APPLICATION OF THE BENTHIC INDEX OF BIOTIC INTEGRITY TO ENVIRONMENTAL MONITORING IN CHESAPEAKE BAY

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Abstract: The Chesapeake Bay benthic index of biotic integrity (B-IBI) was developed to assess benthic community health and environmental quality in Chesapeake Bay. The B-IBI provides Chesapeake Bay monitoring programs with a uniform tool with which to characterize bay-wide benthic community condition and assess the health of the Bay. A probability-based design permits unbiased annual estimates of areal degradation within the Chesapeake Bay and its tributaries with quantifiable precision. However, of greatest interest to managers is the identification of problem areas most in need of restoration. Here we apply the B-IBI to benthic data collected in the Bay since 1994 to assess benthic community degradation by Chesapeake Bay Program segment and water depth. We used a new B-IBI classification system that improves the reliability of the estimates of degradation. Estimates were produced for 67 Chesapeake Bay Program segments. Greatest degradation was found in areas that are known to experience hypoxia or show toxic contamination, such as the mesohaline portion of the Potomac River, the Patapsco River, and the Maryland mainstem. Logistic regression models revealed increased probability of degraded benthos with depth for the lower Potomac River, Patapsco River, Nanticoke River, lower York River, and the Maryland mainstem. Our assessment of degradation by segment and water depth provided greater resolution of relative condition than previously available, and helped define the extent of degradation in Chesapeake Bay.

Keywords: biological indicators, benthic communities, degradation, Benthic Index of Biotic Integrity, Chesapeake Bay, low dissolved oxygen.

1. Introduction

The Chesapeake Bay benthic index of biotic integrity (B-IBI) was developed to assess benthic community health and environmental quality in Chesapeake Bay. The B-IBI evaluates the ecological condition of a sample by comparing values of key benthic community attributes to reference values expected under non-degraded conditions in similar habitat types. It is therefore a measure of deviation from reference conditions. This approach has been applied successfully to estuaries of the mid-Atlantic region and the southeastern United States (Weisberg *et al.*, 1997; Van Dolah *et al.*, 1999; Ranasinghe *et al.*, In Review). It was first applied to Chesapeake Bay in 1994. The application of the B-IBI to Chesapeake Bay has been possible through a partnership among the U.S. EPA Chesapeake Bay Program, the Maryland Department of Natural Resources, and the Virginia Department of Environmental Quality. Academic institutions and the private sector facilitate this partnership.

The B-IBI provides Chesapeake Bay monitoring programs with a uniform tool for characterizing bay-wide benthic community condition. A probability-based sampling design (stratified simple random) is used to estimate the areal extent of conditions in Chesapeake Bay. Annually, twenty-five samples are allocated randomly to each of ten strata. The benthic community condition for each sample is

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assessed, and an estimate for each strata and the Bay as a whole is produced (Llansó *et al.*, 2001). Any region within the tidal portion of the Chesapeake Bay has a known chance of being sampled. The deep (> 12 m) trough of the Maryland mainstem portion of the Bay, which was found to be mostly azoic in the first year of the monitoring program, is excluded from the sampling strata.

The probabilistic design provides an integrated assessment of the Bay's overall condition, and the condition of each stratum, i.e., each of the major western shore tributaries, the eastern shore tributaries as a group, and the Maryland and Virginia mainstems (see Dauer and Llansó, this issue). As bay-wide application of the B-IBI enters its sixth year, sufficient data become available to assess and identify more focused areas in need of restoration. Here we apply the B-IBI to data collected in the Chesapeake Bay since 1994 to assess benthic community degradation by Chesapeake Bay Program segment and water depth. Segments (TMWA, 1999) are Chesapeake Bay regions having similar salinity and hydrographic characteristics.

2. Methods

The Chesapeake Bay B-IBI is calculated by scoring each of several attributes of benthic community structure and function according to thresholds established from reference data distributions. The scores are then averaged across attributes (see Weisberg *et al.*, 1997). Sites with index values of 3 or more (on a 1 to 5 scale) are considered to have good benthic condition indicative of good habitat quality. Weisberg *et al.* (1997) fully validated the B-IBI by calculating classification efficiencies of sites of known sediment quality using independent datasets. Overall, the index correctly distinguished degraded sites from reference sites 93% of the time.

