Chesapeake Bay Benthic Monitoring Program
Innovations and Accomplishments

Daniel M. Dauer ¹, Roberto J. Llansó ², Mike F. Lane ¹
1 – Department of Biological Sciences, Old Dominion University, Norfolk, Virginia 23529
2 - Versar, Inc., Columbia, Maryland 21045
Benthic Indicators, Monitoring Design and Interpretation Issues

Overview

Chesapeake Bay accomplishments

1. Index development
2. Index relationship to watershed stressors
3. Sample allocation
4. Index relationship to habitat quality
5. Causes of degradation (diagnostics)
6. Impaired waters designations – 303(d)
7. Functional metric/index (Secondary productivity)
8. BIBI recalibration
9. International collaboration
(1) Benthic Index of Biotic Integrity (BIBI).
(1) **Benthic Index of Biotic Integrity (BIBI).**

(2) **Establishing relationships between the BIBI and land use patterns, nutrient loads, low dissolved oxygen events, and sediment contaminants at watershed levels.** (Dauer et al. 2000. Estuaries)
(1) Benthic Index of Biotic Integrity (BIBI).

(2) Establishing relationships between the BIBI and land use patterns,
    nutrient loads, low dissolved oxygen events, and sediment
    contaminants at watershed levels. (Dauer et al. 2000. Estuaries)

(3) Implementation of probability-based sampling to generate areal
    estimates of levels of degraded benthos.
    Llansó et al. 2003. Environmental Monitoring
    and Assessment; Dauer and Llansó. 2003. Ibid )
(1) **Benthic Index of Biotic Integrity (BIBI).**  

(2) **Establishing relationships between the BIBI and land use patterns, nutrient loads, low dissolved oxygen events, and sediment contaminants at watershed levels.**  
(Dauer et al. 2000. Estuaries)

(3) **Implementation of probability-based sampling to generate areal estimates of levels of degraded benthos.**  

(4) **Quantifying the relationship between benthic biotic integrity and benthic habitat quality.**  
(5) Diagnostic approaches to causes of degradation of benthic communities.

Low dissolved oxygen
Eutrophication
Sediment Contamination

(Dauer et al. 2002. EPA Technical Report)
(5) Diagnostic approaches to causes of degradation of benthic communities.

- Low dissolved oxygen
- Eutrophication
- Sediment Contamination

(Dauer et al. 2002. EPA Technical Report)

(6) Impaired waters designations of Maryland DNR and Virginia DEQ 303d

Diagnostic approaches to causes of degradation of benthic communities.

- Low dissolved oxygen
- Eutrophication
- Sediment Contamination

(Dauer et al. 2002. EPA Technical Report)

Impaired waters designations of Maryland DNR and Virginia DEQ 303d


Functional metric/index approach

Benthic Secondary Productivity

(7) **Functional metric/index approach**

**Benthic Secondary Productivity**


(8) **BIBI recalibration**

(7) Functional metric/index approach
Benthic Secondary Productivity
Sturdivant et al. 2014. Estuaries and Coasts

(8) BIBI recalibration
(Llansó et al. 2016. VADEQ Technical Report
de-la-Ossa et al. 2016. Ecological Indicators)

(9) International collaboration
(Borja and Dauer. 2008. Ecological Indicators;
Borja et al. 2010. Estuaries and Coasts;
Borja et al. 2012. Ecological Indicators)
An Estuarine Benthic Index of Biotic Integrity (B-IBI) for Chesapeake Bay

Stephen B. Weisberg\textsuperscript{1,2}  
J. Ananda Ranasinghe  
Versar, Inc.  
9200 Rumsey Road  
Columbia, Maryland 21045

Linda C. Schaffner  
Robert J. Diaz  
School of Marine Science  
The College of William and Mary  
Gloucester Point, Virginia 23062

Daniel M. Dauer  
Department of Biological Sciences  
Old Dominion University  
Norfolk, Virginia 23529

Jeffrey B. Feithsen  
Versar, Inc.  
9200 Rumsey Road  
Columbia, Maryland 21045

ABSTRACT: A multimetric benthic index of biotic integrity (B-IBI) was developed using data from Bay sampling programs conducted between 1972 and 1991. Attributes of the index were selected based on the response of 17 candidate measures of benthic condition (metrics) between a set of minimally affected.
(1) **Benthic Index of Biotic Integrity (BIBI).**

**Statistical verification of the Chesapeake Bay benthic index of biotic integrity**

Raymond W. Alden III\(^1\),† D. M. Dauer\(^2\), J. A. Ranasinghe\(^3\), L. C. Scott\(^4\)
and R. J. Llanso\(^4\)

\(^1\)University of Nevada, Las Vegas, NV 89154-1002, U.S.A.
\(^2\)Old Dominion University, Norfolk, VA 23523, U.S.A.
\(^3\)SCCWRP, Westminster, CA 92683, U.S.A.
\(^4\)Versar Inc., Columbia, MD 21045, U.S.A.

**SUMMARY**

The benthic index of biotic integrity (B-IBI) developed for the Chesapeake Bay was statistically simulated and a suite of multivariate statistical techniques. The B-IBI uses a simple scoring system of community metrics to assess benthic community health and to infer environmental quality of benthic habitats in the Bay. Overall, the B-IBI was verified as being sensitive, stable, robust and statistically sound. The effectiveness of the B-IBI increased with salinity, from marginal performance for tidal freshwater to excellent results for polyhaline areas. The greater classification uncertainty in low salinity habitats may arise from difficulties in reliably identifying naturally stressed areas or may be due to regional ecotones of community structure.
Benthic Index of Biotic Integrity (B-IBI)

Fig. 2 – Index development, application and interpretation. Dashed rectangle encloses the primary steps in index development. Adaptive monitoring feedback loops and adaptive change decision drivers are indicted by open arrows.
(i) Defining criteria for degraded and undegraded sites based on nonbiological measures such as bottom-water dissolved oxygen and sediment contaminant concentrations;

(ii) identifying biological measures which respond to (and differ among) degraded and undegraded sites;

(iii) adjusting these responses for habitat differences, if necessary;

(iv) combining responsive measures into an index; and

(v) validating the index using independent data.

Indices formulated on ecological principles and properly validated will better communicate the complexity of ecological integrity.
Benthic Index of Biotic Integrity (B-IBI)

- Summer Index period July 15 – Sept. 30
- 17 Candidate Metrics
- Test Candidate Metrics (reference against degraded)
- Scaled scoring (1-3-5- or 1-3-5-3-1)
- Independent data set
Eleven metrics are used to calculate the B-IBI:

- Shannon-Wiener species diversity index
- Total species abundance
- Total species biomass
- Percent abundance of pollution-indicative taxa
- Percent abundance of pollution-sensitive taxa
- Percent biomass of pollution-indicative taxa
- Percent biomass of pollution-sensitive taxa
- Percent abundance of carnivore and omnivores
- Percent abundance of deep-deposit feeders
- Tolerance Score
- Tanypodini to Chironomidae percent abundance ratio
## Metric selection and scoring thresholds habitat specific (7 habitats determined)

<table>
<thead>
<tr>
<th>Habitat</th>
<th>Bottom Salinity (psu)</th>
<th>Silt-clay (&lt;63 µ) content by weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal freshwater</td>
<td>&lt; 0.5</td>
<td>N/A</td>
</tr>
<tr>
<td>Oligohaline</td>
<td>≥ 0.5 - 5</td>
<td>N/A</td>
</tr>
<tr>
<td>Low Mesohaline</td>
<td>≥ 5 – 12</td>
<td>N/A</td>
</tr>
<tr>
<td>High Mesohaline</td>
<td>≥ 12 - 18</td>
<td>0 - 40</td>
</tr>
<tr>
<td>High Mesohaline</td>
<td>≥ 12 - 18</td>
<td>&gt; 40</td>
</tr>
<tr>
<td>Polyhaline sand</td>
<td>≥ 18</td>
<td>0 - 40</td>
</tr>
<tr>
<td>Polyhaline mud</td>
<td>≥ 18</td>
<td>&gt; 40</td>
</tr>
</tbody>
</table>
Index of Biotic Integrity (IBI)

All Sites

Frequency

Value of Metric

Degraded

Reference
Chesapeake Bay - B-IBI

- Value is the mean of the metric scores
- Range is 1-5
- Values < 3 represent degraded benthos
- Values $\geq 3$ represent undegraded benthos
## B-IBI Thresholds
### Example of Polyhaline Sand Habitat

<table>
<thead>
<tr>
<th>Score</th>
<th>5</th>
<th>3</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shannon-Wiener</td>
<td>$\geq 3.5$</td>
<td>2.7-3.5</td>
<td>$&lt; 2.7$</td>
</tr>
<tr>
<td>Abundance (m$^{-2}$)</td>
<td>$\geq 3,000$-$5,000$</td>
<td>1,500-$3,000$ or $\geq 5,000$-$8,000$</td>
<td>$&lt; 1,500$ or $\geq 8,000$</td>
</tr>
<tr>
<td>Biomass (g m$^{-2}$)</td>
<td>$\geq 5$-$20$</td>
<td>1-5 or $\geq 20$-$50$</td>
<td>$&lt; 1$ or $\geq 50$</td>
</tr>
<tr>
<td>Pollution Indicative species biomass (%)</td>
<td>$\leq 5$</td>
<td>5-15</td>
<td>$&gt; 15$</td>
</tr>
<tr>
<td>Pollution Sensitive species abundance (%)</td>
<td>$\geq 50$</td>
<td>25-50</td>
<td>$&lt; 25$</td>
</tr>
<tr>
<td>Deep deposit feeder abundance (%)</td>
<td>$\geq 25$</td>
<td>10-25</td>
<td>$&lt; 10$</td>
</tr>
</tbody>
</table>
Summary Advantages

Simple communication

Binomial categories

≥ 3 represent undegraded condition
< 3 represent degraded condition

Additional categories

≥ 3 represent undegraded condition
2.9 – 2.7 – Marginal
2.6 – 2.1 – Degraded
≥ 2.0 – Severely degraded
Summary Advantages

Simple communication

Binomial categories

≥ 3 represent undegraded
< 3 represent degraded

Additional categories

≥ 3 undegraded
2.9 – 2.7 – Marginal
2.6 – 2.1 – Degraded
≥ 2.0 – Severely degraded
Summary Advantages

1. Simple communication
2. Metric thresholds become Restoration Goals
3. Metrics can be examined for additional insight into causes of degradation
(1) **Benthic Index of Biotic Integrity (BIBI).**
(1) **Benthic Index of Biotic Integrity (BIBI).**  

(2) **Establishing relationships between the BIBI and land use patterns, nutrient loads, low dissolved oxygen events, and sediment contaminants at watershed levels.**  
(Dauer et al. 2000. Estuaries)

---

**ABSTRACT:** Associations between macrobenthic communities, measures of water column and sediment exposure to anthropogenic activities throughout the watershed were examined for the Chesapeake Bay. Condition of the macrobenthic communities was indicated by a multimetric benthic index of biotic integrity (MBI) that compared deviation of community metrics from values at reference sites assumed to be minimally altered by anthropogenic sources of stress. Correlation analysis was used to examine associations between sites with poor benthic index scores and measures of pollution exposure in the water column and sediment. Low dissolved oxygen events were extensive and strongly correlated with benthic community condition, explaining 41% of the variation in the MBI. Sediment contamination was spatially limited to a few specific locations including Baltimore Harbor and the South Branch Potomac River.
BIBI and Land Use

The graph shows the relationship between percent forested land use and the benthic index of biotic integrity. The correlation coefficient, r, is +0.62, indicating a positive correlation between the two variables.
Development and evaluation of a spatially-explicit index of Chesapeake Bay health

Michael Williams\textsuperscript{a,}\ast, Ben Longstaff\textsuperscript{b}, Claire Buchanan\textsuperscript{c}, Roberto Llano\textsuperscript{d}, William Dennison\textsuperscript{a}

