Appendix B-1. Sediment Quality Indices for Puget Sound: Definitions and Derivations

Since the inception of the Puget Sound Ecosystem Monitoring Program[1] (PSEMP), marine sediment quality has been assessed using the Sediment Quality Triad (SQT) (Long and Chapman, 1985) approach, which integrates data from chemical analyses to determine potential exposure of benthic organisms to toxicants, laboratory toxicity tests to determine relative response, and analyses of the composition of resident benthic assemblages to determine possible in situ adverse effects.

In 2009, Ecology's Marine Sediment Monitoring Team developed a suite of sediment quality indices for consideration for the Puget Sound Partnership (PSP) "Dashboard of Vital Signs" on the health of the ecosystem. All were designed to use existing information and present a report card to environmental managers and interested citizens on both qualitative and quantitative scales. In 2011, the PSP adopted the Sediment Chemistry Index and the Sediment Quality Triad Index, as well as percent of chemical analyses exceeding Washington State Sediment Management Standards (Ecology, 2013), as sediment quality Vital Signs indicators.

Each the Sediment Chemistry Index (SCI), Sediment Toxicity Index (STI), Sediment Benthic Index (SBI), and combined Sediment Quality Triad Index (SQTI) is calculated to a 0-100 scale, with 0 indicating impaired conditions and 100 indicating healthy conditions. The numerical index values are then classified into several quality categories based on biologically relevant critical values, developed using an approach adapted from Bay and Weisberg (2008, 2010).

This appendix describes the derivations, calculations, and classifications of these four indices.

Sediment Chemistry Index

OBJECTIVE: To identify sediments likely to be toxic and/or have adverse effects on benthic invertebrates at each sampling station as a result of exposure to complex mixtures of potentially toxic chemicals in sediments.

The Sediment Chemistry Index (SCI) is based on comparison of measured chemical concentrations to Washington State Sediment Management Standards Sediment Quality Standards (SQS). SQS are sediment chemical concentrations below which adverse biological effects are not expected to occur or above which at least minor adverse impacts on benthic macrofauna are expected always to occur (Ecology, 2013).

Although SQSs have been derived for 47 chemicals or chemical groups, SQSs for only 32 analytes are included in calculation of the SCI (Table 1). Thirteen of the 15 SQSs not included are for phenols and other miscellaneous compounds no longer analyzed-for in the Puget Sound sediment monitoring program. The remaining two SQSs are those for Total HPAH (sum of 9 compounds) and Total LPAH (sum of 6 compounds), not included in calculation of the SCI in order not to "double-count" the contributions of the constituent compounds, though they are used in the calculation of the percent of chemical analyses exceeding Washington State Sediment Management Standards.

[1] Initially called the Puget Sound Ambient Monitoring Program (PSAMP).

Table 1. Washington State Sediment Quality Standards (SQS) used in calculations of Sediment Chemistry Index (SCI) and percentage of analyses exceeding SQS.

Analyte	SQS value (Ecology, 2013)	Analyte	SQS value (Ecology, 2013)
Metals (ppm dry weight)		PAHs (ppm organic carbon*)	
Arsenic	57	Benzo(a)anthracene	110
Cadmium	5.1	Benzo(a)pyrene	99
Chromium	260	Benzo(g,h,i)perylene	31
Copper	390	Chrysene	110
Lead	450	Dibenzo(a,h)anthracene	12
Mercury	0.41	Fluoranthene	160
Silver	6.1	Indeno(1,2,3-c,d)pyrene	34
Zinc	410	Pyrene	1000
		Total Benzofluoranthenes	230
PCBs (ppm organic carbon*)		Total HPAH**	960
Total Aroclors	12	2-Methylnaphthalene	38
		Acenaphthene	16
Phthalates (ppm organic carbon*)		Acenaphthylene	66
Bis(2-ethylhexyl)phthalate	47	Anthracene	220
Butylbenzylphthalate	4.9	Fluorene	23
Diethylphthalate	61	Naphthalene	99
Dimethylphthalate	53	Phenanthrene	100
Di-N-Butylphthalate	220	Total LPAH**	370
Di-n-octyl phthalate	58	Dibenzofuran	15

*Analyte concentrations must be TOC-normalized (Ecology, 2013).