Recently, a series of statistical and simulation studies were conducted to evaluate and optimize the B-IBI (Alden *et al.*, 2002). New sets of metric/ threshold combinations for the tidal freshwater and oligohaline habitats were also developed in those studies with a larger dataset than was available to Weisberg *et al.* (1997) for these two habitats. The results of Alden *et al.* (2002) indicated that the B-IBI is sensitive, stable, robust, and statistically sound.

For the present analysis, we used 1,466 benthic grab samples (440 cm^2 surface area, 0.5-mm screen) from randomly selected sites (one sample per site). Samples were collected from 1994 to 2000 by the Maryland Benthic Monitoring Program and from 1996 to 2000 by the Virginia Benthic Monitoring Program. Samples were sorted, enumerated, and identified to the lowest possible taxon. Ash-free dry weight biomass was determined for each taxon. The B-IBI was calculated for each sample and benthic community condition was classified in two ways. One scheme, currently used by the Chesapeake Bay monitoring programs, classifies benthic community condition into four levels, with B-IBI scores of 3 or more as the breakpoint between degraded and non-degraded conditions (Llansó *et al.*, 2001;

Dauer and Llansó, this issue). Condition is classified as "meets goal" (non-degraded benthic communities with B-IBI ≥ 3.0), marginal (B-IBI = 2.7–2.9), degraded (B-IBI = 2.1–2.6) or severely degraded (B-IBI ≤ 2.0). We show classification of sites according to this convention, but follow habitat-specific recommendations by Alden *et al*. (2002) in the present assessment of benthic community degradation by Chesapeake Bay Program segment and water depth (see below). We used both classification schemes in order to evaluate the results of this study in the context of differences with current methodological applications.

Confidence limits for the B-IBI suggest that the classification system can be improved by distinguishing between degraded, non-degraded, and conditions of intermediate quality (Alden *et al*., 2002). These limits were established by analysis of the original reference and degraded index development datasets. Bootstrap simulations (Alden, 1992) were used to determine 90% confidence limits for reference and degraded index development samples for each of seven habitat types in Chesapeake Bay. Where there was no overlap, index values falling between the confidence limits of the two datasets were defined as of intermediate quality. For the tidal freshwater, oligohaline, and low mesohaline habitats, overlap in the confidence limits produced a class defined by uncertainty, rather than sediment quality, and was termed "indeterminate". According to these ranges (Table 1), samples were classified as either degraded, non-degraded, or of intermediate/indeterminate quality, and the proportion of samples in each of these 3 categories was determined for each of the segments established by the Chesapeake Bay Program. Thus, estimates of the probability of observing degraded or non-degraded benthos in any one segment were obtained by multiplying the proportions in these categories by 100.

A logistic regression model (Hosmer and Lemeshow, 2000) was used to describe the relationship between depth and the probability of degraded condition. This was done to examine within-segment, depth-related differences in condition that may result from exposure to hypoxia or other factors. The model has a binomial outcome that distinguishes between 'degraded condition' and 'otherwise', with depth as the independent variable. For logistic regression models that resulted in a significant fit, depth contours were linked to pre-determined probability ranges using the method of maximum likelihood. The estimated probability is thus a measure of the proportion of area that is degraded within contours.

Probability estimates and 67% and 90% confidence intervals (for low and high confidence) were adjusted for segments with ≥ 5 samples as suggested by Agresti and Caffo (2000). The adjusted intervals tend to perform better than the standard and exact confidence intervals, and cover the true proportion close to the intended α level even at small sample sizes. Exact confidence intervals based on the binomial distribution tend to be wider, and therefore have a higher likelihood of covering the true proportion than specified by the α level. For segments with < 5 samples, adjusted probabilities were calculated but exact confidence intervals were used.

Table 1. B-IBI ranges used to classify samples in 3 categories used in the assessment of benthic community degradation by Chesapeake Bay Program segment and water depth. Ranges are based on 90% confidence limits established by analysis of the original reference and degraded index development datasets.