\textsuperscript{a} University of Maryland Center for Environmental Science, Annapolis Synthesis Center, Suite 301, Annapolis, MD 21401, USA
\textsuperscript{b} NOAA-UMCES Partnership, Cooperative Oxford Laboratory, Oxford, MD 21654, USA
\textsuperscript{c} Interstate Commission on the Potomac River Basin, 51 Monroe St, Suite 4-08, Rockville, MD 20850, USA
\textsuperscript{d} Versar Inc., 9200 Runsey Road, Columbia, MD 21045, USA

\section*{A B S T R A C T}

In an effort to better portray changing health conditions in Chesapeake Bay and support restoration efforts, a Bay Health Index (BHI) was developed to assess the ecological effects of nutrient and sediment loading on 15 regions of the estuary. Three water quality and three biological measures were combined to formulate the BHI. Water quality measures of chlorophyll-a, dissolved oxygen, and Secchi depth were averaged to create the Water Quality Index (WQI), and biological measures of the phytoplankton and benthic indices of biotic integrity (P-IHI and B-IHI, respectively) and the area of submerged aquatic vegetation (SAV) were averaged to create the Biotic Index (BI). The WQI and BI were subsequently averaged to give a BHI value representing ecological conditions over the growing season (i.e., March–October). Lower chlorophyll-a concentrations, higher dissolved oxygen concentrations, deeper Secchi depths,
Fig. 6. The total of developed and agricultural land use (2001) (as % of total area in each reporting region) versus the mean Bay Health Index from 1985 to 2007 using all reporting regions (panel A) and without the James, York and SW tributary regions included (panel B).
Fig. 6. The total of developed and agricultural land use (2001) (as % of total area in each reporting region) versus the mean Bay Health Index from 1985 to 2007 using all reporting regions (panel A) and without the James, York and SW tributary regions included (panel B).
BIBI and Land Use

Population Density per Acre

Benthic Index of Biotic Integrity

$r = +0.70$

Population Density per Acre
BIBI and Land Use

% of low dissolved oxygen events

\[ r = -0.65 \]
BIBI and Land Use

Urban land use - contaminants

$r = + 0.74$
Chl a - Agricultural land use

r = +0.69

Chlorophyll a Concentration

Percent Agricultural Land Use
**TABLE 5.** Correlation of area-weighted exposure variables with watershed variables. Pearson correlation coefficients, probability values, and number of replicates are presented for each watershed variable by exposure variable combination. DO = dissolved oxygen. ERL = effects range-low of Long et al. (1995). TN, TP = total nitrogen, total phosphorus concentration in water column.

<table>
<thead>
<tr>
<th>Watershed Variables</th>
<th>% Bottom DO obs $&lt;$ 2 ppm</th>
<th>No. of Contaminants $&gt;$ ERL</th>
<th>Mean TN (mg L$^{-1}$)</th>
<th>Mean TP (mg L$^{-1}$)</th>
<th>Mean Active Chlorophyll $a$ (µg L$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population density per unit land area</td>
<td>0.679</td>
<td>0.977</td>
<td>-0.473</td>
<td>-0.593</td>
<td>-0.381</td>
</tr>
<tr>
<td></td>
<td>0.031</td>
<td>0.001</td>
<td>0.167</td>
<td>0.071</td>
<td>0.278</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>% Area under agriculture</td>
<td>-0.059</td>
<td>-0.219</td>
<td>0.757</td>
<td>0.446</td>
<td>0.686</td>
</tr>
<tr>
<td></td>
<td>0.871</td>
<td>0.572</td>
<td>0.011</td>
<td>0.196</td>
<td>0.029</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>% Forested area</td>
<td>-0.440</td>
<td>-0.385</td>
<td>-0.328</td>
<td>-0.023</td>
<td>-0.341</td>
</tr>
<tr>
<td></td>
<td>0.204</td>
<td>0.307</td>
<td>0.355</td>
<td>0.949</td>
<td>0.366</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>% Urban area</td>
<td>0.685</td>
<td>0.742</td>
<td>-0.424</td>
<td>-0.517</td>
<td>-0.353</td>
</tr>
<tr>
<td></td>
<td>0.029</td>
<td>0.022</td>
<td>0.222</td>
<td>0.126</td>
<td>0.317</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Total nitrogen loadings per unit land area</td>
<td>0.127</td>
<td>0.479</td>
<td>0.302</td>
<td>-0.278</td>
<td>-0.025</td>
</tr>
<tr>
<td></td>
<td>0.726</td>
<td>0.192</td>
<td>0.397</td>
<td>0.437</td>
<td>0.946</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Point source nitrogen loadings per unit land area</td>
<td>0.529</td>
<td>0.970</td>
<td>-0.360</td>
<td>-0.466</td>
<td>-0.255</td>
</tr>
<tr>
<td></td>
<td>0.116</td>
<td>0.001</td>
<td>0.307</td>
<td>0.174</td>
<td>0.477</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Nonpoint-source nitrogen loadings per unit land area</td>
<td>-0.240</td>
<td>-0.212</td>
<td>0.663</td>
<td>0.032</td>
<td>0.187</td>
</tr>
<tr>
<td></td>
<td>0.451</td>
<td>0.583</td>
<td>0.037</td>
<td>0.929</td>
<td>0.603</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Total phosphorus loadings per unit land area</td>
<td>-0.133</td>
<td>0.052</td>
<td>0.546</td>
<td>-0.076</td>
<td>0.116</td>
</tr>
<tr>
<td></td>
<td>0.713</td>
<td>0.894</td>
<td>0.103</td>
<td>0.835</td>
<td>0.750</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Point source phosphorus loadings per unit land area</td>
<td>0.488</td>
<td>0.963</td>
<td>-0.343</td>
<td>-0.460</td>
<td>-0.254</td>
</tr>
<tr>
<td></td>
<td>0.152</td>
<td>0.001</td>
<td>0.331</td>
<td>0.181</td>
<td>0.479</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Nonpoint-source phosphorus loadings per unit land area</td>
<td>-0.223</td>
<td>-0.216</td>
<td>0.650</td>
<td>0.049</td>
<td>0.322</td>
</tr>
<tr>
<td></td>
<td>0.535</td>
<td>0.577</td>
<td>0.042</td>
<td>0.892</td>
<td>0.365</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>
Summary Relationships

1. **Exposure variables**
   - Low dissolved oxygen events
   - Sediment contaminants

2. **Negative with anthropogenic inputs & activities**
   - Population density
   - Point source loads
   - Total nitrogen loads

3. **Positive with forested land use**
(1) **Benthic Index of Biotic Integrity (BIBI).**

(2) **Establishing relationships between the BIBI and land use patterns, nutrient loads, low dissolved oxygen events, and sediment contaminants at watershed levels.** (Dauer et al. 2000. Estuaries)

(3) **Implementation of probability-based sampling to generate areal estimates of levels of degraded benthos.**

Implementation of probability-based sampling to generate areal estimates of levels of degraded benthos.

(3) Implementation of probability-based sampling to generate areal estimates of levels of degraded benthos.


Optimizing Temporal Sampling Strategies for Benthic Environmental Monitoring Programs

Raymond W. Alden III*, Stephen B. Weisberg†, J. Ananda Ranasinghe‡ and Dan H. Donato*

The Chesapeake Bay Benthic Monitoring Team:

(1) Evaluated the sampling design of the EMAP-VA program.
(2) Recognized the essential importance of areal based estimates of benthic community condition with known confidence intervals unavailable with a fixed-point station design.
(3) Adding probability-based sampling would require reduction in intra-annual seasonal sampling (zero sum budgeting).
(4) An effort to optimize spatial interpretation and minimize reduction in statistical power to detect long-term trends in benthic community condition.
(3) **Implementation of probability-based sampling to generate areal estimates of levels of degraded benthos.**


---

**Optimizing Temporal Sampling Strategies for Benthic Environmental Monitoring Programs**

RAYMOND W. ALDEN III*, STEPHEN B. WEISBERG†, J. ANANDA RANASINGHE‡ and D. "DICK" D. L. JOHNSON§

**Tested**

(1) Homogeneity among seasons.

(2) Power to detect trends in (a) abundance, (b) biomass, (c) diversity and (d) proportional abundance of opportunistic taxa.

(3) Magnitude of differences between reference and degraded sites.

(4) Summer was the optimal season to sample for both power and magnitude of difference between reference and degraded sites.
Implementation of probability-based sampling to generate areal estimates of levels of degraded benthos.


Samples allocated among 10 strata
25 random sites per stratum
Data can be summarized

A. Bay-wide
B. State-wide
C. Tributary
D. Segment
(3) Implementation of probability-based sampling to generate areal estimates of levels of degraded benthos.


Samples allocated among 10 strata
25 random sites per stratum
Data can be summarized
A. Bay-wide
B. State-wide
C. Tributary
D. Segment

Samples from 1994 – 2000
n = 1,446
(3) Implementation of probability-based sampling to generate areal estimates of levels of degraded benthos.

(3) Implementation of probability-based sampling to generate areal estimates of levels of degraded benthos.

(3) Implementation of probability-based sampling to generate areal estimates of levels of degraded benthos.

(3) Implementation of probability-based sampling to generate areal estimates of levels of degraded benthos.

(3) Implementation of probability-based sampling to generate areal estimates of levels of degraded benthos.

(3) Implementation of probability-based sampling to generate areal estimates of levels of degraded benthos.


![Graph showing Total Area (Marginal, Degraded, and Severely Degraded) over time]
Probability (Random) Sampling

Isoplething of condition is possible
Probability (Random) Sampling

Summary Advantages

1. Areal estimates of strata with known CIs
2. Data can be post-hoc stratified
3. Strata can be combined by areal weighting
(1) **Benthic Index of Biotic Integrity (BIBI).**

(2) **Establishing relationships between the BIBI and land use patterns, nutrient loads, low dissolved oxygen events, and sediment contaminants at watershed levels.** (Dauer et al. 2000. Estuaries)

(3) **Implementation of probability-based sampling to generate areal estimates of levels of degraded benthos.**

(4) **Quantifying the relationship between benthic biotic integrity and benthic habitat quality.**
(4) Quantifying the relationship between benthic biotic integrity and benthic habitat quality.