**Excluded from SCI calculation in order not to "double-count" PAH analytes.

Steps to calculate the SCI:

1. **Calculate SQS quotients (SQSq)**: For each of the 32 chemicals listed in Table 1, calculate the SQS quotient by dividing the chemical concentration measured at the station by the respective SQS for that chemical. Nondetects are excluded from SQSq calculation, with one exception: When all constituent compounds in a chemical group (e.g., PCBs) are nondetect, the maximum Reporting Limit for the individual constituents is used as the concentration for the group total, per statute (Ecology, 2013).

2. **Calculate the mean SQS quotient (mSQSq)**: Calculate the mean of the SQS quotients.

   This approach follows the basic methods for calculating and evaluating mean sediment quality guideline quotients (Long et al., 2006).

3. **Calculate the SCI**: Convert the mSQSq into the SCI by inverting and re-scaling. To do so,

divide the mSQSq by the maximum value, 1.5[2], subtract the resulting fraction from 1, and multiply by 100; i,e,

$$SCI = 100*(1 - (mSQSq/1.5)). \qquad \text{Equation 1}$$

Thus, small mSQSq values near zero (i.e., minimum chemical exposure) will result in large SCI values, near 100; and large mSQSq values (i.e., maximum chemical exposure) will result in very small SCI values, near zero.

4. **Determine SCI category using the critical values**, described below.

Critical values

Co-occurrence analyses were used to define critical mSQSq values to separate the sediment chemistry data into four categories of relative quality, ranging from **Minimum** to **Maximum Exposure** to chemical mixtures as evidenced by increasing toxicological responses in sensitive laboratory bioassays and increasingly adverse responses indicated with multiple benthic indices (Long et al., 2012). Three critical mSQSq values: 0.1, 0.3, and 0.5, were identified based on the relationship of Puget Sound sediment chemistry data to matching toxicity and benthos data from 664 Puget Sound sediment monitoring samples collected from 1997 through 2009.

Converted from the SQS quotient scale to the 0-100 SCI scale (Equation 1), the critical mSQSq values of 0.1, 0.3, and 0.5 correspond to SCI values of $93.\overline{3}$, 80.0, and $66.\overline{6}$, respectively (Table 2).

Table 2. Sediment Chemistry Index (SCI) categories of exposure to toxicants, based on Mean SQS quotient (mSQSq) critical values.

SCI Category	mSQSq	SCI Value	Notes
Minimum exposure	**<0.1**	**>$93.\overline{3}$– 100.0**	Most of these samples have no chemicals exceeding their SQS values.
Low exposure	**0.1 - <0.3**	**>80.0 - $93.\overline{3}$**	Most of these samples have 1 chemical exceeding its SQS value.
Moderate exposure	**0.3 - <0.5**	**>$66.\overline{6}$ - 80.0**	Most of these samples have 2 or 3 chemicals exceeding their SQS values.
Maximum exposure	**≥0.5**	**0 - $66.\overline{6}$**	Most of these samples have ≥3 chemicals exceeding their SQS values.

Puget Sound Partnership Targets

Target values for sediment chemistry should be those in a range in which adverse benthic effects and toxicity are the least probable. This would occur in the *Minimum Exposure* category of the

[2] The highest SQS quotient observed in PSEMP sediment monitoring results from 664 samples collected during 1997-2009, the dataset used to develop the index, was 1.34; hence, 1.5 was adopted as the ceiling in development of the SCI (Long et al., 2012).

SCI.

Thus, two of the three sediment quality index targets adopted by the PSP in 2011 are:

- Sediment chemistry measures reflecting "minimum exposure", as defined by having a Sediment Chemistry Index (SCI) score of >93.3.
- No chemistry measurements exceeding the WA Sediment Quality Standard (SQS) values.

Sediment Toxicity Index

OBJECTIVE: To evaluate the relative degree of toxicity of sediments, as measured by laboratory tests.

Toxicity of Puget Sound sediments has been gauged primarily by two tests conducted on each sample: the amphipod mortality test, a test of acute toxicity of the solid sediment, and the sea urchin fertilization test, a test of subacute toxicity in the sediment porewater. For budgetary reasons, only the amphipod test will be conducted in future, and only once every 5 years.