	Category		
Habitat	*Degraded*	*Non-Degraded*	*Intermediate/Indeterminate*
Tidal Freshwater	< 2.5	> 3.5	2.5–3.5
Oligohaline	< 2.5	> 3.7	2.5–3.7
Low Mesohaline	< 3.0	> 3.4	3.0–3.4
High Mesohaline Sand	< 2.7	> 3.0	2.7–3.0
High Mesohaline Mud	< 2.2	> 2.5	2.2–2.5
Polyhaline Sand	< 1.8	> 3.7	1.8–3.7
Polyhaline Mud	< 2.3	> 3.0	2.3–3.0

3. Results

Figure 1 shows benthic community condition for each of the random samples. Condition has been classified according to the convention currently used by the Chesapeake Bay monitoring programs (see Methods). The figure clearly shows areas with a greater concentration of samples with degraded or severely degraded benthos (e.g., lower Potomac River, Maryland mainstem, Patapsco River), and areas with predominantly good benthos (e.g., Virginia mainstem).

Table 2 lists the probabilities of observing degraded benthos, non-degraded benthos, or benthos of intermediate condition (indeterminate for low salinity habitats) by Chesapeake Bay Program segment. Condition has been classified according to Table 1. Regions with degraded benthos occurring in more than half of the segment area (> 50% probability) were considered cause of concern, and are shown in red in Figure 2. Segments with predominantly good benthos (> 50% probability) are also shown in this figure. The confidence of the estimate is expressed by the intensity of the color. High color intensity indicates high confidence (the 90% confidence interval is within the 50–100% probability range). Low color intensity indicates low confidence (the 67% confidence interval is within the 50–100% probability range). Benthic community condition estimates for which the lower 67% confidence limit was ≤ 50% were categorized as "other".

Depth-related changes in the probability of observing degraded benthos were statistically significant at the 90% confidence level for five segments: Patapsco River (PATMH), Maryland mainstem (Segments CB2OH and CB3OH), Nanticoke River (NANMH), and lower York River (YRKPH). Other segments had significant relationships with depth but the intersect of the regression model was not significant. Figure 3 illustrates depth relationships for 4 segments. Although the intersect was not significant, we have included the Potomac River (Segment