A comparison of two methods for estimating the status of benthic habitat quality in the Virginia Chesapeake Bay

Robert J. Diaz\textsuperscript{a,*}, G. Randy Cutter Jr.\textsuperscript{b}, Daniel M. Dauer\textsuperscript{c}

\textsuperscript{a}Virginia Institute of Marine Science, College of William and Mary, P.O. Box 1346, Gloucester Pt., VA 23062, USA
\textsuperscript{b}Center for Coastal and Ocean Mapping, University of New Hampshire, 24 Colvos Rd., Durham, NH 03824, USA
\textsuperscript{c}Department of Biological Sciences, Old Dominion University, Norfolk, VA 23529, USA

Received 7 June 2002; received in revised form 31 August 2002; accepted 13 September 2002

Abstract

Macroboral communities in Chesapeake Bay, USA, have been intensively monitored since 1985. In 1996, the monitoring was expanded to include summer time stratified random sampling to produce unbiased estimates of community metrics that could be used to assess system-wide trends.
<table>
<thead>
<tr>
<th>BIBI</th>
<th>OSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species diversity $H'$</td>
<td>Depth of apparent color RPD layer:</td>
</tr>
<tr>
<td></td>
<td>Scored 0 for</td>
</tr>
<tr>
<td></td>
<td>0 RPD to 6 for &gt;3.8 cm</td>
</tr>
<tr>
<td>Total abundance</td>
<td>Estimated successional stage:</td>
</tr>
<tr>
<td></td>
<td>Scored −4 for azoic conditions to 6 for Stage III</td>
</tr>
<tr>
<td>Total biomass</td>
<td>Presence of gas voids in sediment:</td>
</tr>
<tr>
<td></td>
<td>Scored −2</td>
</tr>
<tr>
<td>% Abundance of pollution-indicative taxa</td>
<td>Apparent presence of low dissolved oxygen:</td>
</tr>
<tr>
<td>% Abundance of pollution-sensitive taxa</td>
<td></td>
</tr>
<tr>
<td>% Biomass of pollution-sensitive taxa</td>
<td></td>
</tr>
<tr>
<td>% Biomass &gt;5 cm below sediment–water interface</td>
<td></td>
</tr>
</tbody>
</table>

Each metric gets a score of:
5: >50th percentile of reference sites
3: 5th to 50th percentile
1: <5th percentile
Table 5
Association between indices of biotic integrity and habitat quality

<table>
<thead>
<tr>
<th>Biotic integrity (BIBI)</th>
<th>Habitat quality OSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Strong relationship, 24% (56 stations)</td>
</tr>
<tr>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>May occur due to biotic factors, 39% (89)</td>
</tr>
<tr>
<td></td>
<td>Not likely, 10% (23)</td>
</tr>
<tr>
<td></td>
<td>Strong relationship, 27% (62)</td>
</tr>
</tbody>
</table>
Table 5
Association between indices of biotic integrity and habitat quality

<table>
<thead>
<tr>
<th>Biotic integrity (BIBI)</th>
<th>Habitat quality OSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

Low → Strong relationship, 24% (56 stations)
Table 5
Association between indices of biotic integrity and habitat quality

<table>
<thead>
<tr>
<th>Biotic integrity (BIBI)</th>
<th>Habitat quality OSI</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>High</td>
<td>Not likely, 10% (23)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5
Association between indices of biotic integrity and habitat quality

<table>
<thead>
<tr>
<th>Biotic integrity (BIBI)</th>
<th>Habitat quality OSI</th>
<th>May occur due to biotic factors, 39% (89)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5
Association between indices of biotic integrity and habitat quality

<table>
<thead>
<tr>
<th>Biotic integrity (BIBI)</th>
<th>Habitat quality OSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

Strong relationship, 27% (62)
Habitat Quality and Biotic Integrity

Summary Relationships

1. Independent estimates of habitat quality and biotic integrity
2. Logical relationships confirmed
5) Diagnostic approaches to causes of degradation of benthic communities.

**Low dissolved oxygen**

**Eutrophication**

**Sediment Contamination**

(Dauer et al. 2002. EPA Technical Report)
Anoxia or Hypoxia

Eutrophication without low DO

Contaminants

Exposure Variables
Causes of benthic community degradation

I. Sediment contamination
   Discriminant function

II. Organic enrichment (absent low DO)
   Excessive abundance metric

III. Low dissolved oxygen
   Insufficient abundance metric
Causes of benthic community degradation

I. Sediment contamination

Discriminant function
Causes of benthic community degradation

I. Sediment contamination

   Linear discriminant function

   63 benthic metrics

   Two stress groups

      Contaminant

      Others

   Validation rate – 85%
Figure 2. Discriminant function classification efficiencies for individual habitat types for the Baywide discriminant function for classifying severely degraded and degraded sites (including Low D.O. sites) into the Contaminant and Other stress groups. Numbers above the bars indicate the number of observations within each habitat type.
Table 3. Percent of the stratum placed into the sediment contaminant effect group using the contaminant discriminant function of Dauer et al. 2002 (posterior probability > 0.5). Data from 1996-2002. Elizabeth River data includes the intensive 1999 event and 25 random samples of the watershed from 2000-2002.

<table>
<thead>
<tr>
<th>Stratum</th>
<th>N</th>
<th>Percentage of stratum in Contaminant Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower (VA) Mainstem</td>
<td>175</td>
<td>10.9</td>
</tr>
<tr>
<td>Upper Bay Mainstem</td>
<td>175</td>
<td>17.7</td>
</tr>
<tr>
<td>MD Eastern Tributaries</td>
<td>175</td>
<td>16.6</td>
</tr>
<tr>
<td>Patuxent River</td>
<td>175</td>
<td>20.0</td>
</tr>
<tr>
<td>MD Middle Mainstem</td>
<td>175</td>
<td>17.1</td>
</tr>
<tr>
<td>MD Western Tributaries</td>
<td>175</td>
<td>24.6</td>
</tr>
<tr>
<td>Potomac River</td>
<td>175</td>
<td>31.4</td>
</tr>
<tr>
<td>James River</td>
<td>175</td>
<td>30.9</td>
</tr>
<tr>
<td>Rappahannock River</td>
<td>175</td>
<td>37.1</td>
</tr>
<tr>
<td>York River</td>
<td>175</td>
<td>38.3</td>
</tr>
<tr>
<td>Elizabeth River</td>
<td>275</td>
<td>52.4</td>
</tr>
</tbody>
</table>

![Graph showing percentage of stratum]

Figure 2. Percentage of stratum with a B-JBI value < 2.7 and placed into the Contaminant Group with a posterior probability > 0.5.
Figure 5. Diagnostic discriminant tool results and an interpolation fitting algorithm used here to classify the Elizabeth River watershed benthic communities into categories distinguished by the type of stress experienced by those communities. Red shading indicates degraded benthic communities stressed by toxic contamination (posterior probability in Contaminant Group > 0.5), with higher color intensity indicating higher probabilities of contaminant effects (>0.5 to <0.7; >=0.7 to <0.9; >=0.9). Salmon shading indicates degraded benthic communities stressed by other sources (posterior probability in Contaminant Group <=0.5). Green indicates good benthic community condition.
Causes of benthic community degradation

I. Sediment contamination
   Discriminant function

II. Organic enrichment (absent low DO)
   Excessive abundance metric

III. Low dissolved oxygen
   Insufficient abundance metric
Index of Biotic Integrity (IBI)

Reference Sites

Insufficient Abundance

Excess Abundance

Value of Metric

Frequency

5th  25th  75th  95th

1  3  5  3  1
Degradation Categories

Contaminant effect (p > 0.9) in samples with a BIBI < 3.0

State-wide comparison of degradation

Tributary strata

Western Patuxent Potomac Eastern Rappa York James

Contaminant (Cont)
Cont & Excessive Abundance
Cont & Insufficient Abundance
Excessive Abundance
Insufficient Abundance
Degradation Categories

Contaminant effect (p > 0.9) in samples with a BIBI < 3.0

Tributary strata

Remove Insufficient Abundance

Contaminant (Cont)
Cont & Excessive Abundance
Cont & Insufficient Abundance
Excessive Abundance
Insufficient Abundance
Degradation Categories

Contaminant effect (p > 0.9) in samples with a BIBI < 3.0

Remove Excessive Abundance

Tributary strata

Contaminant (Cont)
Cont & Excessive Abundance
Cont & Insufficient Abundance
Excessive Abundance
Insufficient Abundance
Degradation Categories

Contaminant effect (p > 0.9) in samples with a BIBI < 3.0

Rescale to emphasize contaminant concerns

Contaminant (Cont)
Cont & Excessive Abundance
Cont & Insufficient Abundance
Excessive Abundance
Insufficient Abundance

Tributary strata
Degradation Categories

Contaminant effect (p > 0.9) in samples with a BIBI < 3.0

Add data from the Elizabeth River Southern Branch

Tributary strata

Contaminant (Cont)
Cont & Excessive Abundance
Cont & Insufficient Abundance
Excessive Abundance
Insufficient Abundance
Degradation Categories

Contaminant effect (p > 0.9) in samples with a BIBI < 3.0

Tributary strata

Rescale for data from the Elizabeth River Southern Branch

Summary Contaminant Pattern among strata

Contaminant (Cont)
Cont & Excessive Abundance
Cont & Insufficient Abundance
Excessive Abundance
Insufficient Abundance
Degradation Categories

Contaminant effect (p > 0.9) in samples with a BIBI < 3.0

State-wide comparison of degradation

Tributary strata

Contaminant (Cont)
Cont & Excessive Abundance
Cont & Insufficient Abundance
Excessive Abundance
Insufficient Abundance
Degradation Categories

Contaminant effect (p > 0.9) in samples with a BIBI < 3.0

Remove contaminant and Excessive Abundances

Summary Low DO Pattern among strata

Tributary strata

Contaminant (Cont)
Cont & Excessive Abundance
Cont & Insufficient Abundance
Excessive Abundance
Insufficient Abundance
Degradation Categories

Contaminant effect (p > 0.9)
in samples with a BIBI < 3.0

Excessive abundance - Eutrophication

Tributary strata

Contaminant (Cont)
Cont & Excessive Abundance
Cont & Insufficient Abundance
Excessive Abundance
Insufficient Abundance
Degradation Categories

Contaminant effect (p > 0.9) in samples with a BIBI < 3.0

Excessive abundance - Rescaled

Tributary strata

Contaminant (Cont)
Cont & Excessive Abundance
Cont & Insufficient Abundance
Excessive Abundance
Insufficient Abundance
Degradation Categories

Contaminant effect ($p > 0.9$) in samples with a BIBI < 3.0

Add Pagan River data

Tributary strata

Pagan River
Degradation Categories

Contaminant effect (p > 0.9) in samples with a BIBI < 3.0

Rescaled for Pagan River data

Tributary strata

Western, Patuxent, Potomac, Eastern, Rappa, York, James, Pagan
Pagan River prior to 1996

- TN annual mean: -1.8 mg/L (summer mean: -3.5 mg/L)
- TP annual mean: 0.8 mg/L (summer mean: 1.3 mg/L)
- Chlorophyll a levels: 30 - 140 µg/L (summer mean: 100 µg/L)

Secchi depth: 0.4m

Little vertical stratification
One sewage treatments plant
Two meat packing plants in Smithfield
Degradation Categories

Contaminant effect ($p > 0.9$) in samples with a BIBI < 3.0

Rescaled for Pagan River data
Diagnostic approaches to causes of degradation

Summary

1. Sediment contamination
   Linear discriminant function

2. Moderate eutrophication
   Single metric (excessive abundance)

3. Low dissolved oxygen
   Single metric (insufficient abundance)
(5) Diagnostic approaches to causes of degradation of benthic communities.

- Low dissolved oxygen
- Eutrophication
- Sediment Contamination

(Dauer et al. 2002. EPA Technical Report)

(6) Impaired waters designations of Maryland DNR and Virginia DEQ 303d

(Llansó et al. 2009)
Assessing ecological integrity for impaired waters decisions in Chesapeake Bay, USA

Roberto J. Llansó,*, Daniel M. Dauerb, Jon H. Vølstadb,c

* Versar Inc., Ecological Sciences and Applications, 9200 Ramsey Road, Columbia, Maryland 21045, USA
b Department of Biological Sciences, Old Dominion University, Norfolk, Virginia 23529, USA
c Institute of Marine Research, P.O. Box 1870 Nordnes, 5817 Bergen, Norway

ARTICLE INFO
Keywords:
Ecological integrity
Benthic community condition
Impaired waters assessment
Biological criteria
Chesapeake Bay

ABSTRACT
To meet the requirements of the Clean Water Act, the States of Maryland and
biological criteria for identifying impaired waters in Chesapeake Bay and repair
the Chesapeake Bay benthic index of biotic integrity (B-IBI) is the basis for
Working together with the states and the US Environmental Protection Agency
impairment decisions based on the B-IBI. The impaired waters decision approach,
for benthic habitat-dependent indices in a Bay segment (equivalent to water bodies
Framework Directive) with a statistical test of impairment. The method takes
consideration in reference conditions, sampling variability, multiple habitats, and so
method to 1430 probability-based benthic samples in 85 Chesapeake Bay seg-
ments were considered impaired for benthic community condition. The final
consider benthic condition in combination with key stresses such as dis-

Years 2000-2004
1,430 samples
85 segments
To meet the requirements of the Clean Water Act, the States of Maryland and Virginia are using benthic biological criteria for identifying impaired waters in Chesapeake Bay and reporting their overall condition.