Test outcomes are percent survival of amphipods in test sediments compared to controls and percent successful fertilization of sea urchin gametes in test sediment porewater compared to controls. Typically, 5 replicates of each sample are tested simultaneously. In each batch (generally 10-20 test samples), five replicates (typically) of a negative-control sample are tested simultaneously with the test samples. Results are reported as mean control-adjusted outcomes.

The Sediment Toxicity Index (STI) was developed to combine the results of different tests. The steps to calculate the STI, as given below, refer to averaging the results of two or more tests, but of course can be applied to a single test.

Steps to calculate the STI:

1. **Use reported toxicity results in STI calculation**: Because the test labs report the results as mean control-adjusted outcomes, the results are already scaled from 0 to 100 (i.e., lowest to highest amphipod survival and sea urchin fertilization, respectively). Thus, the reported toxicity results are used directly to calculate the STI.
2. **Truncate results greater than 100**: In some cases, the test outcomes are higher for test samples than control samples. In those cases, the mean control-adjusted amphipod survival or sea urchin fertilization results are greater than 100. These values are truncated to 100 for use in calculating the STI value.
3. **Calculate the Sediment Toxicity Index (STI) value**: Calculate the mean of the truncated control-adjusted test results of both the amphipod survival and the sea urchin fertilization tests. The tests are given equal weight. This mean is used as the STI value.
4. **Classify the results for each test separately** into one of the following categories based on empirically-derived critical values. These critical values were developed following previously published principles and methods (Birch et al., 2008; Carr and Biedenbach, 1999; Phillips et al., 2001; Thursby et al., 1997; Bay et al., 2007, 2009). For brevity, "test results" and "control results" refer to the respective means of the replicates of the test sample and batch negative-control samples.

- *Non-Toxic*: Samples in which test results were not statistically significantly lower than the control results, or in which test results were statistically significantly lower than control results but were ≥ 90% of control results.
- *Low Toxicity*: Samples in which test results were statistically significantly lower than control results and < 90% of control results but ≥ 80% of control results.
- *Moderate Toxicity*: Samples in which test results were statistically significantly lower than control results and < 80% of control results but ≥ 50% of control results.
- *High Toxicity*: Samples in which test results were statistically significantly lower than control results and < 50% of control results, i.e., functionally equivalent to an EC50 or LC50.

5. **"Average" the categories**: Following the approach of Bay et al. (2007, 2009), for each sample, assign the outcome categories for each test a whole-number score from 1 (non-toxic) to 4 (high toxicity), then calculate the average of the two scores. If the resulting average score is not a whole number, round it to the nearest whole number (e.g., 1.5 is rounded to 2). Convert the result back to a descriptive category: 1 = Non-Toxic, 2 = Low Toxicity, 3 = Moderate Toxicity, and 4=High Toxicity (Table 3). Again, each test is given equal weight.

   By rounding the average score, the procedure is biased in the direction of protection of the environment. For example, a non-toxic score (1) from one test and a low-toxicity score (2) from the other test average to 1.5, which is rounded to 2, for an indication of overall Low Toxicity for the sediment from that sample.

Note: The STI numerical value and STI category are derived independently of each other.

Table 3. Sediment Toxicity Index (STI) categories of toxicity, based on "averaged" categorical scores of the tests used (Steps 4 and 5, above). The numerical STI value is the mean of the control-adjusted results for the tests used.

STI category	STI Value	Description
Non-toxic	Mean control-adj. test results	Mean control-adjusted test results were not significantly lower than the controls **or** were ≥90% of controls
Low toxicity	Mean control-adj. test results	Mean control-adjusted test results were significantly lower than the controls **and** between <90-80% of controls
Moderate toxicity	Mean control-adj. test results	Mean control-adjusted test results were significantly lower than the controls **and** between <80-50% of controls
High toxicity	Mean control-adj. test results	Mean control-adjusted test results were significantly lower than the controls **and** <50% of controls

Target

Although the STI was not adopted by the PSP as a sediment quality Vital Sign indicator, mention of target values is still relevant to the health of Puget Sound.

