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Development and evaluation of a spatially-explicit index of Chesapeake Bay health

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ABSTRACT

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-IBI and B-IBI, 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, higher phytoplankton and benthic indices relative to ecological health-based thresholds, and more extensive SAV area relative to restoration goal areas, characterized the least-impaired regions. The WQI, P-IBI and BHI were significantly correlated with (1) regional river flow ($r = -0.64$, -0.57 and -0.49, respectively; $p < 0.01$), (2) nitrogen (N), phosphorus (P) and sediment loads (all positively correlated with flow), and (3) the sum of developed and agricultural land use (highest annual $r^2 = 0.86$, 0.71 and 0.68, respectively) in most reporting regions, indicating that the BHI is strongly regulated by nutrient and sediment loads from these land uses. The BHI uses ecological health-based thresholds that give an accurate representation of the health conditions in Chesapeake Bay and was the basis for an annual, publicly released environmental report card that debuted in 2007.

1. Introduction

Increasing nutrient inputs to receiving waters have been associated with rising human population densities, changes in land use, and the intensification of agricultural practices in watersheds (Cole et al., 1993; Howarth et al., 1996; Galloway, 1998; Boyer et al., 2002). Problems associated with water quality degradation are increasingly a threat to aquatic systems worldwide, particularly in estuaries (Valiela et al., 1997; Howarth et al., 2000). For example, nutrient enrichment from urban wastewater and agricultural runoff is responsible for excessive phytoplankton production, the decline of submerged aquatic vegetation, increasing abundance of nuisance algae blooms, and the increasing extent and duration of hypoxic and anoxic waters in many areas of the United States (Turner and Rabalias, 1991; Vitousek et al., 1997; Bricker et al., 2007), including Chesapeake Bay (Boesch et al., 2001; Fisher et al., 2006).

Multimetric indices are important resource and ecosystem management tools that can give a robust indication of ecosystem status. Ecosystem indices include those dealing with benthic macroinvertebrates (Weisberg et al., 1997; Engle and Summers, 1999; Borja et al., 2000; Borja et al., 2007), stream macroinvertebrates and fish (Barbour et al., 1992; Kerans and Karr, 1994; Hughes et al., 1998), phytoplankton (Buchanan et al., 2005; Lacouture et al., 2006) and submerged aquatic vegetation (Dennison et al., 1993). Different metrics can be combined to create health status indices and assessments, and this has been done in several coastal ecosystems in order to document the effects and extent of eutrophication (Jordan and Vaas, 2000; Pantus and Dennison, 2005; Ecosystem Health Monitoring Program, 2007; Borja et al., 2004; Borja and Dauer, 2008; Dennison et al., 2009).

In this paper, we describe the development and evaluation of a spatially-explicit Chesapeake Bay Health Index, or BHI. Components of the BHI are derived from chlorophyll-a and dissolved oxygen concentrations, Secchi depth, a phytoplankton and a benthic macroinvertebate index of biotic integrity (P-IBI and B-IBI, respectively), and the area of submerged aquatic vegetation (SAV). Data

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collected by Chesapeake Bay Program (CBP) monitoring programs during 1985–2007 (23 years) were the basis for developing the BHI. All of the metrics used in the BHI are well characterized and exhibit strong responses to eutrophication in the Chesapeake Bay (Fisher et al., 2006; Bricker et al., 2007). Thresholds used in the BHI are rooted in the concept of ecosystem health and used to quantify the status of each metric relative to water quality and biotic conditions. The least-impaired, or most desirable, habitat conditions have low chlorophyll-a concentrations, high dissolved oxygen (DO) concentrations, deep Secchi depths, high IBI values relative to ecological health-based thresholds and large SAV areas relative to historical distributions.

The BHI is intended for use as a spatially-explicit (i.e., to compare amongst various reporting regions) management tool to evaluate the status of water quality and biotic conditions that are strongly affected by nutrient and sediment loadings. Although two multimetric indices (P-IBI and B-IBI) used in this overarching index (BHI) are described in detail elsewhere (Weisberg et al., 1997; Lacouture et al., 2006), the Water Quality Index (WQI) and BHI are novel ecosystem health assessment indices. Hence, the objectives of this paper are to describe the methodological development and application of these indices and evaluate their robustness by determining their (1) sensitivity to variable flow regimes, (2) relationships with the proportion of developed and agricultural land use and (3) ranking among reporting regions.