1. The impaired waters decision approach combines multiple benthic habitat-dependent indices in a Bay segment (equivalent to water bodies) with a statistical test of impairment.

2. The method takes into consideration uncertainty in reference conditions, sampling variability, multiple habitats, and sample size.

3. Twenty-two segments were considered impaired for benthic community condition.
(6) Impaired waters designations of Maryland DNR and Virginia DEQ 303d (Llansó et al. 2009)

303D Assessment 2000-2004

Impaired Segment

Impaired but BIBI ≥ 3.0
(6) Impaired waters designations of Maryland DNR and Virginia DEQ

303d (Llansó et al. 2009)

303D Assessment 2009-2014

Impaired Segment

Impaired but BIBI $\geq$ 3.0

New impaired segment
(6) Impaired waters designations of Maryland DNR and Virginia DEQ 303d (Llansó et al. 2009)

303D Assessment 2000-2004

Impaired Segment

Impaired but BIBI ≥ 3.0

New impaired segment

303d Assessment 2000-2004
(6) Impaired waters designations of Maryland DNR and Virginia DEQ

303d (Llansó et al. 2009)

303D Assessment 2009-2014

Impaired Segment

Impaired but BIBI ≥ 3.0

New impaired segment
(6) Impaired waters designations of Maryland DNR and Virginia DEQ 303d (Llansó et al. 2009)
Impaired waters designations of Maryland DNR and Virginia DEQ 303d (Llansó et al. 2009)
Impaired waters designations of Maryland DNR and Virginia DEQ

(6) Impaired waters designations of Maryland DNR and Virginia DEQ 303d (Llansó et al. 2009)

Assessing ecological integrity for impaired waters decisions in Chesapeake Bay, USA


**School of Biology and Environmental Studies, Old Dominion University, Norfolk, VA 23529, USA

ABSTRACT

Incorporating the requirements of the Clean Water Act, the States of Maryland and Virginia are using the following biological criteria to identify impaired waters in Chesapeake Bay and reporting their overall condition. The Chesapeake Bay Impaired Waters Assessment utility and methodology (CBIAU) is the basis for these findings and criteria. Working together with the states and the US Environmental Protection Agency, we developed a method for maintenance decisions based on the CBIAU. In the 2014-2014 Pilot Study, the impaired waters decision approach continues to provide a clear path for states to comply with the current regulations.

23 impaired segments in 2009-2014

22 segments in 2000-2004

15 impaired segments in common

The previous five impaired segments of the Elizabeth River watershed are not listed – inadequate sample size.
Fig. 1. Proposed decision process for assessing impaired waters in Chesapeake Bay.
Assessing ecological integrity for impaired waters decisions in Chesapeake Bay, USA
Roberto J. Llansó a,b, Daniel M. Dauer b, Jon H. Vølstad a,c


Fig. 1. Proposed decision process for assessing impaired waters in Chesapeake Bay.
Causes of benthic community degradation

I. Sediment contamination
   Discriminant function

II. Organic enrichment (absent low DO)
   Excessive abundance metric

III. Low dissolved oxygen
   Insufficient abundance metric
Causes of benthic community degradation

I. Sediment contamination
   Discriminant function

II. Organic enrichment (absent low DO)
   Excessive abundance metric

III. Low dissolved oxygen
   Insufficient abundance metric
Assessing ecological integrity for impaired waters decisions in Chesapeake Bay, USA

Roberto J. Llansó, Daniel M. Dauer, Jon H. Vølstad

Assessing ecological integrity for impaired waters decisions in Chesapeake Bay, USA
Roberto J. Llansó a,c, Daniel M. Dauer b, Jon H. Vølstad a,c


Evaluate B-IBI for other stressors

OTHER STRESSORS IDENTIFIED?

YES

Aquatic life fails
Cause: Pollutants
B-IBI corroborative

Develop TMDL to correct pollutants
Pollutants corrected

NO

Aquatic life fails
Cause: Pollution
Unknown source

No TMDL required
Sediment Contaminant Discriminant Tool (SCDT) with p > 0.5

  - Develop TMDL to correct pollutants.
  - Pollutants corrected.

- **NO**: Excessive Abundance
  - **YES**: Eutrophication without low DO
    - Develop TMDL to reduce nutrients.
    - Nutrients corrected.
  - **NO**: Aquatic life fails. Cause: Pollution. Unknown source.
    - No TMDL required.
Assessing ecological integrity for impaired waters decisions in Chesapeake Bay, USA
Roberto J. Llansó a,c, Daniel M. Dauer b, Jon H. Vølstad a,c


SCDT
Sediment Contaminant Discriminant Tool
p > 0.5

Insufficient Abundance

YES

Aquatic life fails
Cause: Pollutants
B-IBI corroborative

Develop TMDL to correct pollutants

Pollutants corrected

NO

Eutrophication with low DO

Develop TMDL to reduce nutrients

Nutrients corrected

NO

Aquatic life fails
Cause: Pollution
Unknown source

No TMDL required
Summary

1. Water body test developed

2. Compares recent benthic samples with original reference sample

3. Combines different habitats

4. Diagnostic approaches can be applied
(5) Diagnostic approaches to causes of degradation of benthic communities.

Low dissolved oxygen
Eutrophication
Sediment Contamination

(Dauer et al. 2002. EPA Technical Report)

(6) Impaired waters designations of Maryland DNR and Virginia DEQ 303d (Llansó et al. 2003)

(7) Functional metric/index approach
(7) Functional metric/index approach

Benthic secondary productivity
(7) Functional metric/index approach

Benthic secondary productivity
Functional metric/index approach

Benthic secondary productivity
(7) Functional metric/index approach

Benthic secondary productivity

Preliminary evaluations of secondary productivity estimates as indicators of the ecological value of the benthos to higher trophic levels in Chesapeake Bay

Prepared by

Principal Investigators:

Daniel M. Dauer
Michael F. Lane
Roberto J. Llansó
Robert Diaz

Submitted to:

Virginia Department of Environmental Quality
629 East Main Street
Richmond, Virginia 23230

December, 2011
Production equation matters
Estuarine pattern of benthic secondary production
Low dissolved oxygen effects
Contaminant effects
Trophic transfer challenges
Susceptibility to predation
Microbial sinks
Functional metric/index approach - Benthic secondary productivity

Sturdivant et al. 2014. Estuaries and Coasts

Production equation matters

Figure 2. Benthic Secondary Productivity as a function of Total Community Biomass using the Edgar equation. Equation applied for each species and summed.

Figure 3. Benthic Secondary Productivity as a function of Total Community Biomass using the Brey equation. Equation applied for each species and summed.
Production equation matters

Edgar (1990)

\[ P = 0.0049 \times B^{0.80} T^{0.89} \]

- \( P \) - per sample daily macrobenthic production
- \( B \) - per sample standing crop biomass (mg AFDW)
- \( T \) - water temperature in °C
Production equation matters

Brey’s (2001)

\[
\log_{10}(P/B) = 7.947 - 2.294 \times \log_{10}(w) - (2409.856 \times 1/T) + (0.168 \times 1/D) + (0.194 \times \text{Subtid}) + (0.180 \times \text{InfEpi}) + (0.174 \times \text{Tax1}) - (0.188 \times \text{Tax2}) + (0.330 \times \text{Tax3}) + (582.851 \times \log_{10}(w) \times 1/T)
\]

- \(w\) - mean body mass per individual expressed in kJ
- \(D\) - sample depth in meters
- \(T\) - temperature in K and several discrete (dummy) variables which took the following form:

**Dummy variables**

- \(\text{Subtid}\) increases the P/B ratio with a depth of > 1 meter
- \(\text{InfEpi}\) is set to 1 if the organism is infaunal also resulting in an increase in the P/B ratio
- \(\text{Tax1}, \text{Tax2}\) and \(\text{Tax3}\) are dummy variables that identify specific taxon effects - (1) annelid or crustacean; (2) echinoderm or (3) an insect, respectively, and 0 if otherwise.
Functional metric/index approach - Benthic secondary productivity

Sturdivant et al. 2014. Estuaries and Coasts

Production equation matters
Estuarine pattern of benthic productivity
Low dissolved oxygen effects
Contaminant effects
Trophic transfer challenges
Susceptibility to predation
Microbial sinks
Production equation matters

Estuarine pattern of benthic secondary production

Low dissolved oxygen effects

Contaminant effects

Trophic transfer challenges

Susceptibility to predation

Microbial sinks
(7) **Functional metric/index approach - Benthic secondary productivity**

Estuarine pattern of benthic secondary production

Figure 6. Mean standing stock biomass (gC/m²) by the habitat types of Weisberg et al. (1997). Bar indicates one standard error. All random data from 1996 - 2009 n = 3,919.
Figure 5. Mean secondary production (gC/m²/yr) by the habitat types of Weisberg et al. (1997). Bar indicates one standard error. All random data from 1996-2009 n = 3,919.
Estuarine pattern of benthic secondary production
(7) Functional metric/index approach - Benthic secondary productivity

Estuarine pattern of benthic secondary production
(7) Functional metric/index approach - Benthic secondary productivity

Estuarine pattern of benthic secondary production

Figure 21. Chesapeake Bay Program segments showing levels of benthic secondary productivity (see insert at top).
Functional metric/index approach - Benthic secondary productivity
Sturdivant et al. 2014. Estuaries and Coasts

Production equation matters
Estuarine pattern of benthic secondary production
Low dissolved oxygen effects
Contaminant effects
Trophic transfer challenges
   Susceptibility to predation
   Microbial sinks
(7) **Functional metric/index approach - Benthic secondary productivity**

Sturdivant et al. 2014. Estuaries and Coasts

Low dissolved oxygen effects
Figure 14. Mean community abundance by the CBP benthic strata. Bar indicates one standard error. UPB – Upper Mainstem, MWT – Maryland Western Tributaries, MET – Maryland Eastern Tributaries.

Figure 15. Mean B-IBI by the habitat types by the CBP benthic strata. Bar indicates one standard error.