Target values for sediment toxicity should be those in a range that are non-toxic relative to the controls. This would occur in the *Non-Toxic* category, where all of the control-adjusted test results are not significantly lower than their respective control values or are at least 90% of their respective control values. (Note – a definition, rather than a specific value, is assigned here, since this value for each station can fall within a wide numeric range, depending on the difference between the station and control results.)

Sediment Benthic Index

OBJECTIVE: To classify the health of the resident benthic invertebrate assemblage.

The benthic invertebrate community is a key element of Puget Sound, performing ecosystem services such as processing of nutrients. Changes in the organisms can indicate responses of the ecosystem to stressors. Because benthic organisms are in constant contact with the sediments, and a very large proportion of them ingest sediment to obtain their food, they are a biological endpoint integrating any contamination in the sediments.

Current, interim method of classifying the benthos

Since 1997, all Puget Sound sediment monitoring program benthic invertebrate samples have been assessed by Best Professional Judgment (BPJ) of two or more benthic experts, using multiple lines of evidence, as either "affected" or "unaffected" by natural or anthropogenic stressors.

Ecology's Marine Sediment Monitoring Team is working to develop a multimetric index which will (a) be more efficient and objective to calculate, (b) make use of additional habitat and sample information, (c) enable classification of benthic community health into more than two categories, and (d) be adopted by the PSP as a Vital Signs indicator. Examples of such indices include the AZTI Marine Biologic Index (AMBI) (e.g., Gillett et al., 2015), Multivariate AMBI (M-AMBI) (e.g., Pelletier et al., in press), and the Benthic Quality Index (BQI) (e.g., Ranasinghe et al., 2013).

In the interim, the current method will continue to be used.

Steps to calculate the Interim SBI:

1. **Examine multiple lines-of-evidence**:
    - Levels of 9 calculated univariate benthic measures: total abundance; taxa richness; Pielou's evenness; species dominance (Swartz et al., 1985); and abundances of annelids, arthropods, molluscs, echinoderms, and miscellaneous taxa.
    - Presence, absence, and abundance of stress-sensitive and -tolerant species.
    - Best Professional Judgment – includes consideration of known habitat characteristics, e.g., grain size, TOC, depth, salinity.
2. **Designate assemblage as either "Adversely Affected" or "Unaffected"** (Table 4).
3. **Assign a numeric value**: An interim numeric value will be used until a new marine benthic

index (0-100 scale) is developed.

- *Unaffected* (SBI=100) – Typically defined by high abundance, taxa richness, evenness, and dominance index values; high abundance of stress-sensitive species such as arthropods and echinoderms; low abundance of stress-tolerant species of annelids and molluscs.
- *Adversely Affected* (SBI=50) – Typically defined by low taxa richness, evenness, and dominance; low abundance of stress-sensitive species such as arthropods and echinoderms; high abundance of stress-tolerant species of annelids and molluscs.
- Azoic (SBI=0) – No live benthic organisms. Azoic samples are necessarily classified as *Adversely Affected*.

Table 4. Interim Sediment Benthic Index (SBI) categories.

Interim SBI Category	**Interim SBI Value**	**Description**
Unaffected	**100**	High abundance, taxa richness, evenness, and dominance index values; high abundance of stress-sensitive species such as arthropods and echinoderms; low abundance of stress-tolerant species of annelids and molluscs
Adversely Affected	**50**	Low taxa richness, evenness, and dominance; low abundance of stress-sensitive species such as arthropods and echinoderms; high abundance of stress-tolerant species of annelids and molluscs
	0	No live benthic organisms

Future work to refine categories of relative benthic community health

We will continue working to develop a numeric benthic health index (0-100 scale) that can be used to separate the benthic infaunal community data into four categories of relative benthic health (e.g., Ranasinghe et al., 2013):

- *Reference*
- *Low Disturbance*
- *Moderate Disturbance*
- *High Disturbance*

Target

Although the Interim SBI was not adopted by the PSP as a sediment quality Vital Sign indicator, mention of target values is still relevant to the health of Puget Sound. It is hoped that the new multimetric benthic index under development will be adopted.

