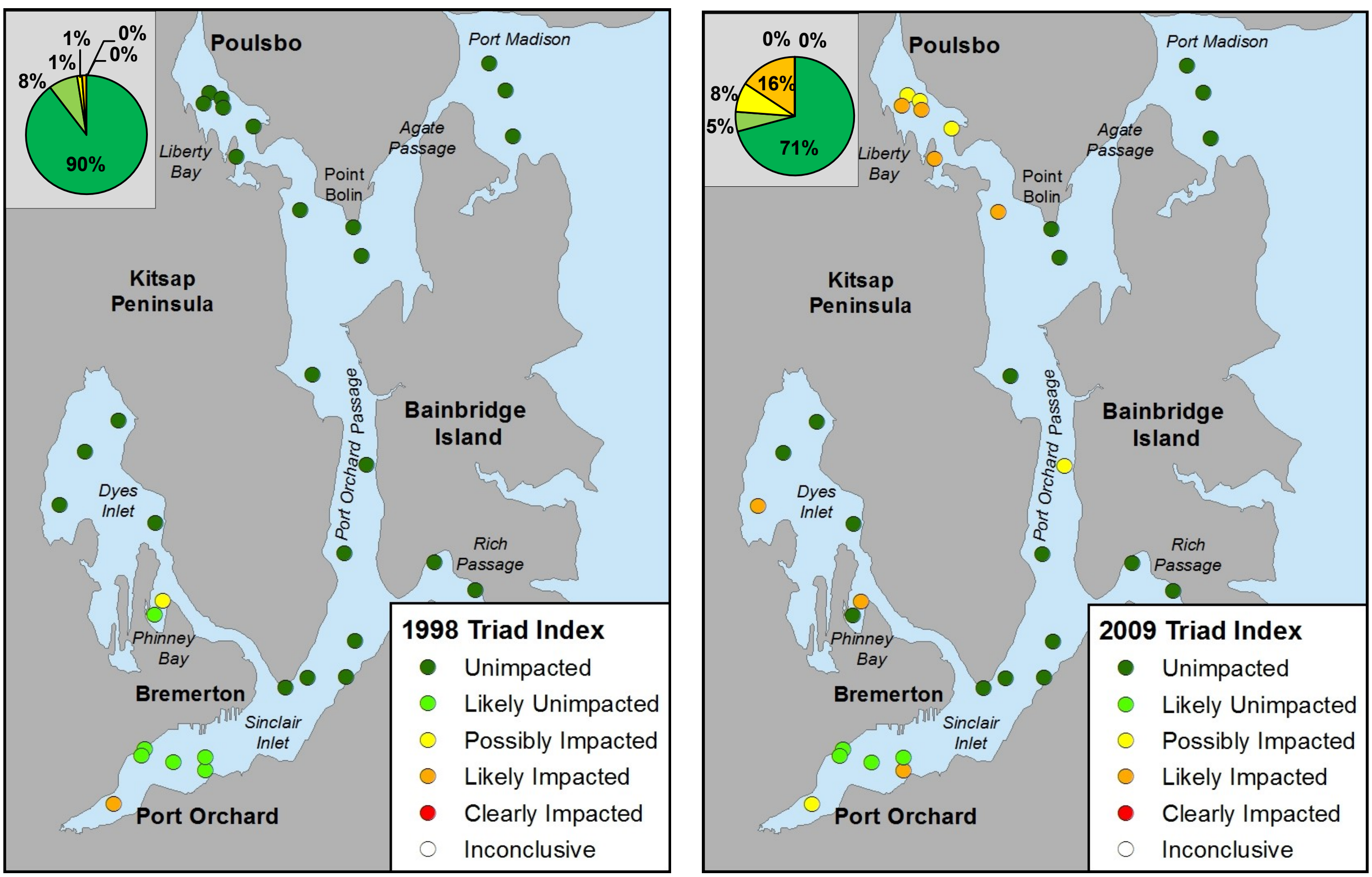

Figure 5. Spatial patterns at sampling stations and estimated spatial extent (percent of area, shown in pie chart) for the Sediment Quality Triad Index results in the Bainbridge Basin. The spatial extent of *unimpacted* sediments decreased significantly (α=0.05) and the spatial extent of *impacted* sediments increased statistically significantly from 1998 to 2009.