Figure 16. Mean species per sample by the CBP benthic strata. Bar indicates one standard error.
(7) Functional metric/index approach - Benthic secondary productivity

Sturdivant et al. 2014. Estuaries and Coasts

90% reduction in benthic production
Fig. 4. Dissolved oxygen concentration and daily macrobenthic production for the continuously monitored hypoxic and normoxic sites in 2007 and 2008. There was a sigmoid relationship between DO and daily macrobenthic production ($df = 39, F = 10.31, p = 0.0003$). Squares represent 2007 data; triangles represent 2008 data. Solid symbols indicate the hypoxic (H) sites, and hollow symbols the normoxic (N) sites.
(7) **Functional metric/index approach - Benthic secondary productivity**

Sturdivant et al. 2014. Estuaries and Coasts

Low dissolved oxygen effects

### Table 3: Comparison of oxygen condition and mean daily macrobenthic production

**(a) By phylum (±1SE)**

<table>
<thead>
<tr>
<th></th>
<th>Mollusca</th>
<th>Annelida</th>
<th>Arthropoda</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normoxia</td>
<td>40.8 (4.4) a</td>
<td>9.6 (0.4) a</td>
<td>3.2 (0.3) a</td>
</tr>
<tr>
<td>Mild hypoxia</td>
<td>6.5 (3.1) a,b</td>
<td>3.7 (0.4) b</td>
<td>0.7 (0.2) b</td>
</tr>
<tr>
<td>Hypoxia</td>
<td>3.0 (2.5) b</td>
<td>2.5 (0.4) b</td>
<td>0.2 (0.1) b</td>
</tr>
</tbody>
</table>

*p* values: *p*<0.0005

**(b) By class (±1SE)**

<table>
<thead>
<tr>
<th></th>
<th>Bivalvia</th>
<th>Gastropoda</th>
<th>Polychaeta</th>
<th>Oligochaeta</th>
<th>Amphipoda</th>
<th>Isopoda</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normoxia</td>
<td>39.9 (4.4) a</td>
<td>0.8 (0.3)</td>
<td>7.7 (0.3) a</td>
<td>1.8 (0.3) a</td>
<td>1.5 (0.2) a</td>
<td>0.5 (0.1)</td>
</tr>
<tr>
<td>Mild hypoxia</td>
<td>6.2 (3.1) a,b</td>
<td>0.3 (0.1)</td>
<td>3.4 (0.4) b</td>
<td>0.3 (0.1) a,b</td>
<td>0.5 (0.2) a,b</td>
<td>0.1 (0.0)</td>
</tr>
<tr>
<td>Hypoxia</td>
<td>2.9 (2.5) b</td>
<td>0.1 (0.0)</td>
<td>2.4 (0.4) b</td>
<td>0.1 (0.0) b</td>
<td>0.1 (0.0) b</td>
<td>0.0 (0.0)</td>
</tr>
</tbody>
</table>

*p* values: *p*<0.0005; ns: not significant

Letter differences denote significance

**Taxocene patterns (Used Edgar’s equation)**
(7) Functional metric/index approach - Benthic secondary productivity

Sturdivant et al. 2014. Estuaries and Coasts

Low dissolved oxygen effects

Table 6. Compilation of the major hypoxia resistant species collected at the 4 continuously monitored sites: in 2007, hypoxic Site 18 (hyp) and normoxic Site 25 (norm); in 2008, hypoxic Site 11 (hyp) and normoxic Site 12 (norm). Values in the table represent the percentage of macrobenthic production contributed by each species by site; abundances are in parentheses and dash denotes no data. For taxon group: A = annelid, B = bivalve

<table>
<thead>
<tr>
<th>Taxon (group)</th>
<th>Hypoxia LT₅₀ (h)</th>
<th>Site 18 (hyp)</th>
<th>Site 25 (norm)</th>
<th>Site 11 (hyp)</th>
<th>Site 12 (norm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heteromastus filiformis (A)</td>
<td>168–312</td>
<td>–</td>
<td>0.1 (32)</td>
<td>3.3 (12)</td>
<td>0.1 (1)</td>
</tr>
<tr>
<td>Loimia medusa (A)</td>
<td>72–113</td>
<td>0.8 (2)</td>
<td>1.8 (3)</td>
<td>–</td>
<td>1.2 (1)</td>
</tr>
<tr>
<td>Macoma balthica (B)</td>
<td>212–1658</td>
<td>2.1 (2)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Nereis succinea (A)</td>
<td>62–84</td>
<td>0.8 (1)</td>
<td>0.1 (1)</td>
<td>27.5 (20)</td>
<td>28.7 (17)</td>
</tr>
<tr>
<td>Parapriomaspio pinnata (A)</td>
<td>–</td>
<td>77.5 (48)</td>
<td>47 (79)</td>
<td>52.2 (52)</td>
<td>33.6 (50)</td>
</tr>
<tr>
<td>Streptosspio benedicti (A)</td>
<td>43</td>
<td>1.3 (2)</td>
<td>1.4 (11)</td>
<td>3.6 (12)</td>
<td>3.5 (19)</td>
</tr>
<tr>
<td>Tubificoides spp. (A)</td>
<td>720</td>
<td>1.3 (3)</td>
<td>–</td>
<td>–</td>
<td>0.3 (3)</td>
</tr>
</tbody>
</table>

Polychaete tolerance

Rosenberg (1972), Warren (1976), Kravitz (1983)
Breitburg et al. (2003)
Tevesz et al. (1980), Hines & Comtois (1985), Giere et al. (1999)
Low dissolved oxygen effects
Lower Potomac River (POTMH)

<table>
<thead>
<tr>
<th>Water Depth (m)</th>
<th>Mean Secondary Productivity (g C/m²/yr)</th>
<th>n</th>
<th>% of samples with no benthos</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.00</td>
<td>243.00</td>
<td>75</td>
<td>8.0</td>
</tr>
<tr>
<td>10.00</td>
<td>43.11</td>
<td>103</td>
<td>39.8</td>
</tr>
<tr>
<td>15.00</td>
<td>14.94</td>
<td>48</td>
<td>41.7</td>
</tr>
<tr>
<td>20.00</td>
<td>4.96</td>
<td>18</td>
<td>72.2</td>
</tr>
</tbody>
</table>
(7) **Functional metric/index approach** - **Benthic secondary productivity**

Sturdivant et al. 2014. Estuaries and Coasts

Production equation matters
Estuarine pattern of benthic secondary production
Low dissolved oxygen effects
**Contaminant effects**
Trophic transfer challenges
  Susceptibility to predation
  Microbial sinks
(7) Functional metric/index approach - Benthic secondary productivity

Contaminant effects
Functional metric/index approach - Benthic secondary productivity


Contaminant effects

10 benthic strata
BIBI
Biomass
Benthic Productivity
Figure 15. Mean B-IBI by the habitat types by the CBP benthic strata. Bar indicates one standard error.

Figure 13. Mean standing stock biomass (gC/m²) by the CBP benthic strata. Bar indicates one standard error.
Figure 12. Mean secondary production (gC/m²/yr) by the CBP benthic strata. Bar indicates one standard error.

(7) Functional metric/index approach - Benthic secondary productivity

Figure 21. Chesapeake Bay Program segments showing levels of benthic secondary productivity (see insert at top).

Figure 28. CBP segments and high urban land-use. Shown are secondary productivity values in gC/m²/yr. Colors correspond to the intervals of Figure 21. Segments with no color and cross-hatching are located in either the Maryland Western Tributaries benthic stratum or the Elizabeth River watershed.
Functional metric/index approach - Benthic secondary productivity

Production equation matters
Estuarine pattern of benthic secondary production
Low dissolved oxygen effects
Contaminant effects
Trophic transfer challenges
  Susceptibility to predation
  Microbial sinks
Trophic transfer challenges
Susceptibility to predation
Microbial sinks

Develop species specific estimates of potential availability of the benthic production to higher trophic levels.

Important ecological factors are:

1. **protective coverings** such as molluscan shells and crustacean exoskeletons that reduce predation,
2. **depth of dwelling** within the sediment that might provide a refuge from predation,
3. **body size factors** that affect strength of protective coverings and/or age-related sediment depth dwelling location, and
4. **general behaviors** that can modify susceptibility to predation, e.g., rapid motility.
(7) **Functional metric/index approach - Benthic secondary productivity**

- Trophic transfer challenges
  - Susceptibility to predation
  - Microbial sinks
- Anoxia
- Contaminants
Mesohaline segments

Benthic IBI

JMSMH  POTMH  PATMH  SBEMH
Mesohaline segments

Abundance

Total Community Abundance (#/m²)

- JMSMH
- POTMH
- PATMH
- SBEMH
Mesohaline segments

Biomass

Total community biomass (g C/m²)

JMSMH | POTMH | PATMH | SBEMH
Mesohaline segments

Secondary Productivity

Brey's productivity (gC/m²/yr)

JMSMH

POTMH

PATMH

SBEMH
(7) Functional metric/index approach - Benthic secondary productivity

Trophic transfer challenges
Susceptibility to predation
Microbial sinks
Anoxia
Contaminants
VERSAR, INC.*

Ecological Sciences and Applications
9200 Rumsey Road, Columbia, Maryland 21045

OLD DOMINION UNIVERSITY

Department of Biological Sciences
Old Dominion University, Norfolk, Virginia 23529

CHESAPEAKE BAY B-IBI RECALIBRATION

Prepared by

Principal Investigators:

    Roberto J. Llansó*
    Daniel M. Dauer
    Michael F. Lane

Submitted to:

Cindy S. Johnson
Chesapeake Bay Monitoring Manager
Virginia Department of Environmental Quality
629 East Main Street
Richmond, Virginia 23219

August 2016

<table>
<thead>
<tr>
<th>Habitat</th>
<th>a priori Classification</th>
<th>Sample #</th>
<th>Number</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal Freshwater</td>
<td>Reference</td>
<td>55</td>
<td>40</td>
<td>72.7</td>
</tr>
<tr>
<td></td>
<td>Degraded</td>
<td>161</td>
<td>58</td>
<td>36.0</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>216</td>
<td>98</td>
<td>45.4</td>
</tr>
<tr>
<td>Oligohaline</td>
<td>Reference</td>
<td>24</td>
<td>17</td>
<td>70.8</td>
</tr>
<tr>
<td></td>
<td>Degraded</td>
<td>111</td>
<td>70</td>
<td>63.1</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>135</td>
<td>87</td>
<td>64.4</td>
</tr>
<tr>
<td>Low Mesohaline</td>
<td>Reference</td>
<td>92</td>
<td>51</td>
<td>55.4</td>
</tr>
<tr>
<td></td>
<td>Degraded</td>
<td>214</td>
<td>156</td>
<td>72.9</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>306</td>
<td>207</td>
<td>67.6</td>
</tr>
<tr>
<td>High Mesohaline Sand</td>
<td>Reference</td>
<td>189</td>
<td>91</td>
<td>48.2</td>
</tr>
<tr>
<td></td>
<td>Degraded</td>
<td>58</td>
<td>32</td>
<td>55.2</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>247</td>
<td>123</td>
<td>49.8</td>
</tr>
<tr>
<td>High Mesohaline Mud</td>
<td>Reference</td>
<td>106</td>
<td>30</td>
<td>28.3</td>
</tr>
<tr>
<td></td>
<td>Degraded</td>
<td>309</td>
<td>241</td>
<td>78.0</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>415</td>
<td>271</td>
<td>65.3</td>
</tr>
<tr>
<td>Polyhaline Sand</td>
<td>Reference</td>
<td>240</td>
<td>163</td>
<td>67.9</td>
</tr>
<tr>
<td></td>
<td>Degraded</td>
<td>46</td>
<td>23</td>
<td>50.0</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>286</td>
<td>186</td>
<td>65.0</td>
</tr>
<tr>
<td>Polyhaline Mud</td>
<td>Reference</td>
<td>47</td>
<td>18</td>
<td>38.3</td>
</tr>
<tr>
<td></td>
<td>Degraded</td>
<td>179</td>
<td>164</td>
<td>91.6</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>226</td>
<td>182</td>
<td>80.5</td>
</tr>
<tr>
<td>Overall</td>
<td></td>
<td>1831</td>
<td>1154</td>
<td>63.0</td>
</tr>
</tbody>
</table>