A benchmark/target interim value for the benthic community in a sample should be a determination of *Unaffected* condition of the benthos in that sample.

Upon completion of benthic index development work, a benchmark/target value for benthos should be a determination of *Reference* condition of the benthos in that sample.

Sediment Quality Triad Index

OBJECTIVE: To classify and describe the relative quality of the sediments based on a weight of evidence.

The Sediment Quality Triad Index (SQTI) was generated following the Multiple Lines of Evidence (MLOE) approach developed by the Southern California Coastal Water Research Project (SCCWRP) for California's State Water Board's Water Quality Control Plan – Sediment Quality Objectives (Bay et. al., 2009).

All 32 possible combinations of the four SCI, four STI, and two Interim SBI categories were generated and ordered, first by SBI, then by STI, then by SCI. Then the combinations were grouped by increasing potential for chemically mediated effects (combinations of STI and SCI) and severity of biological effects (combinations of STI and SBI) into five SQTI categories (Table 5). Two of the 30 combinations gave inconsistent indications of ecosystem health and thus were combined to create a 6th SQTI category, *Inconclusive*.

Thirty discrete numerical values were generated by evenly dividing the range from 100 to 0 by the rank order of the combination (Table 5), i.e.,

$$SQTI=100*(\text{combination rank}/29) \qquad \text{Equation 2}$$

No values were assigned to the two combinations in the *Inconclusive* category.

Table 6 contains a description of the six SQTI categories.

The SQTI will be revised, using a similar MLOE approach, once the multi-metric benthic index under development is completed and validated.

Steps to calculate the SQTI:

1. **Determine the SCI, STI, and SBI categories** based on the sample results, as above.
2. **Assign the SQTI category** and value **based on that combination** (Table 5).

Table 5. Derivation of Sediment Quality Triad Index (SQTI) from Sediment Chemistry Index (SCI), Sediment Toxicity Index (STI), and interim Sediment Benthic Index (SBI), using multiple-lines-of-evidence approach (following Bay et al., 2009).

Combine STI and SCI to get A→		*A: Potential for Chemically Mediated Effects*	Combine results of A and B to get SQTI ↓		*B: Severity of Biological Effects*	← Combine STI and SBI to get B	
STI Category	SCI Category		**SQTI Category**	**SQTI Value**		Interim SBI Category	STI Category
Non-Toxic	Minimal exposure	*Minimal potential*	**Unimpacted**	**100.00**	*Unaffected*	Unaffected	Non-Toxic
Non-Toxic	Low exposure	*Minimal potential*	**Unimpacted**	**96.55**	*Unaffected*	Unaffected	Non-Toxic
Non-Toxic	Moderate exposure	*Low potential*	**Unimpacted**	**93.10**	*Unaffected*	Unaffected	Non-Toxic
Low	Minimal exposure	*Minimal potential*	**Unimpacted**	**89.66**	*Unaffected*	Unaffected	Low
Low	Low exposure	*Low potential*	**Unimpacted**	**86.21**	*Unaffected*	Unaffected	Low
Moderate	Minimal exposure	*Low potential*	**Unimpacted**	**82.76**	*Unaffected*	Unaffected	Moderate
Non-Toxic	High exposure	*Moderate potential*	**Likely unimpacted**	**79.31**	*Unaffected*	Unaffected	Non-Toxic
Low	Moderate exposure	*Moderate potential*	**Likely unimpacted**	**75.86**	*Unaffected*	Unaffected	Low
Low	High exposure	*Moderate potential*	**Likely unimpacted**	**72.41**	*Unaffected*	Unaffected	Low
Moderate	Low exposure	*Moderate potential*	**Likely unimpacted**	**68.97**	*Unaffected*	Unaffected	Moderate
Moderate	Moderate exposure	*Moderate potential*	**Likely unimpacted**	**65.52**	*Unaffected*	Unaffected	Moderate
Non-Toxic	Minimal exposure	*Minimal potential*	**Likely unimpacted**	**62.07**	*Moderate effect*	Adversely affected	Non-Toxic
Non-Toxic	Low exposure	*Minimal potential*	**Likely unimpacted**	**58.62**	*Moderate effect*	Adversely affected	Non-Toxic
High	Minimal exposure	*Moderate potential*	**Possibly impacted**	**55.17**	*Low effect*	Unaffected	High
High	Low exposure	*Moderate potential*	**Possibly impacted**	**51.72**	*Low effect*	Unaffected	High
High	Moderate exposure	*Moderate potential*	**Possibly impacted**	**48.28**	*Low effect*	Unaffected	High
Non-Toxic	Moderate exposure	*Low potential*	**Possibly impacted**	**44.83**	*Moderate effect*	Adversely affected	Non-Toxic
Low	Low exposure	*Low potential*	**Possibly impacted**	**41.38**	*High effect*	Adversely affected	Low
Moderate	Minimal exposure	*Low potential*	**Possibly impacted**	**37.93**	*High effect*	Adversely affected	Moderate
High	High exposure	*High potential*	**Likely impacted**	**34.48**	*Low effect*	Unaffected	High
Non-Toxic	High exposure	*Moderate potential*	**Likely impacted**	**31.03**	*Moderate effect*	Adversely affected	Non-Toxic
Low	Moderate exposure	*Moderate potential*	**Likely impacted**	**27.59**	*High effect*	Adversely affected	Low
Low	High exposure	*Moderate potential*	**Likely impacted**	**24.14**	*High effect*	Adversely affected	Low
Moderate	Low exposure	*Moderate potential*	**Likely impacted**	**20.69**	*High effect*	Adversely affected	Moderate
Moderate	Moderate exposure	*Moderate potential*	**Likely impacted**	**17.24**	*High effect*	Adversely affected	Moderate
High	Minimal exposure	*Moderate potential*	**Likely impacted**	**13.79**	*High effect*	Adversely affected	High
High	Low exposure	*Moderate potential*	**Likely impacted**	**10.34**	*High effect*	Adversely affected	High