Bainbridge Basin Sediment Quality Compared to All of Puget Sound

Comparison of the 2009 Bainbridge Basin Sediment Quality Triad Index results to those for Central Puget Sound in 2008-2009 and for the 1997-2003 Puget Sound baseline shows similar proportions of area in the *unimpacted* category. However, Bainbridge Basin had significantly (α=0.05) higher percent area *likely impacted* and significantly lower percent area *likely unimpacted* than did Central Sound or all of Puget Sound (Figure 6). Likewise, the Central Sound region in 2008-2009 had a higher proportion of area in the *likely impacted* category and lower proportion of area in the *likely unimpacted* category than for Puget Sound in 1997-2003.

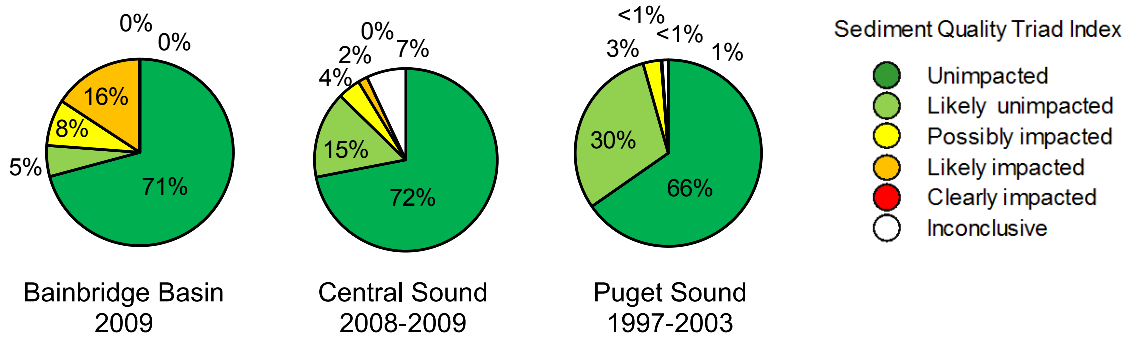

Figure 6. Spatial extent (percent of area) for the Sediment Quality Triad Index categories for the Bainbridge Basin in 2009 (from Figure 5), compared to Central Sound 2008-2009 and the Puget Sound 1997-2003 baseline. Note that although the Bainbridge Basin is geographically part of the Central Sound region, the 2009 Bainbridge Basin samples are not included in the Central Sound 2009 samples.

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

Ecology's Chemistry and Triad Indices, and also the percent of chemicals exceeding Washington State Sediment Quality Standards (SQS), were adopted by the Puget Sound Partnership (PSP) in 2010 to serve as "Vital Signs" indicators of the condition of Puget Sound (www.psp.wa. gov/vitalsigns/index.php).