Table 5. Classification efficiencies within habitat type and across all habitat types for both Reference and Degraded sites based on B-IBI values scored using thresholds defined in Weisberg et al. (1997) and Alden et al. (2002) and the entire calibration and validation datasets assembled for this project.
<table>
<thead>
<tr>
<th>Habitat</th>
<th>a priori Classification</th>
<th>Sample #</th>
<th>Number</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal Freshwater</td>
<td>Reference</td>
<td>22</td>
<td>15</td>
<td>68.2</td>
</tr>
<tr>
<td></td>
<td>Degraded</td>
<td>161</td>
<td>49</td>
<td>30.4</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>183</td>
<td>64</td>
<td>35.0</td>
</tr>
<tr>
<td>Oligohaline</td>
<td>Reference</td>
<td>9</td>
<td>5</td>
<td>55.6</td>
</tr>
<tr>
<td></td>
<td>Degraded</td>
<td>111</td>
<td>32</td>
<td>28.8</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>120</td>
<td>37</td>
<td>30.8</td>
</tr>
<tr>
<td>Low Mesohaline</td>
<td>Reference</td>
<td>33</td>
<td>25</td>
<td>75.8</td>
</tr>
<tr>
<td></td>
<td>Degraded</td>
<td>214</td>
<td>101</td>
<td>47.2</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>247</td>
<td>126</td>
<td>51.0</td>
</tr>
<tr>
<td>High Mesohaline Sand</td>
<td>Reference</td>
<td>65</td>
<td>53</td>
<td>81.5</td>
</tr>
<tr>
<td></td>
<td>Degraded</td>
<td>58</td>
<td>18</td>
<td>31.0</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>123</td>
<td>71</td>
<td>57.7</td>
</tr>
<tr>
<td>High Mesohaline Mud</td>
<td>Reference</td>
<td>39</td>
<td>32</td>
<td>82.1</td>
</tr>
<tr>
<td></td>
<td>Degraded</td>
<td>309</td>
<td>159</td>
<td>51.5</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>348</td>
<td>191</td>
<td>54.9</td>
</tr>
<tr>
<td>Polyhaline Sand</td>
<td>Reference</td>
<td>81</td>
<td>77</td>
<td>95.1</td>
</tr>
<tr>
<td></td>
<td>Degraded</td>
<td>46</td>
<td>9</td>
<td>19.6</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>127</td>
<td>86</td>
<td>67.7</td>
</tr>
<tr>
<td>Polyhaline Mud</td>
<td>Reference</td>
<td>15</td>
<td>15</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Degraded</td>
<td>179</td>
<td>70</td>
<td>39.1</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>194</td>
<td>85</td>
<td>43.8</td>
</tr>
<tr>
<td>Overall</td>
<td></td>
<td>1342</td>
<td>660</td>
<td>49.2</td>
</tr>
</tbody>
</table>

Table 6. Classification efficiencies within habitat type and across all habitat types for both Reference and Degraded sites based on B-IBI values scored using **new thresholds** and the validation dataset assembled for this project.
Figure 1. Comparison of thresholds between the original Reference dataset of Weisberg et al. (1997) and the new Reference dataset assembled for this project for Shannon index ($H'$).
Figure 2. Comparison of thresholds between the original Reference dataset of Weisberg et al. (1997) and the new Reference dataset assembled for this project for abundance (#/m²)
Figure 3. Comparison of thresholds between the original Reference dataset of Weisberg et al. (1997) and the new Reference dataset assembled for this project for biomass (g AFDW/m²)
Figure 4. Comparison of thresholds between the original Reference dataset of Weisberg et al. (1997) and the new Reference dataset assembled for this project for abundance of pollution indicative taxa (%)
Figure 5. Comparison of thresholds between the original Reference dataset of Weisberg et al. (1997) and the new Reference dataset assembled for this project for abundance of pollution sensitive taxa (%)
Figure 6. Comparison of thresholds between the original Reference dataset of Weisberg et al. (1997) and the new Reference dataset assembled for this project for biomass of pollution indicative taxa (%)
Figure 7. Comparison of thresholds between the original Reference dataset of Weisberg et al. (1997) and the new Reference dataset assembled for this project for biomass of pollution sensitive taxa (%)
Figure 8. Comparison of thresholds between the original Reference dataset of Weisberg et al. (1997) and the new Reference dataset assembled for this project for **abundance of carnivore and omnivores (%)**
Figure 9. Comparison of thresholds between the original Reference dataset of Weisberg et al. (1997) and the new Reference dataset assembled for this project for abundance of deep-deposit feeders (%)
Figure 10. Comparison of thresholds between the original Reference dataset of Weisberg et al. (1997) and the new Reference dataset assembled for this project for abundance of pollution indicative freshwater and oligohaline taxa (%), upper panel, and abundance of pollution sensitive oligohaline taxa (%), lower panel.
(7) **Functional metric/index approach**

**Benthic Secondary Productivity**

Sturdivant et al. 2014. Estuaries and Coasts

---

(8) **BIBI recalibration**

de-la-Ossa et al. 2016. Ecological Indicators)

---

(9) **International collaboration**

(Borja and Dauer. 2008. Ecological Indicators;
Borja et al. 2010. Estuaries and Coasts;
Borja et al. 2012. Ecological Indicators)
Assessing the environmental quality status in estuarine and coastal systems: Comparing methodologies and indices

A. Borja a,*, D.M. Dauer b

aAZTI-Tecnalia, Marine Research Division, Herrera Kaia, Portualdea s/n, 20110 Pasai, Spain
bDepartment of Biological Sciences, Old Dominion University, Norfolk, VA 23529, USA

ABSTRACT

Increasingly, on a worldwide scale, legislation has been adopted to determine the ecological integrity of surface waters including streams, rivers, lakes, estuaries and coastal waters. An integral part of determining ecological integrity is the measurement of biological integrity, typically emphasizing analyses of plankton, benthos, macroalgae and fish. In the development of protocols for evaluating biological integrity, benthic macroinvertebrate communities are the most consistently emphasized biotic component of aquatic ecosystems. A plethora of methodologies with hundreds of indices, metrics and evaluation tools are presently available. An ecologically parsimonious approach dictates that investigators should place greater emphasis on evaluating the suitability of indices that already exist prior to developing new ones. Hence, the authors organized within the American Society of Limnology and Oceanography 2006 Summer Meeting, 4–9 June 2006, in Victoria, BC, Canada, a special session with the objective to compare methodologies, applications and interpretations existing in various countries and attempting to contribute to an improved understanding of the suitability of such approaches when using benthic communities. From the 25 contributions presented in this session, eight manuscripts were selected to be included in the upcoming special issue, which will provide a comprehensive, state-of-the-art assessment of existing methods for evaluating ecological integrity.

Table 1 – Environmental indicators

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Summarizes and simplifies complex data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conveys information—easily understood by the public, media, resource users, and decision-makers</td>
</tr>
<tr>
<td></td>
<td>Characteristics</td>
</tr>
<tr>
<td></td>
<td>Ecological relevance—based upon a conceptual model (theoretically, empirically or heuristically well founded)</td>
</tr>
<tr>
<td></td>
<td>Feasible—data to calculate index can be reliably and cost-effectively collected</td>
</tr>
<tr>
<td></td>
<td>Threshold or reference value—users are able to assess significance of indicator value</td>
</tr>
<tr>
<td></td>
<td>Representative—able to measure status and trends that are relevant to policy decisions</td>
</tr>
<tr>
<td></td>
<td>Sensitivity—reflects response to management actions</td>
</tr>
</tbody>
</table>

Note: an index that is representative and sensitive captures information relevant to anthropogenic actions—degradative and restorative.
## International collaboration

(Borja and Dauer. 2008. Ecological Indicators; Borja et al. 2010. Estuaries and Coasts; Borja et al. 2012. Ecological Indicators)

### Table 1 – Environmental indicators

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summarizes and simplifies complex data</td>
<td>Ecological relevance—based upon a conceptual model (theoretically, empirically or heuristically well founded)</td>
</tr>
<tr>
<td>Conveys information—easily understood by the public, media, resource users, and decision-makers</td>
<td>Feasible—data to calculate index can be reliably and cost-effectively collected</td>
</tr>
<tr>
<td>Threshold or reference value—users are able to assess significance of indicator value</td>
<td>Representative—able to measure status and trends that are relevant to policy decisions</td>
</tr>
</tbody>
</table>
| Sensitivity—reflects response to management actions | Note: an index that is representative and sensitive captures information relevant to anthropogenic actions—degradative and restorative.
Fig. 2 – Index development, application and interpretation. Dashed rectangle encloses the primary steps in index development. Adaptive monitoring feedback loops and adaptive change decision drivers are indicted by open arrows.
Summarize European Water Framework Directive approaches
Ecosystem services and ecosystem function

Fig. 2 – Index development, application and interpretation. Dashed rectangle encloses the primary steps in index development. Adaptive monitoring feedback loops and adaptive change decision drivers are indicted by open arrows.
Summarize European Water Framework Directive approaches

Ecosystem services and ecosystem function

Fig. 1 - The DPSIR approach showing relationships between drivers–pressure–state–impact–responses variables. Also indicated are the primary drivers of management decisions. Societal responses meant to halt, ameliorate, mitigate or reverse unacceptable conditions are shown by open arrows. Dashed inset shows the impact assessment components with open arrows indicating adaptive monitoring feedback loops.
Medium- and Long-term Recovery of Estuarine and Coastal Ecosystems: Patterns, Rates and Restoration Effectiveness

Ángel Borja · Daniel M. Dauer · Michael Elliott · Charles A. Simenstad

Received: 4 March 2010/Revised: 26 June 2010/Accepted: 8 September 2010/Published online: 24 September 2010 © Coastal and Estuarine Research Federation 2010

Abstract Many estuarine and coastal marine ecosystems have increasingly experienced degradation caused by multiple stressors. Anthropogenic pressures alter natural ecosystems and the ecosystems are not considered to have the resilience to rapidly recover. The recovery framework include (1) restoration of degraded habitats which includes all aspects of dredging and disposal; (2) recovery by complete removal of stressors limiting natural ecosystem processes, which includes tidal marsh and inundation restoration; (3) recovery by speed of organic degradation which includes tidal marsh refugia.
Summarize European Water Framework Directive approaches
Ecosystem services and ecosystem function

Table 2 Summary of time for recovery, for different biological elements and substrata, under different pressures

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Substrata</th>
<th>Intertidal/subtidal</th>
<th>Biological elements</th>
<th>Time for recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment disposal</td>
<td>Soft</td>
<td>Intertidal</td>
<td>Meio and macrofauna</td>
<td>3–18 months</td>
</tr>
<tr>
<td>Marsh restoration</td>
<td>Soft</td>
<td>Subtidal</td>
<td>Fishes</td>
<td>1–2 years</td>
</tr>
<tr>
<td>Oxygen depletion</td>
<td>Soft</td>
<td>Subtidal</td>
<td>Macroinvertebrates</td>
<td>2 years</td>
</tr>
<tr>
<td>Land claim</td>
<td>Soft</td>
<td>Intertidal</td>
<td>Macroinvertebrates</td>
<td>2 years</td>
</tr>
<tr>
<td>Oil-refinery discharge</td>
<td>Soft/hard</td>
<td>Intertidal/subtidal</td>
<td>Macroinvertebrates, fishes</td>
<td>2–3 years</td>
</tr>
<tr>
<td>Dyke and marina construction</td>
<td>Soft</td>
<td>Intertidal/subtidal</td>
<td>Macroinvertebrates, fishes</td>
<td>2–3 years</td>
</tr>
<tr>
<td>Lagoon isolation</td>
<td>Soft</td>
<td>Subtidal</td>
<td>Molluscs</td>
<td>&gt;3 years</td>
</tr>
<tr>
<td>Aggregate dredging</td>
<td>Soft</td>
<td>Subtidal</td>
<td>Macroinvertebrates, epifauna</td>
<td>2–4 years</td>
</tr>
<tr>
<td>TBT</td>
<td>Soft</td>
<td>Subtidal</td>
<td>Macroinvertebrates</td>
<td>3–5 years</td>
</tr>
<tr>
<td>Dredging</td>
<td>Soft</td>
<td>Intertidal/subtidal</td>
<td>Sea grasses, macroinvertebrates, fishes</td>
<td>2–5 years</td>
</tr>
<tr>
<td>Sediment disposal</td>
<td>Soft</td>
<td>Subtidal</td>
<td>Sea grass, macroinvertebrates, fishes</td>
<td>&gt;5 years</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>Soft</td>
<td>Subtidal</td>
<td>Macroinvertebrates</td>
<td>&gt;3-&gt;6 years</td>
</tr>
<tr>
<td>Realignment of coastal defences</td>
<td>Soft</td>
<td>Intertidal</td>
<td>Marshes and macroinvertebrates</td>
<td>&gt;6 years</td>
</tr>
<tr>
<td>Fish farm</td>
<td>Soft</td>
<td>Subtidal</td>
<td>Macroinvertebrates</td>
<td>2-&gt;7 years</td>
</tr>
<tr>
<td>Physical disturbance</td>
<td>Soft/hard</td>
<td>Intertidal/deep sea</td>
<td>Macroinvertebrates, megafauna</td>
<td>3-&gt;7 years</td>
</tr>
<tr>
<td>Pulp mill</td>
<td>Soft</td>
<td>Subtidal</td>
<td>Macroinvertebrates</td>
<td>6–8 years</td>
</tr>
<tr>
<td>Oil spill</td>
<td>Soft/hard</td>
<td>Intertidal/subtidal</td>
<td>Various</td>
<td>2–10 years</td>
</tr>
<tr>
<td>Fish trawling</td>
<td>Sand–gravel</td>
<td>Subtidal</td>
<td>Macroinvertebrates, fishes</td>
<td>2.5–10 years</td>
</tr>
<tr>
<td>Wastewater discharge</td>
<td>Soft</td>
<td>Subtidal</td>
<td>Fishes</td>
<td>3–10 years</td>
</tr>
<tr>
<td>Sewage sludge disposal</td>
<td>Soft</td>
<td>Subtidal</td>
<td>Macroinvertebrates</td>
<td>3-&gt;14 years</td>
</tr>
<tr>
<td>Mine tailings</td>
<td>Soft</td>
<td>Subtidal</td>
<td>Macroinvertebrates</td>
<td>4-&gt;15 years</td>
</tr>
<tr>
<td>Marsh and tidal restoration</td>
<td>Soft</td>
<td>Intertidal/subtidal</td>
<td>Vegetation, fishes, birds</td>
<td>5–20 years</td>
</tr>
<tr>
<td>Wastewater discharge</td>
<td>Soft</td>
<td>Subtidal</td>
<td>Macroinvertebrates, sea grasses</td>
<td>7–20 years</td>
</tr>
<tr>
<td>Land claim</td>
<td>Soft</td>
<td>Subtidal</td>
<td>Zostera marina</td>
<td>&gt;20 years</td>
</tr>
<tr>
<td>Wastewater discharge</td>
<td>Hard</td>
<td>Intertidal</td>
<td>Macroalgae</td>
<td>&gt;6-&gt;22 years</td>
</tr>
</tbody>
</table>
Summarize European Water Framework Directive approaches
Ecosystem services and ecosystem function

