Sediment Quality Indicators for Puget Sound
Indicator Definitions, Derivations, and Graphic Displays

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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. Calculations are based on comparison to Washington State Sediment Quality Standards[1].

- **Calculate the "Sediment Chemistry Index" (*SCI*)**
  - **Calculate *SQS quotients***: For 41 chemicals with WA State Sediment Quality Standards (SQS), calculate an ***SQS quotient*** for every station and every year by dividing the chemical concentration measured at the station by the respective *SQS* for that chemical.
  - **Calculate the *mean SQS quotient***: For every station, every year, calculate the mean of all *SQS* quotients for all chemicals with SQS standards. This is the ***mSQSq*** for each station. This approach follows the basic methods for calculating and evaluating mean sediment quality guideline quotients (Long et al., 2006).
  - **Calculate the *Sediment Chemistry Index*:** For every station, every year, convert the *mSQSq* into the ***Sediment Chemistry Index (SCI)*** by scaling the *mSQSq* values of 0.00 – 1.50 from 100 to 0 (i.e., minimum to maximum chemical exposure).
    - **SCI is calculated using the formula: *SCI* = 100*(1 – (*mSQSq*/1.5)).**

- **Select "critical" *mSQSq* values that can be used to separate the sediment chemistry data into four categories of relative quality**

  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 collected at 664 Puget Sound sediment monitoring stations. These three mSQSq values define four categories 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.

  The four categories[2] include:

  - **Minimum Exposure –** Samples in which the **mSQSq is <0.1 (corresponding SCI = >93.$\overline{3}$ - 100)**, most of these samples have no chemicals exceeding their SQS values.
  - **Low Exposure –** Samples in which the **mSQSq is 0.1 - <0.3 (corresponding SCI = >80 - 93.$\overline{3}$)**, most of these samples have one chemical exceeding its SQS value.

[1] Washington State Sediment Quality Standards (WA State Dept of Ecology, 1995) 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.

[2] Category names for chemistry, toxicity, benthos, and SQTI are from Bay et al, 2009 developed for the state of California's *Multiple Line of Evidence* method)

- **Moderate Exposure –** Samples in which the **mSQSq is 0.3 - <0.5 (corresponding SCI = >66.$\overline{6}$-80)**, most of these samples have two or three chemicals exceeding their SQS values.
- **Maximum Exposure –** Samples in which the **mSQSq is ≥0.5 (corresponding SCI = 0 - 66.$\overline{6}$)**, most of these samples have more than three chemicals exceeding their SQS values.

Sediment Chemistry Category	Mean SQS Quotient	Sediment Chemistry Index
Minimum exposure	<0.1	>93.$\overline{3}$– 100.0
Low exposure	0.1 - <0.3	>80.0 - 93.$\overline{3}$
Moderate exposure	0.3 - <0.5	>66.$\overline{6}$ - 80.0
Maximum exposure	≥0.5	0 - 66.$\overline{6}$

- **SCI Benchmark/Target**
  - **Proposed:** Benchmark/target values for chemistry measured in a sample should be those in a range in which adverse benthic effects and toxicity are the least probable. This would occur in the Minimal Exposure category, where the mSQS is <0.1 and the SCI is >**93.$\overline{3}$**
  - **Sediment Quality Index Targets (2 of 3) adopted by Puget Sound Partnership (June 2011):**
    - By 2020, all Puget Sound regions and bays should:
      - Have sediment chemistry measures reflecting "minimum exposure", as defined by having a Sediment Chemistry Index (SCI) score of >93.3.
      - Have no chemistry measurements exceeding the Sediment Quality Standard (SQS) values set in Washington State.

Sediment Toxicity Index

OBJECTIVE: To evaluate and compare the relative degree of toxicity of each sampling station

- **Calculate the *"Sediment Toxicity Index"* (*STI*)**
  - **Examine results of each toxicity test:** Two toxicity tests are used to gauge the toxicity of Puget Sound sediments: the amphipod mortality test (refs), a test of acute toxicity of the sediment, and the sea urchin fertilization test (refs), a test of subacute toxicity in the sediment porewater.
  - **Use reported toxicity results in STI calculation:** 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 simultaneoulsy with the test samples. The test labs report the results as mean control-adjusted outcomes, which 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 **Sediment Toxicity Index (STI)**.

- **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.
- **Calculate the *Sediment Toxicity Index:*** For every station, every year, calculate the mean of the truncated test results normalized to the negative controls from both the amphipod survival and the sea urchin fertilization tests. Both tests are given equal weight. This mean is used as the ***STI***.