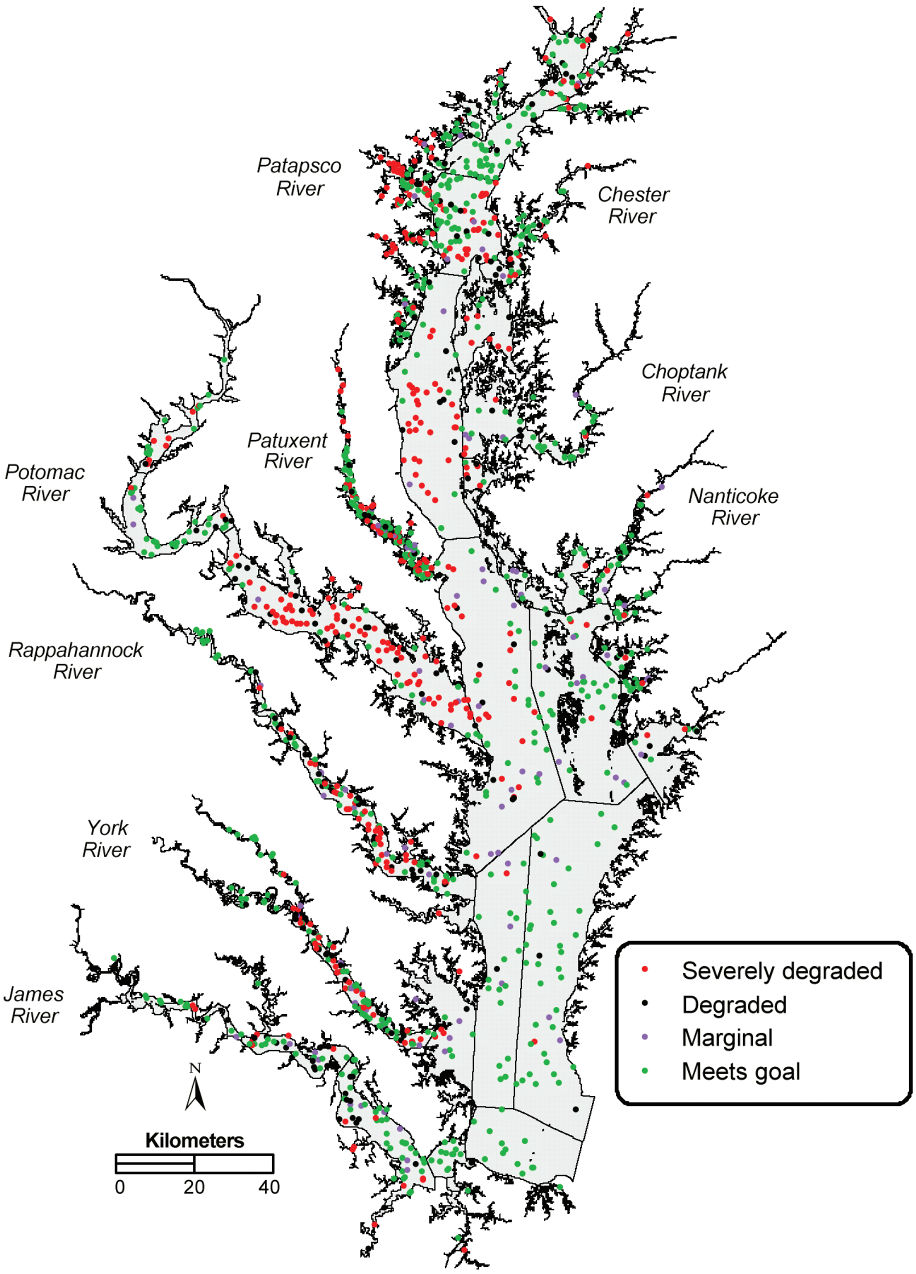

Figure 1. Benthic community condition for each of 1,466 samples collected 1994–2000 by the Maryland and Virginia benthic monitoring programs.