High	Moderate exposure	*Moderate potential*	**Likely impacted**	**6.90**	*High effect*	Adversely affected	High
Moderate	High exposure	*High potential*	**Clearly impacted**	**3.45**	*High effect*	Adversely affected	Moderate
High	High exposure	*High potential*	**Clearly impacted**	**0.00**	*High effect*	Adversely affected	High
Moderate	High exposure	*High potential*	**Inconclusive**	**NA**	*Unaffected*	Unaffected	Moderate
Low	Minimal exposure	*Minimal potential*	**Inconclusive**	**NA**	*High effect*	Adversely affected	Low

Table 6. Sediment Quality Triad Index (SQTI), based on multiple lines of evidence.

SQTI Category	SQTI Value	Description
Minimum exposure	**>81– 100**	*Confident that contamination and/or other stressors are not causing significantly adverse impacts* to aquatic life in the sediment.
Likely Unimpacted	**>57 - 81**	*Contamination and/or other stressors are not expected to cause adverse impacts* to aquatic life in the sediment, but some disagreement among lines of evidence reduces certainty that the site is unimpacted.
Possibly Impacted	**>36 - 57**	*Contamination and/or other stressors may be causing adverse impacts* to aquatic life in the sediment, but the level of impact is either small or is uncertain because of disagreement among lines of evidence.
Likely Impacted	**>5 - 36**	*Evidence of contaminant and/or other stressor*-related *impacts* to aquatic life in the sediment *is persuasive*, in spite of some disagreement among lines of evidence.
Clearly Impacted	**0 - 5**	Sediment *contamination and/or other stressors are causing clear and severe adverse impacts* to aquatic life in the sediment.
Inconclusive	**NA**	Disagreement among or within lines of evidence suggests that either the *data are suspect* or additional information is needed for classification.

Puget Sound Partnership Target

Target values for sediment quality should be those in a range in which adverse benthic effects and toxicity are the least probable. This would occur in the *Unimpacted* category of the SQTI.

Thus, the 3rd of the three sediment quality index targets adopted by the PSP in 2011 is:

- Combined measures of sediment chemistry, toxicity, and the health of bottom-dwelling marine life (i.e., the benthos) reflecting "unimpacted" conditions, as defined by having a Sediment Quality Triad Index (SQTI) score of >83.

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