- **Use empiric*ally-derived "critical" va*lues published in the literature to separate the sediment toxicity data into four categories of relative quality**
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  The categorical component of the STI is formed by combining categorized responses of the individual tests for a given sample into one of four categories to depict overall sediment toxicity for that sample.

  - Classify the results for each test for each sample 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.
  - 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. Again, each test is given equal weight.

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

- **STI Benchmark/Target**
  - Benchmark/target values for toxicity measured in a sample 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 relative quality of the benthos at each station.

- **Current /interim method of classifying the benthos**
  - **Examine multiple lines-of-evidence:** For every station, every year, determine whether the station's assemblage of benthic invertebrates was "affected" or "unaffected" by either natural or anthropogenic stressors. This is currently determined by examining multiple lines-of-evidence:
    - **Levels of 9 calculated benthic indices** (abundance; taxa richness; evenness; species dominance; and annelid, arthropod, mollusc, echinoderm, and miscellaneous taxa abundance)
    - 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)

- **Designate each station as either "Adversely Affected" or "Unaffected" and assign a Sediment Benthic Index (SBI) value**

  An interim benthos designation will be used until a new marine benthic index (100-0 scale) is developed through on-going work with the Southern California Coastal Water Research Project (SCCWRP). The binary designations of "adversely affected" and "unaffected" are assigned interim values of 50 and 100, respectively, until a more refined 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.

- **Future work to separate the benthos data into four categories of relative quality**

  We continue working with SCCWRP to come up with a numerical benthic health index (100-0 scale) that can be used to separate the benthic infaunal community data into four categories of relative benthic health.

  These four categories include:

  - Reference
  - Low Disturbance
  - Moderate Disturbance
  - High Disturbance

- **SBI Benchmark/Target**
  - 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 with SCCWRP, 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 in each sampling station and throughout a survey area based on a weight-of-evidence.

- **Generate Sediment Quality Triad Index (SQTI) categories that can be used to place samples into categories of relative quality**

  Six SQTI assessment categories are 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). Using MLOE, all possible combinations of the 4 chemistry, 4 toxicity, and 2 interim benthos[3] categories are generated to describe each sample. The 32 combinations[4] are summarized into 6 categories, placing samples in groups of relative quality (after Bay et. al., 2009).

  The 6 SQTI categories include:

  - **Unimpacted –** *Confident that contamination and/or other stressors are not causing significantly adverse impacts* to aquatic life in the sediment.
  - **Likely Unimpacted** – *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** – *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** – *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** – Sediment *contamination and/or other stressors are causing clear and severe adverse impacts* to aquatic life in the sediment.
  - **Inconclusive** – Disagreement among or within lines of evidence suggests that either the *data are suspect* or additional information is needed for classification.

- **Calculate the "Sediment Quality Triad Index" (*SQTI*)**

  - **Order 30 of 32 combinations:** Organize all but the 2 "inconclusive" combinations from highest to poorest sediment quality based on severity of biological effects. This is accomplished by ordering 30 of the 32 *Unimpacted* to *Clearly Impacted* combinations by the

[3] This will be finalized to 4 benthos categories upon completion of the current Puget Sound benthic index development work with SCCWRP.
[4] There will be 64 possible combinations of results after completion of the current Puget Sound benthic index development work with SCCWRP.

highest benthos measure, then by the highest toxicity measure, then by the highest chemical measure. The two *Inconclusive* categories are not included in this ordering.

- **Rank each of the 30 ordered parameter combinations:** Each of the 30 ordered combinations is ranked from 29-0 (i.e., highest to poorest quality benthos, toxicity, chemical measures).
- **Assign an SQTI value (100-0) to each set of ranked parameter combination:** The combination rank is converted to an SQTI value based on a 100-0 scale (again, from highest to poorest quality benthos, toxicity, chemical measures). Thirty discrete SQTI values, ranging from 100 to 0, are generated.
    - **SQTI values are calculated using the formula: SQTI=100*(combination rank/29)**
- **SQTI index scores[5] –**
    - **Unimpacted – SQTI = >81-100.**
    - **Likely Unimpacted – SQTI = >57-81.**
    - **Possibly Impacted – SQTI = >36-57.**
    - **Likely Impacted – SQTI = >5-36.**
    - **Clearly Impacted – SQTI = 0-5.**
    - **Inconclusive – no SQTI designated.**

- **SQTI Benchmark/Target**
    - **Proposed:** Benchmark values for SQTI should be to classify 100% of samples within the **"Unimpacted"** category; **SQTI>83**
    - **Sediment Quality Index Targets (1 of 3) Adopted by Puget Sound Partnership (June 2011):**
        - By 2020, all Puget Sound regions and bays should:
            - Have 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.