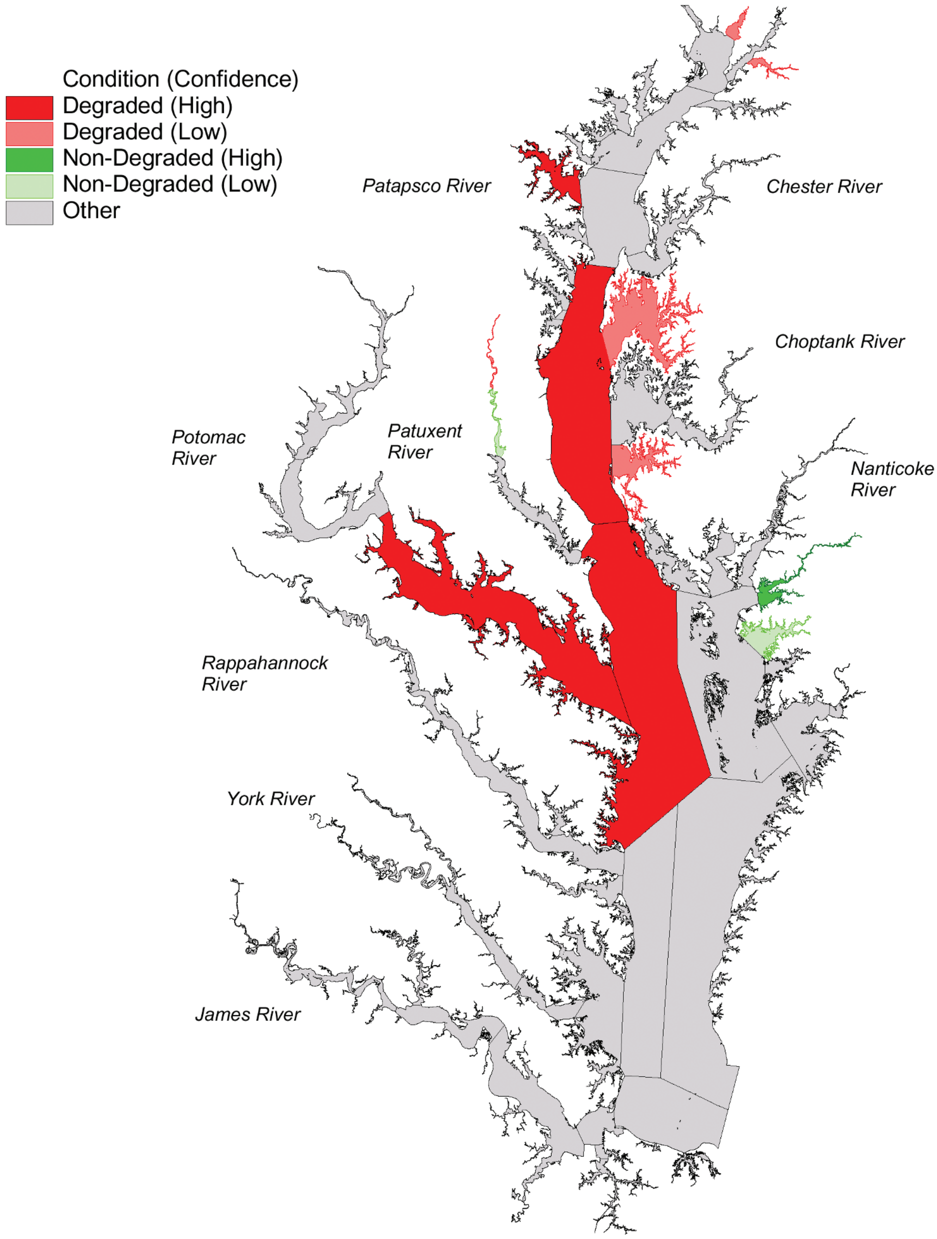

Figure 2. Chesapeake Bay Program segments with a >50% probability of observing degraded or non-degraded (good quality) benthos.

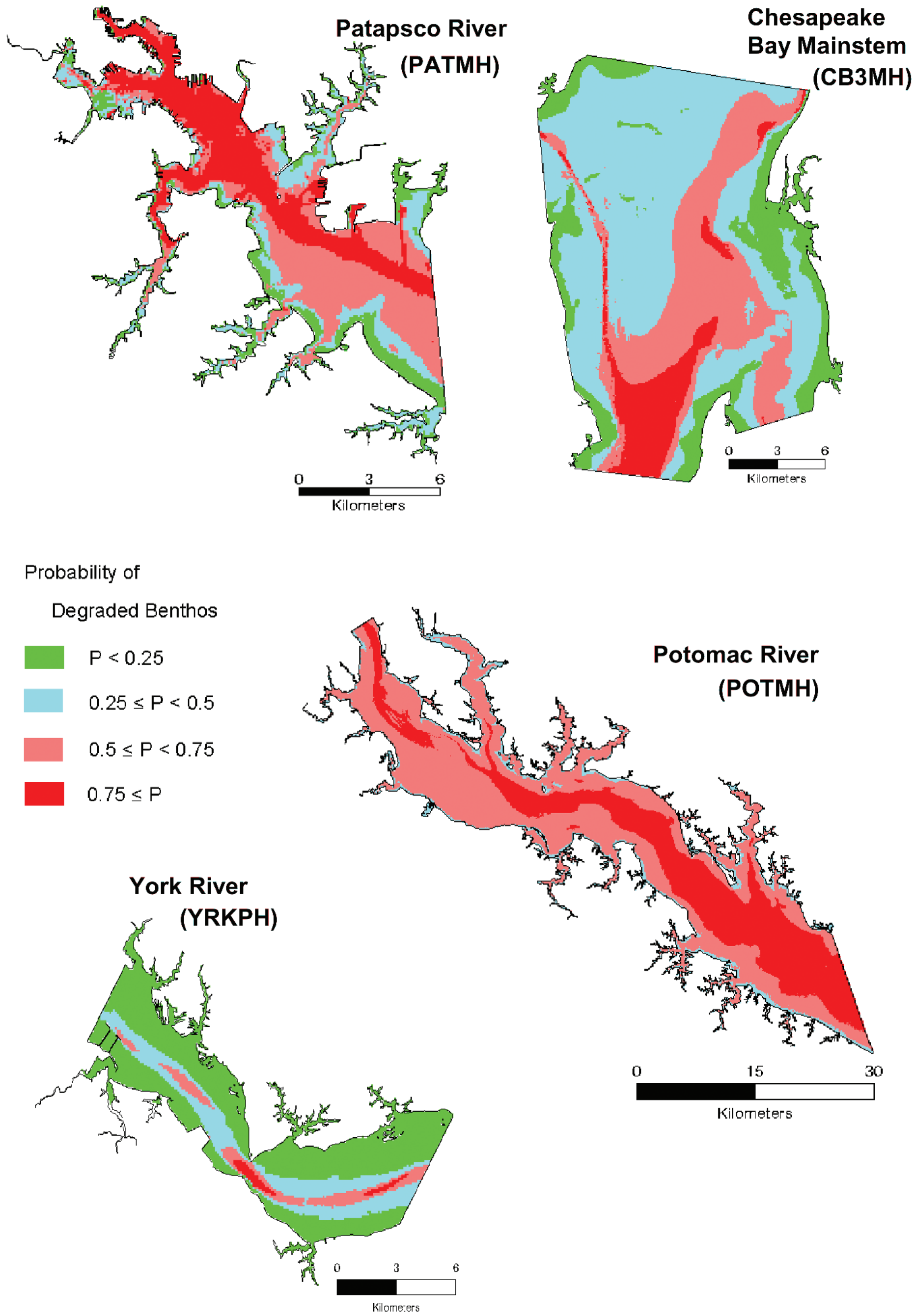

Figure 3. Depth-related changes in probability of observing degraded benthos for four segments for which regression models were statistically significant at the 90% confidence level.