Benthic recovery rates

Fig. 2 A conceptual model of changes to the state of Nervión estuary (Basque Country, northern Spain) with increasing (increasing wastewater discharge volume) and decreasing (wastewater treatment improvement) pressure (adapted from Elliott et al. (2007)). (a) Complete resilience; (b) incomplete resilience
The importance of setting targets and reference conditions in assessing marine ecosystem quality

Ángel Borja\textsuperscript{a,}\textsuperscript{*}, Daniel M. Dauer\textsuperscript{b}, Antoine Grémare\textsuperscript{c}

\textsuperscript{a} AZTI - Tecnalia, Marine Research Division, Herrera Koa, Portugaletea s/n, 20110 Pasai, Spain
\textsuperscript{b} Department of Biological Sciences, Old Dominion University, Norfolk, VA 23529, USA
\textsuperscript{c} Station Marine d’Arcachon, UMR 5805, Université Bordeaux 1 – CNRS, 2 rue du Professeur Jolyot, F33120 Arcachon, France

\textbf{ARTICLE INFO}

\textbf{Article history:}
Received 2 February 2011
Received in revised form 17 June 2011
Accepted 19 June 2011

\textbf{Keywords:}
Reference conditions
Targets
Benthic status
Ecological status
Indicators
M-AMBI

\textbf{ABSTRACT}

Assessing benthic quality status of marine and transitional water habitats requires to set up both: (i) tools (i.e. indices) to assess the relative quality of the considered habitat, and (ii) reference conditions for which such indices can be computed and used to infer the absolute ecological status (ES) of the considered habitat. The development of indices, their comparison and the assessment of the causes of their discrepancies have been largely discussed but less attention has been paid to the methods used for the setting of adequate reference conditions, although this step is clearly crucial for the sound assessment of ES. This contribution reviews the approaches available in setting both reference conditions (pristine areas, hindcasting, modelling and best professional judgment) and targets (baseline set in the past, current baseline and directional/trends). We scored the use of pristine or minimally impacted conditions as the best single method; however, the other methods were judged as adequate then combined with best professional judgment. The case of multivariate AMBI (AZTI’s Marine Biotic Index) is used to highlight the importance of setting correct reference conditions. Hence, data from 29 references, including 14 countries from Europe and North America, and both coastal (15 cases) and transitional (17 cases) waters, have been used to study the response of multivariate AMBI to human pressures. Results show that the inability of this index to detect human pressure is in most cases linked with the use of inappropriate methods for setting reference conditions.

© 2011 Elsevier Ltd. All rights reserved.
Fig. 1. The DPSIR approach showing relationships between Drivers-Pressure-State of change-Impact-Responses variables, in assessing environmental quality status in marine waters. Environmental status can be considered as a gradation from pristine conditions (high status in absence of human pressures) to an irrecoverable status (bad status, in a maximum human pressure). Assessment systems need to set reference conditions or baseline targets along the pressure (and subsequent state) gradient to assist in status assessment and for monitoring progress against time and actions. In this step the development and validation of impact assessment methods is needed. Adapted from Borja and Dauer (2008) and Cochrane et al. (2010). BPJ—best professional judgment.
The development of indices, their comparison and the assessment of the causes of their discrepancies have been largely discussed but less attention has been paid to the methods used for the setting of adequate reference conditions, although this step is clearly crucial for the sound assessment of ES.

This contribution reviews the approaches available in setting both reference conditions:

- Pristine areas
- Hindcasting
- Modelling and
- Best Professional Judgment

and targets:

- Baseline set in the past
- Current baseline and
- Directional/trends

We scored the use of pristine or minimally impacted conditions as the best single method.
Chesapeake Bay accomplishments

1. Index development
2. Index relationship to watershed stressors
3. Sample allocation
4. Index relationship to habitat quality
5. Causes of degradation (diagnostics)
6. Impaired waters designations – 303(d)
7. Functional metric/index (Secondary productivity)
8. BIBI recalibration
9. International collaboration
(9) **International collaboration**
(Borja and Dauer. 2008. Ecological Indicators; Borja et al. 2010. Estuaries and Coasts; Borja et al. 2012. Ecological Indicators)

(10) **Index comparisons - Chesapeake Bay**
Application of two indices of benthic community condition in Chesapeake Bay

J. Ananda Ranasinghe\textsuperscript{1,*\dagger}, Jeffrey B. Frithsen\textsuperscript{2}, Frederick W. Kutz\textsuperscript{3}, John F. Paul\textsuperscript{4}, David E. Russell\textsuperscript{3}, Richard A. Batiuk\textsuperscript{5}, Jeffrey L. Hyland\textsuperscript{6}, John Scott\textsuperscript{7} and Daniel M. Dauer\textsuperscript{8}

\textsuperscript{1}Southern California Coastal Water Research Project, 7171 Fenwick Lane, Westminster, CA 92683-5218, U.S.A.
\textsuperscript{2}National Center for Environmental Assessment, Office of Research and Development (8601), U.S. Environmental Protection Agency, 401 M Street, SW, Washington, DC 20460, U.S.A.
\textsuperscript{3}Environmental Science Center, U.S. Environmental Protection Agency, 701 Mapes Road, Fort Meade, MD 20755-5350, U.S.A.
\textsuperscript{4}Atlantic Ecology Division, U.S. Environmental Protection Agency, 27 Tarzwell Dr., Narragansett, RI 02882, U.S.A.
\textsuperscript{5}Chesapeake Bay Program, U.S. Environmental Protection Agency, 410 Severn Avenue, Annapolis, MD 21403, U.S.A.
\textsuperscript{6}NOAA, National Ocean Service, 219 Ft. Johnson Road, Charleston, SC 29412-9110, U.S.A.
\textsuperscript{7}Science Applications International Corporation, 165 Dean Knauss Drive, Narragansett, RI 02882, U.S.A.
\textsuperscript{8}Department of Biological Sciences, Old Dominion University, Norfolk, VA 23529, U.S.A.
(10) Index comparisons - Chesapeake Bay
(Ranasinghe et al. 2002. Environmetrics)
(10) Index comparisons - Chesapeake Bay
(Ranasinghe et al. 2002. Environmetrics)
1. **B-IBI** includes several community measures and weights them equally using a simple scoring system that compares them against values expected for undegraded sites. It includes measures of species diversity, productivity, indicator species and trophic composition.

2. **The EMAP-VP BI** uses discriminant function coefficients to weight contributions of species diversity and the abundances of two indicator families.

3. The two indices agreed on degraded or undegraded classifications for benthos at **81.3%** of the sites.

4. The **B-IBI** was more conservative than the EMAP-VP BI, **classifying 72.7% of the disagreements as degraded**. Many of the classification disagreements were at sites with index values close to, but on opposite sides of, the degraded–undegraded thresholds.
Assessing benthic community condition in Chesapeake Bay: does the use of different benthic indices matter?

Roberto J. Llansó · Jon H. Vølstad · Daniel M. Dauer · Jodi R. Dew
Compared (1) BIBI, (2) MAIA, and (3) EMAP_VP

1. Higher level of degradation with BIBI
2. Other indices classified degraded samples as good at higher rate
3. There were sample design interactions with level of degradation.
(10) Index comparisons - Chesapeake Bay
(Llanso et al. 2009. Environmental Monitoring and Assessment)

Fig. 1 Linear regressions between the values of three indices calculated on the Chesapeake Bay Mid-Atlantic Integrated Assessment (MAIA) (a) and National Status & Trends (NS&T) (b) survey datasets. Reference lines indicate degraded/nondegraded thresholds.
Index comparisons - Chesapeake Bay

(Llanso et al. 2009. Environmental Monitoring and Assessment)

Fig. 5  Percent of Type I and Type II errors (sites misclassified) by three indices, for Mid-Atlantic Integrated Assessment (MAIA) (a) and National Status & Trends (NS&T) (b) survey datasets.