Station Weighting and Weighted Average Index Values

OBJECTIVE: To adjust the contribution of each sampling station's respective SCI, STI, SBI, and SQTI values to the average index value calculated for a selected sampling frame. Each station index value is adjusted by that station's spatial weighting for that sampling frame, as pre-determined and defined by the probabilistic sampling design. Weighted average index values can then be calculated for the sampling frame.

- **SCI, STI, SBI, and SQTI weighting for sampling frame estimates**
    - Station spatial weighting is applied to each index value for each station when calculating the mean of each index value for a designated sampling frame (e.g.., sediment monitoring region, urban bay).
    - Each station within the sampling frame is assigned an area weight (km^2) equal to other stations in that sampling frame. The weight is calculated based on the size of the sampling frame divided by the number of stations in the sampling frame.

- **Weighted Average Index Values[6]**

[5] SQTI scores are not continuous, as they are generated from 30 discrete rank values rather than continuous data.
[6] Stations with "inconclusive" index scores are omitted from these calculations, and not included in the weighted average index value for a sampling frame.

- A **weighted average** for any of the indices within a sampling frame is then calculated using the following formula: $\sum_i A_i w_i \,/\, \sum_i w_i$, where A_i=index value for station *i*, w_i=area weight (km^2) for station *i*.

Incidence and Spatial Extent of Sediment Quality Indicators for a Sampling Frame

OBJECTIVE: To calculate the number of samples within a sampling frame for each indicator category (incidence), and the size of a geographic area (km^2) of the sampling frame represented by each indicator category (spatial extent).

- For each of the sediment quality indicators, SCI, STI, SBI, and SQTI, calculated for each station within a sampling frame, the number of sampling stations within each indicator category is determined (incidence) and geographically depicted on a map, along with the size (km^2) of the geographic area represented by each indicator category (spatial extent).

Graphic Displays **(for MSMP website, Dashboard Indicators and GMAP)**

- **MSMP website**
  - **Develop a series of one-page graphic displays** (spatial and temporal trends and geographic comparisons) for the Sediment Quality Triad and each individual triad component, including:
    - Sediment Quality Triad Index
    - Sediment Chemistry Index
    - Sediment Toxicity Index
    - Sediment Benthic Index

  - **"One-pagers" of each of the four types**, above, will include the following:

    - **6 Urban Bay/Region/Puget Sound depictions on separate posters:**
      - Elliott Bay (1998, 2007)/ Central Region (1998-1999, 2007-2009)/Puget Sound (1997-2003, 2004-2014)
      - Commencement Bay (1999, 2008)/ Central Region (1998-1999, 2007-2009)/Puget Sound (1997-2003, 2004-2014)
      - Bainbridge Basin (1998, 2009)/ Central Region (1998-1999, 2007-2009)/Puget Sound (1997-2003, 2004-2014)
      - Bellingham Bay (1997, 2006, 2010)/Strait of Georgia Region (1997, 2006)/Puget Sound (1997-2003, 2004-2014)
      - Budd Inlet/5 South Puget Sound Bays (1999, 2011)/South Puget Sound Region (1999, 2011)/Puget Sound (1997-2003, 2004-2014)
      - Everett Harbor (1997, 2007, 2012)/Whidbey Basin Region (1997, 2007)/Puget Sound (1997-2003, 2004-2014)

    - **8 Region/Puget Sound depictions on one poster:**
      - Strait of Georgia (1997, 2006)/Puget Sound (1997-2003, 2004-2014)
      - Whidbey Basin (1997, 2007)/Puget Sound (1997-2003, 2004-2014)
      - Central Puget Sound (1998, 2008/09)/Puget Sound (1997-2003, 2004-2014)
      - South Puget Sound (1999, 2011)/Puget Sound (1997-2003, 2004-2014)
      - Hood Canal (1999, 2004, 2012)/Puget Sound (1997-2003, 2004-2014)
      - San Juan Islands (2002/03, 2013)/Puget Sound (1997-2003, 2004-2014)

        - Eastern Strait of Juan de Fuca (2002/03, 2014)/Puget Sound (1997-2003, 2004-2014)
        - Admiralty Inlet (2002/03, 2015)/Puget Sound (1997-2003, 2004-2014)
- **Dashboard/GMAP displays**
    - simplified bar graphics of one component
    - comparison of regions/urban bays over time

References

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