Table 2. Probabilities (and SE) of observing degraded benthos, non-degraded benthos, or benthos of intermediate condition (indeterminate for low salinity habitats) for each of 67 Chesapeake Bay Program segments for which samples were collected by the Maryland and Virginia benthic monitoring programs, 1994–2000. Probabilities and standard errors were adjusted according to Agresti and Caffo (2000) for segments with ≥ 5 samples. Standard errors were used to calculate 67% (± SE) and 90% (± 1.65 x SE) confidence limits. Exact confidence limits were used for segments with < 5 samples, and are not shown in the table. Adjusted probabilities may not add to 100%. Segments codes: TF = tidal freshwater, OH = oligohaline, MH = mesohaline, PH = polyhaline. See TMWA (1999) for segment location.

Segment	*River/Water Body*	*No. of Sites*	*P Deg.*	*P Non-deg.*	*P Interm.*
BACOH	Back	9	61.5 (13.5)	23.1 (11.7)	30.8 (12.8)
BIGMH	Big Annemessex	14	16.7 (8.8)	44.4 (11.7)	50.0 (11.8)
BOHOH	Bohemia	2	66.7 —	33.3 —	33.3 —
BSHOH	Bush	10	35.7 (12.8)	21.4 (11.0)	57.1 (13.2)
CB1TF	Maryland mainstem	25	31.0 (8.6)	24.1 (7.9)	51.7 (9.3)
CB2OH	Maryland mainstem	44	20.8 (5.9)	35.4 (6.9)	47.9 (7.2)
CB3MH	Maryland mainstem	81	42.4 (5.4)	44.7 (5.4)	15.3 (3.9)
CB4MH	Maryland mainstem	49	76.6 (4.3)	11.1 (3.8)	14.8 (3.8)
CB5MH	Maryland mainstem	60	58.3 (4.7)	19.0 (4.1)	25.0 (4.5)
CB6PH	Virginia mainstem	22	11.5 (6.3)	42.3 (9.7)	53.8 (9.8)
CB7PH	Virginia mainstem	44	4.2 (2.9)	54.2 (7.2)	45.8 (7.2)
CB8PH	Virginia mainstem	12	12.5 (8.3)	37.5 (12.1)	62.5 (12.1)
CHKOH	Chickahominy	1	40.0 —	40.0 —	60.0 —
CHOMH1	Choptank	14	33.3 (11.1)	44.4 (11.7)	33.3 (11.1)
CHOMH2	Choptank	19	30.4 (9.6)	43.5 (10.3)	34.8 (9.9)
CHOOH	Choptank	8	16.7 (10.8)	33.3 (13.6)	66.7 (13.6)
CHSMH	Chester	38	45.2 (7.7)	33.3 (7.3)	26.2 (6.8)
CHSOH	Chester	4	50.0 —	37.5 —	37.5 —
CHSTF	Chester	1	60.0 —	40.0 —	40.0 —
CRRMH	Corrotoman	3	57.1 —	42.9 —	28.6 —
EASMH	Eastern Bay	12	68.8 (11.6)	25.0 (10.8)	18.8 (9.8)
ELKOH	Elk	10	28.6 (12.1)	28.6 (12.1)	57.1 (13.4)
FSBMH	Fishing Bay	7	36.4 (14.5)	45.5 (15.0)	36.4 (14.5)
GUNOH	Gunpowder	10	50.0 (13.4)	14.3 (9.4)	50.0 (13.4)
HNGMH	Honga	4	25.0 —	62.5 —	37.5 —
JMSMH	James	60	32.8 (5.9)	26.6 (5.5)	43.8 (6.2)
JMSOH	James	31	51.4 (8.4)	11.4 (5.4)	42.9 (8.4)
JMSPH	James	13	11.8 (7.8)	47.1 (12.1)	52.9 (12.1)
JMSTF	James	17	19.0 (8.6)	28.6 (9.9)	61.9 (10.6)
LAFMH	Lafayette	1	40.0 —	60.0 —	40.0 —