Fig. 6  Percent of Chesapeake Bay (+SE) with degraded benthic condition as measured by three indices, for Chesapeake Bay Program (CBP) (a) and Mid-Atlantic Integrated Assessment (MAIA) (b) survey designs. \( N = 250 \) and 244, respectively. * Significant difference by confidence interval overlap test, NS not significant.
Assessing estuarine benthic quality conditions in Chesapeake Bay: A comparison of three indices

A. Borja a,*, D.M. Dauer b, R. Díaz c, R.J. Llansó d, I. Muxika e, J.G. Rodríguez a, L. Schaffner f

* AZTI-Tecnalia, Marine Research Division, Herrera Koia, Portugalete s/n, 20980 Pasai, Spain
b Department of Biological Sciences, Old Dominion University, Norfolk, VA 23529, USA
c Department of Biological Sciences, School of Marine Science, Virginia Institute of Marine Science, The College of William and Mary, Gloucester Point, VA 23062, USA
d Versar Inc., 9200 Ramsey Road, Columbus, MD 21045, USA

ARTICLE INFO

Article history
Received 16 October 2006
Received in revised form
15 January 2007
Accepted 21 January 2007

ABSTRACT

Legislation in US and Europe has been adopted to determine the ecological integrity of estuarine and coastal waters, including, as one of the most relevant elements, the benthic macroinvertebrate communities. It has been recommended that greater emphasis should be placed on evaluating the suitability of existing indices prior to developing new ones. This study compares two widely used measures of ecological integrity, the benthic index of biotic integrity (B-IBI) developed in USA and the European AZTI’s Marine Biotic Index (AMBI) and its multivariate extension, the M-AMBI. Specific objectives were to identify the frequency, magnitude, and nature of differences in assessment of Chesapeake Bay sites as ‘degraded’ or

Table 5 - Correlation coefficients between indices, environmental and structural parameters, by salinity zone

<table>
<thead>
<tr>
<th></th>
<th>Polyhaline (33)</th>
<th>High mesohaline (99)</th>
<th>Low mesohaline (150)</th>
<th>Oligohaline (26)</th>
<th>Tidal freshwater (18)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMBI-M-AMBI</td>
<td>-0.887</td>
<td>-0.887</td>
<td>-0.884</td>
<td>-0.551</td>
<td>-0.551</td>
</tr>
<tr>
<td>AMBI-B-IBI</td>
<td>-0.515</td>
<td>-0.515</td>
<td>-0.551</td>
<td>-0.413</td>
<td>-0.413</td>
</tr>
<tr>
<td>M-AMBI-B-IBI</td>
<td>0.745</td>
<td>0.748</td>
<td>0.651</td>
<td>0.355</td>
<td>0.355</td>
</tr>
<tr>
<td>AMBI-Depth</td>
<td>0.502</td>
<td>0.527</td>
<td>0.293</td>
<td>-0.322</td>
<td>-0.489</td>
</tr>
<tr>
<td>AMBI-Salinity</td>
<td>-0.217</td>
<td>-0.058</td>
<td>0.130</td>
<td>-0.060</td>
<td>-0.581</td>
</tr>
<tr>
<td>AMBI-Oxygen</td>
<td>-0.291</td>
<td>-0.402</td>
<td>-0.954</td>
<td>0.047</td>
<td>-0.369</td>
</tr>
<tr>
<td>AMBI-TOC</td>
<td>-0.108</td>
<td>0.182</td>
<td>0.388</td>
<td>0.113</td>
<td>-0.300</td>
</tr>
<tr>
<td>AMBI-Silt/Clay</td>
<td>-0.059</td>
<td>0.261</td>
<td>0.365</td>
<td>-0.005</td>
<td>-0.132</td>
</tr>
<tr>
<td>AMBI-Richness</td>
<td>-0.514</td>
<td>-0.714</td>
<td>-0.933</td>
<td>-0.084</td>
<td>-0.021</td>
</tr>
<tr>
<td>AMBI-Diversity</td>
<td>-0.815</td>
<td>-0.753</td>
<td>-0.739</td>
<td>-0.154</td>
<td>-0.181</td>
</tr>
<tr>
<td>M-AMBI-Depth</td>
<td>-0.316</td>
<td>-0.310</td>
<td>-0.405</td>
<td>0.294</td>
<td>-0.188</td>
</tr>
<tr>
<td>M-AMBI-Salinity</td>
<td>0.260</td>
<td>0.110</td>
<td>-0.284</td>
<td>0.232</td>
<td>0.341</td>
</tr>
<tr>
<td>M-AMBI-Oxygen</td>
<td>0.388</td>
<td>0.347</td>
<td>0.524</td>
<td>0.243</td>
<td>0.631</td>
</tr>
<tr>
<td>M-AMBI-TOC</td>
<td>0.017</td>
<td>-0.314</td>
<td>-0.459</td>
<td>-0.313</td>
<td>-0.381</td>
</tr>
<tr>
<td>M-AMBI-Silt/Cay</td>
<td>-0.024</td>
<td>-0.445</td>
<td>-0.483</td>
<td>-0.357</td>
<td>-0.292</td>
</tr>
<tr>
<td>M-AMBI-Richness</td>
<td>0.816</td>
<td>0.332</td>
<td>0.981</td>
<td>0.017</td>
<td>0.050</td>
</tr>
<tr>
<td>M-AMBI-Diversity</td>
<td>0.831</td>
<td>0.931</td>
<td>0.918</td>
<td>0.063</td>
<td>0.084</td>
</tr>
</tbody>
</table>

Table 3 - Number of sites classified as meets goal, marginal, degraded, and very degraded by the B-IBI and the M-AMBI

<table>
<thead>
<tr>
<th></th>
<th>Meets goal</th>
<th>Marginal</th>
<th>Degraded</th>
<th>Severely degraded</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-IBI Meets Goal</td>
<td>63 (44)</td>
<td>14 (11)</td>
<td>17 (11)</td>
<td>4 (1)</td>
<td>98 (67)</td>
</tr>
<tr>
<td>Marginal</td>
<td>5 (5)</td>
<td>8 (8)</td>
<td>4 (3)</td>
<td>2 (1)</td>
<td>19 (17)</td>
</tr>
<tr>
<td>Degraded</td>
<td>31 (26)</td>
<td>17 (16)</td>
<td>18 (16)</td>
<td>10 (9)</td>
<td>76 (67)</td>
</tr>
<tr>
<td>Very degraded</td>
<td>7 (7)</td>
<td>10 (10)</td>
<td>27 (24)</td>
<td>38 (38)</td>
<td>82 (79)</td>
</tr>
<tr>
<td>Total</td>
<td>106 (82)</td>
<td>49 (45)</td>
<td>66 (54)</td>
<td>54 (49)</td>
<td>275 (230)</td>
</tr>
</tbody>
</table>

Numbers in parentheses exclude tidal freshwater and oligohaline sites.
Assessing estuarine benthic quality conditions in Chesapeake Bay: A comparison of three indices

A. Borja a,*, D.M. Dauer a, R. Díaz c, R.J. Llansó d, I. Muxika a, J.G. Rodriguez a, L. Schaffner c

a AZTI-Tecnalia, Marine Research Division, Herrera Koia, Portugalete s/n, 20100 Pasai, Spain
b Department of Biological Sciences, Old Dominion University, Norfolk, VA 23529, USA
c Department of Biological Sciences, School of Marine Science, Virginia Institute of Marine Science, The College of William and Mary, Gloucester Point, VA 23062, USA
d Versar Inc., 9200 Ramsey Road, Columbia, MD 21045, USA

<table>
<thead>
<tr>
<th></th>
<th>M-AMBI</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Meets goal</td>
<td>Marginal</td>
</tr>
<tr>
<td>B-IBI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meets Goal</td>
<td>63 (44)</td>
<td>14 (11)</td>
</tr>
<tr>
<td>Marginal</td>
<td>5 (5)</td>
<td>8 (8)</td>
</tr>
<tr>
<td>Degraded</td>
<td>31 (26)</td>
<td>17 (16)</td>
</tr>
<tr>
<td>Very degraded</td>
<td>7 (7)</td>
<td>10 (10)</td>
</tr>
<tr>
<td>Total</td>
<td>106 (82)</td>
<td>49 (45)</td>
</tr>
</tbody>
</table>

Numbers in parentheses exclude tidal freshwater and oligohaline sites.
Assessing estuarine benthic quality conditions in Chesapeake Bay: A comparison of three indices

Table 5 – Correlation coefficients between indices, environmental and structural parameters, by salinity zone

<table>
<thead>
<tr>
<th></th>
<th>Polyhaline (30)</th>
<th>High mesohaline (99)</th>
<th>Low mesohaline (102)</th>
<th>Oligohaline (26)</th>
<th>Tidal freshwater (18)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMBI-M-AMBI</td>
<td>-0.887</td>
<td>-0.897</td>
<td>-0.884</td>
<td>-0.513</td>
<td>-0.472</td>
</tr>
<tr>
<td>AMBI-B-IBI</td>
<td>-0.615</td>
<td>-0.617</td>
<td>-0.591</td>
<td>-0.413</td>
<td>-0.500</td>
</tr>
<tr>
<td>M-AMBI-B-IBI</td>
<td>0.743</td>
<td>0.744</td>
<td>0.851</td>
<td>0.255</td>
<td>0.441</td>
</tr>
<tr>
<td>AMBI-Depth</td>
<td>0.562</td>
<td>0.517</td>
<td>0.233</td>
<td>-0.522</td>
<td>-0.469</td>
</tr>
<tr>
<td>AMBI-Salinity</td>
<td>-0.217</td>
<td>-0.058</td>
<td>0.130</td>
<td>-0.060</td>
<td>-0.541</td>
</tr>
<tr>
<td>AMBI-Oxygen</td>
<td>-0.591</td>
<td>-0.462</td>
<td>-0.404</td>
<td>0.047</td>
<td>-0.345</td>
</tr>
<tr>
<td>AMBI-TOC</td>
<td>-0.108</td>
<td>0.482</td>
<td>0.388</td>
<td>0.113</td>
<td>-0.300</td>
</tr>
<tr>
<td>AMBI-Silt/Clay</td>
<td>-0.016</td>
<td>0.281</td>
<td>0.369</td>
<td>-0.025</td>
<td>-0.132</td>
</tr>
<tr>
<td>AMBI-Richness</td>
<td>0.634</td>
<td>0.714</td>
<td>-0.655</td>
<td>-0.084</td>
<td>-0.021</td>
</tr>
<tr>
<td>AMBI-Diversity</td>
<td>0.635</td>
<td>0.753</td>
<td>-0.759</td>
<td>-0.154</td>
<td>-0.151</td>
</tr>
<tr>
<td>M-AMBI-Depth</td>
<td>-0.316</td>
<td>-0.570</td>
<td>-0.449</td>
<td>0.294</td>
<td>-0.188</td>
</tr>
<tr>
<td>M-AMBI-Salinity</td>
<td>0.265</td>
<td>0.110</td>
<td>-0.244</td>
<td>0.232</td>
<td>0.161</td>
</tr>
<tr>
<td>M-AMBI-Oxygen</td>
<td>0.388</td>
<td>0.547</td>
<td>0.524</td>
<td>-0.142</td>
<td>0.611</td>
</tr>
<tr>
<td>M-AMBI-TOC</td>
<td>0.037</td>
<td>-0.594</td>
<td>-0.499</td>
<td>-0.353</td>
<td>-0.301</td>
</tr>
<tr>
<td>M-AMBI-Silt/Clay</td>
<td>-0.024</td>
<td>-0.445</td>
<td>-0.483</td>
<td>-0.337</td>
<td>-0.292</td>
</tr>
<tr>
<td>M-AMBI-Richness</td>
<td>0.836</td>
<td>0.922</td>
<td>0.881</td>
<td>0.837</td>
<td>0.850</td>
</tr>
<tr>
<td>M-AMBI-Diversity</td>
<td>0.831</td>
<td>0.931</td>
<td>0.918</td>
<td>0.863</td>
<td>0.884</td>
</tr>
<tr>
<td>B-IBI-Depth</td>
<td>-0.116</td>
<td>-0.557</td>
<td>-0.370</td>
<td>0.260</td>
<td>0.226</td>
</tr>
<tr>
<td>B-IBI-Salinity</td>
<td>0.571</td>
<td>-0.105</td>
<td>-0.290</td>
<td>-0.347</td>
<td>0.165</td>
</tr>
<tr>
<td>B-IBI-Oxygen</td>
<td>0.328</td>
<td>0.624</td>
<td>0.359</td>
<td>0.217</td>
<td>0.064</td>
</tr>
<tr>
<td>B-IBI-TOC</td>
<td>-0.218</td>
<td>-0.381</td>
<td>-0.219</td>
<td>-0.442</td>
<td>0.012</td>
</tr>
<tr>
<td>B-IBI-Silt/Clay</td>
<td>-0.242</td>
<td>-0.239</td>
<td>-0.240</td>
<td>-0.204</td>
<td>0.116</td>
</tr>
<tr>
<td>B-IBI-Richness</td>
<td>0.754</td>
<td>0.661</td>
<td>0.517</td>
<td>-0.084</td>
<td>0.240</td>
</tr>
<tr>
<td>B-IBI-Diversity</td>
<td>0.533</td>
<td>0.773</td>
<td>0.657</td>
<td>0.278</td>
<td>0.304</td>
</tr>
</tbody>
</table>

Bold and underlined numbers are significant at $p < 0.001$; underlined numbers are significant at $p < 0.01$. Number of sites in parentheses.