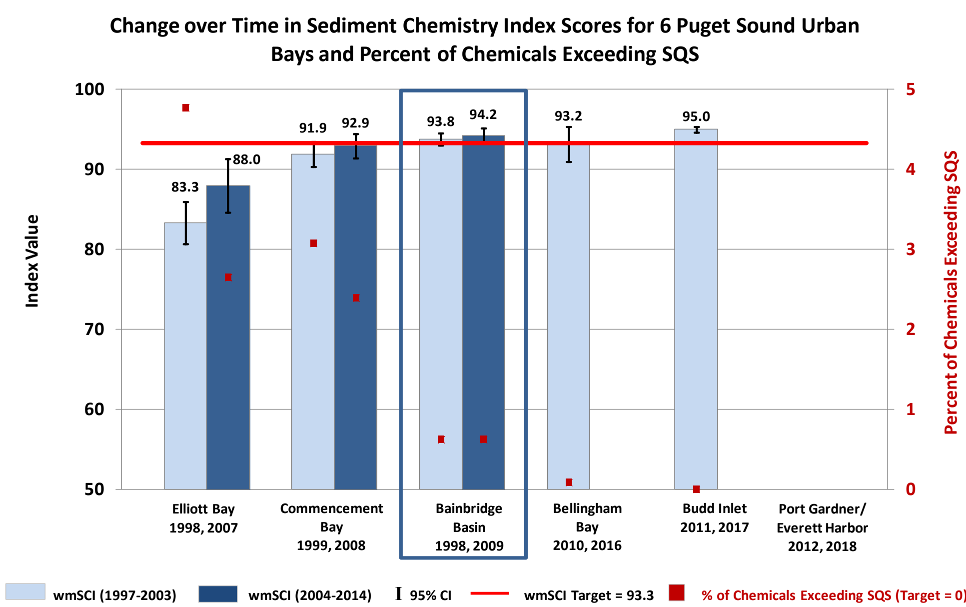

Figure 7. Weighted mean Sediment Chemistry Index values and 95% confidence intervals for urban embayments sampled from 1998 to 2011 (Urban Bays baseline) and resampled from 2007 to 2009.

Weighted mean Chemistry and Triad Index values are compared among the urban bays, and between repeated years of sampling to determine changes over time. They are also compared with 2020 target values selected by the PSP.

The weighted mean Chemistry Index values for Bainbridge Basin surpassed the 2020 target value of 93.3, indicating highest quality (Figure 7). The target value corresponds to the minimum value of the *minimum exposure* category, not weighted by percent area.

The percent of chemicals exceeding SQS remained the same between 1998 and 2009 (Figure 7) and did not meet the target of zero.

The weighted mean Triad Index value for the 2009 Bainbridge Basin survey was below the PSP target value of 81 (highest quality), corresponding to the minimum value, unweighted, in the *unimpacted* category (Figure 8). However, the 95% confidence interval did include the target value, so statistically, the target was met. The 2009 Bainbridge Basin Triad value was statistically significantly lower than the 1998 Triad value (α=0.05).

Elliott Bay, also, only statistically met the target value. Commencement Bay met the target value, but Bellingham Bay and Budd Inlet did not.

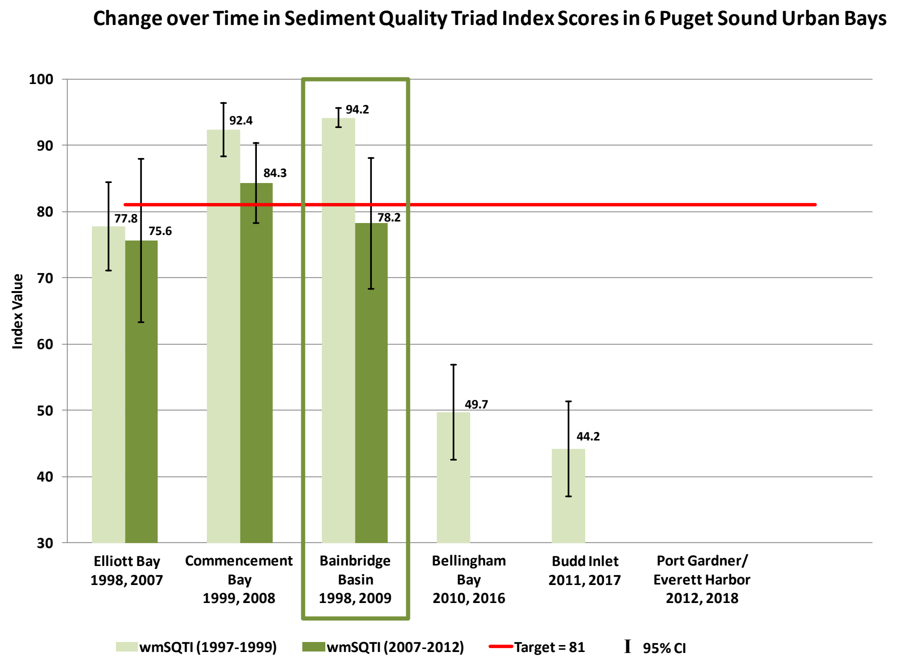

Figure 8. Weighted mean Sediment Quality Triad Index values and 95% confidence intervals for all urban embayments sampled from 1998 to 2011 (Urban Bays baseline) and resampled from 2007 to 2009.