Table 2—Continued

Segment	*River/Water Body*	*No. of Sites*	*P Deg.*	*P Non-deg.*	*P Interm.*
LCHMH	Little Choptank	8	66.7 (13.6)	16.7 (10.8)	33.3 (13.6)
LYNPH	Lynnhaven Inlet	1	40.0 —	40.0 —	60.0 —
MAGMH	Magothy	17	57.1 (10.8)	28.6 (9.9)	23.8 (9.3)
MANMH	Manokin	12	25.0 (10.8)	62.5 (12.1)	25.0 (10.8)
MIDOH	Middle	12	18.8 (9.8)	12.5 (8.3)	81.3 (9.8)
MOBPH	Mobjack Bay	15	31.6 (10.7)	26.3 (10.1)	52.6 (11.5)
MPNOH	Mattaponi	7	27.3 (13.4)	54.5 (15.0)	36.4 (14.5)
MPNTF	Mattaponi	5	22.2 (13.9)	44.4 (16.6)	55.6 (16.6)
NANMH	Nanticoke	16	20.0 (8.9)	60.0 (11.0)	30.0 (10.2)
NANOH	Nanticoke	1	40.0 —	60.0 —	40.0 —
NANTF	Nanticoke	3	42.9 —	42.9 —	42.9 —
NORTF	Northeast	5	66.7 (15.7)	22.2 (13.9)	33.3 (15.7)
PATMH	Patapsco	56	61.7 (6.3)	21.7 (5.3)	20.0 (5.2)
PAXMH	Patuxent	134	37.0 (4.1)	42.8 (4.2)	21.7 (3.5)
PAXOH	Patuxent	14	27.8 (10.6)	66.7 (11.1)	16.7 (8.8)
PAXTF	Patuxent	3	71.4 —	28.6 —	28.6 —
PIAMH	Piankatank	1	60.0 —	40.0 —	40.0 —
PMKOH	Pamunkey	8	33.3 (13.6)	25.0 (12.5)	58.3 (14.2)
PMKTF	Pamunkey	3	28.6 —	42.9 —	57.1 —
POCMH	Pocomoke	9	30.8 (12.8)	38.5 (13.5)	46.2 (13.8)
POCOH	Pocomoke	1	60.0 —	40.0 —	40.0 —
POTMH	Potomac	124	72.7 (3.9)	9.4 (2.6)	19.5 (3.5)
POTOH	Potomac	37	24.4 (6.7)	34.1 (7.4)	46.3 (7.8)
POTTF	Potomac	19	43.5 (10.3)	17.4 (7.9)	47.8 (10.4)
RHDMH	Rhode	6	50.0 (15.8)	40.0 (15.5)	30.0 (14.5)
RPPMH	Rappahannock	106	49.1 (4.8)	23.6 (4.1)	29.1 (4.3)
RPPOH	Rappahannock	6	50.0 (15.8)	30.0 (14.5)	40.0 (15.5)
RPPTF	Rappahannock	10	14.3 (9.4)	50.0 (13.4)	50.0 (13.4)
SASOH	Sassafras	11	33.3 (12.2)	13.3 (8.8)	66.7 (12.2)
SBEMH	Elizabeth	2	50.0 —	50.0 —	33.3 —
SEVMH	Severn	13	52.9 (12.1)	29.4 (11.1)	29.4 (11.1)
SOUMH	South	11	33.3 (12.2)	46.7 (12.9)	33.3 (12.2)
TANMH	Tangier Sound	45	18.4 (5.5)	55.1 (7.1)	30.6 (6.6)
WICMH	Wicomico	13	17.6 (9.2)	76.5 (10.3)	17.6 (9.2)
WSTMH	West	7	36.4 (14.5)	45.5 (15.0)	36.4 (14.5)
YRKMH	York	69	41.1 (5.8)	23.3 (4.9)	38.4 (5.7)
YRKPH	York	31	28.6 (7.6)	31.4 (7.8)	45.7 (8.4)

POTMH) in Figure 3 because the regression was highly significant (p = 0.003) and a large proportion of samples in the main channel routinely fail the B-IBI. Contours are based on depth intervals in meters obtained from the regression model at four pre-determined probability ranges.

4. Discussion

Our B-IBI analysis shows greatest degradation in areas that are known to experience hypoxia. Hypoxia is most frequent and extensive in the mainstem of the Bay and the mesohaline Potomac River (Dauer *et al.*, 1992; Ranasinghe *et al.*, 1994; Dauer *et al.*, 2000). The Patapsco River also experiences hypoxia, but sediment contamination is a problem in this and other upper western shore tributaries (U.S. EPA, 1999; Dauer *et al.*, 2000; McGee *et al.*, 2001). Other western shore tributaries such as the Back and Severn Rivers also showed a > 50% probability of observing degraded benthos, but we had less than 67% confidence in the estimate.

Benthic community degradation clearly increased with water depth, principally in the mainstem of the Bay, and the Patapsco, Potomac, and York Rivers. Higher probabilities of observing degraded benthos with depth in these segments are associated with low dissolved oxygen conditions (Dauer *et al.*, 2000). Degradation in the upper portion of the Bay (Bohemia and Northeast Rivers) is probably associated with nutrient enrichment. Thirty percent of the sites sampled during 1996–2000 in the upper Bay by the Maryland long-term benthic monitoring program failed to meet the restoration goals due to excess abundance, excess biomass, or both (Llansó *et al.*, 2001). Excess abundance and biomass are phenomena usually associated with eutrophic conditions (Pearson and Rosenberg, 1978). Benthic community condition was best in two eastern shore tributaries (the Manokin and Wicomico Rivers) and in the oligohaline portion of the Patuxent River.

The application of the B-IBI to Chesapeake Bay provides an objective method for distinguishing degraded from non-degraded benthic communities bay-wide. The B-IBI provides context for evaluating the effectiveness of Bay management activities and a well-defined endpoint for restoration activities. Currently, Chesapeake Bay benthic monitoring programs use a B-IBI score of 3 as a quantitative benchmark against which to measure the health of benthos. While there are certain advantages to using a system for which samples are classified as meeting or not meeting the restoration goals, the identification of samples that are of intermediate quality improves the resolution of the interpretation of relative condition (Alden *et al.*, 2002). The classification approach of Alden *et al.* (2002) also has the advantage of using confidence limits to classify B-IBI scores. The use of confidence limits to define the relative condition of the benthos (both at the B-IBI classification stage and in estimating segment-wide degradation) should produce more reliable results with fewer Type I errors (false alarms). On the other hand, if one quantitative benchmark is desirable to better track progress toward restoration, emphasizing the "severely degraded" category of current monitoring programs may be more informative than using a "meets goal" approach, and may add further resolution in the evaluation of patterns of degradation (Dauer and Llansó, this issue).

The B-IBI threshold for the "severely degraded" condition of current monitoring programs is, for most habitats in Chesapeake Bay, very close to the cut-off level used to define degraded conditions in the present study. Thus, Chesapeake Bay areas with high concentration of samples with severely degraded benthos (lower Potomac River, Maryland mainstem, Patapsco River, Figure 1) were identified as areas of concern in this analysis (Figure 2). However, the likelihood of observing benthos of intermediate quality was high for some areas that usually meet the restoration goals, indicating that a sizable portion of the samples in those areas had B-IBI values falling below best reference conditions. For example, the Virginia mainstem shows the least amount of degradation (Figure 1), but our analysis suggests that this region may benefit from further improvements in water quality. In deciding what approach to use, consensus among Chesapeake Bay partners must first be built if widespread applicability of the method is warranted.

One limitation of our analysis is small segment size. As more years of data are added, the temporal variability component of the estimate increases. Probability estimates are also average values for Bay segments and do not reflect local variation in benthic community condition. However, with sufficient sample size the condition of larger segments can be assessed with relatively high confidence, and further resolution with depth may help define the extent of degradation. For example, by comparing segments in Figure 3, the more extensive degradation affecting shallow waters in the Potomac River becomes evident. Regardless of the approach used to estimate benthic community degradation, our assessment agrees well with results of previous characterizations (e.g., Dauer *et al.*, 2000) which suggest dissolved oxygen stress as the more serious and widespread problem affecting benthic communities in the Bay. Our assessment of degradation by segment and water depth provides a greater resolution of relative condition than previously available. The study illustrates one application of the Chesapeake Bay index of biotic integrity that may be useful to management in their effort to identify areas most in need of restoration. Similar applications to other estuaries with other indices of benthic condition may be comparably useful.

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