Summary and Conclusions

Sediments in almost half (47%) of the Bainbridge Basin in 2009 had *minimal exposure* to contaminants, were *non-toxic*, had *unaffected* benthos, and were therefore classified as *unimpacted*. But almost one-quarter of the area (24%) had sediments classified as *possibly* or *likely impacted*, due to *adversely affected* benthos and some degree of toxicity. The remainder had *low exposure* to contaminants and/or *low toxicity*, some also with *adversely affected* benthos.

Although the spatial extent of exposure to contaminants was statistically unchanged from 1998, the spatial extent of both *toxic* sediment and *adversely affected* benthos increased, resulting in a deterioration in overall sediment quality. The majority of the *impacted* sediments occurred in terminal inlets, with the greatest clustering of negative changes taking place in Liberty Bay. Sediments in Liberty Bay were *unimpacted* in 1998 and *possibly-likely impacted* in 2009.

It is not possible to determine from this survey the causes of the declines found in sediment quality. Other factors, of natural or human origin, which were not measured, may have been important. Further study would be required.

Recommendations

- Continue annual PSEMP sediment quality monitoring to determine spatial status and temporal trends in regions and bays. Expand surveys to other environmentally important bays and the nearshore.
- 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 in conjunction with sediment monitoring which may be affecting the benthos, such as (1) water quality measures, including near-bottom dissolved oxygen, pH, and nutrient levels, and (2) rates of sediment deposition, mixing, and resuspension.
- Perform additional statistical analyses to examine relationships among the chemistry, toxicity, and benthos data.
- Collaborate with other researchers to try to determine possible factors contributing to declines in benthic health.

References

Bay, S.M., and S.B. Weisberg. 2012. Framework for interpreting sediment quality triad data. Integrated Environmental Assessment and Management 8:589–596. doi: 10.1002/ieam.118. 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 Publication No. 09-03-121. Olympia, WA. https://fortress.wa.gov/ecy/publications/summarypages/0903121.html.

Dutch, M., E. Long, S. Weakland, V. Partridge, and K. Welch. 2012. Sediment Quality Indicators for Puget Sound: Indicator Definitions, Derivations, and Graphic Displays. Washington State Department of Ecology unpublished report. Olympia, WA. www.ecy.wa.gov/programs/eap/psamp.

Ecology (Washington State Department of Ecology). 1995. Sediment Management Standards. Chapter 173-204, WAC. Washington State Department of Ecology Publication No. 96-252. Olympia, WA. http://apps.leg.wa.gov/WAC/default.aspx?cite=173-204.

Long, E.R., M. Dutch, S. Aasen, K. Welch, and M.J. Hameedi. 2005. Spatial extent of degraded sediment quality in Puget Sound (Washington State, USA) based upon measures of the Sediment Quality Triad. Environmental Monitoring and Assessment 111(1-3):173-222. http://link.springer.com/article/10.1007/s10661-005-8220-7.

Long, E.R., M. Dutch, V. Partridge, S. Weakland, and K. Welch. 2013. 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 doi: 10.1002/ieam.1309. http://onlinelibrary.wiley.com/doi/10.1002/ieam.1309/full.

[1] Now called the Puget Sound Ecosystem Monitoring Program (PSEMP).

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Data for this project are available at Ecology's Environmental Information Management (EIM) website www.ecy.wa.gov/eim/index.htm. Search User Study ID, UWI2009.

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