2. Study site

The Chesapeake Bay watershed drains a 172,000 km^2 area and the Bay itself is 11,666 km^2, the largest estuary in the United States (Fig. 1). Estimates of land cover in the watersheds of each reporting region were determined by the Chesapeake Bay Program (H. Weinberg, University of Maryland) from a 30 m $\times$ 30 m grid based on Landsat 7 ETM + imagery. Land cover in 2001 within the entire Chesapeake Bay watershed was 59% forest, 28% agricultural, 9% urban, 4% open water and wetlands, and <1% barren areas. Nutrient inputs are from a variety of sources, including urban and agricultural runoff, industrial wastes, and the effluent from wastewater treatment facilities. Although nitrogen (N) inputs from sewage effluent increased between 1963 and 1989, the removal of phosphorus (P) from effluent, due to the ban on detergent P in 1986 and by managed P removal, has reduced P concentrations in effluent (Magnien et al., 1992). Similarly, application of BNR technology (biological N reduction, which employs successive oxic and anoxic conditions to induce denitrification) has significantly reduced summer N concentrations in effluent in some tributaries, such as the Patuxent River (Boynton et al., 1995). However, with population density expected to substantially increase in the watershed over the next decade (2007 Chesapeake Bay Health and Restoration Assessment, www.chesapeakebay.net/status_population.aspx?menuitem=19794), increasing wastewater volume and high winter N concentrations

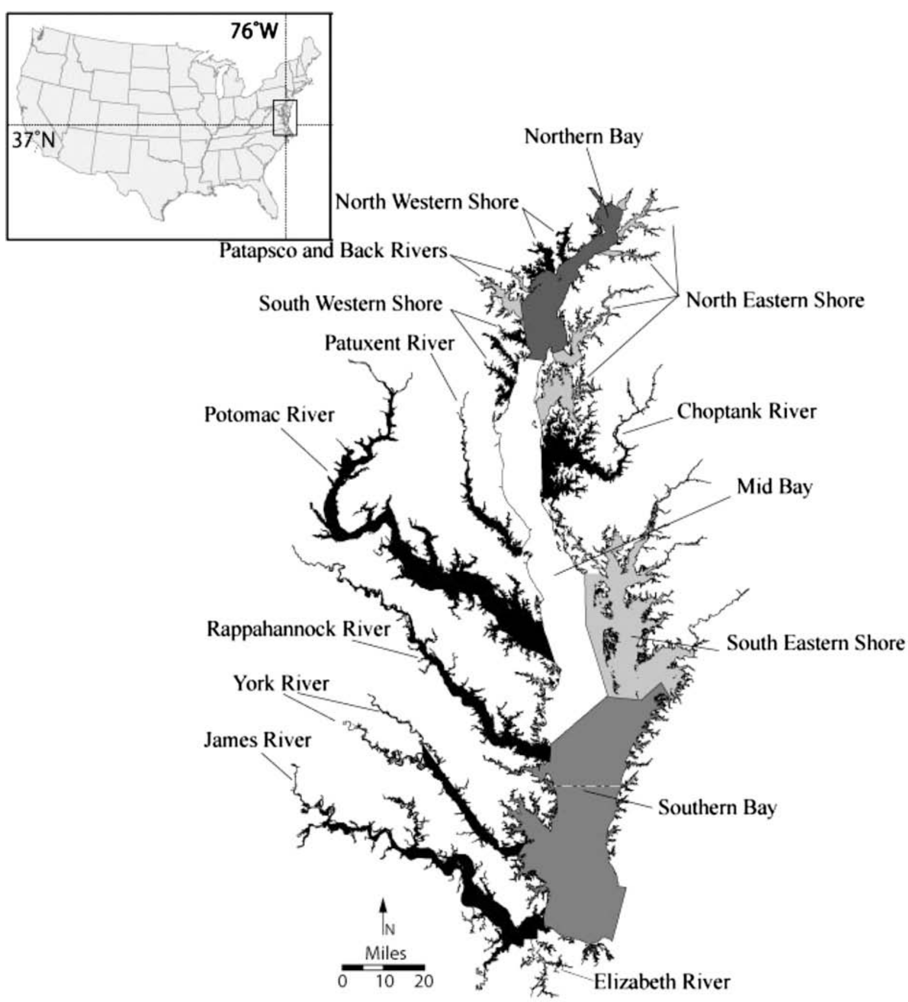

Fig. 1. Location of the Chesapeake Bay on the eastern seaboard of the continental USA. Reporting regions used in this analysis are identified.

are likely to load the estuary with even more N and P unless dramatic increases in the implementation and effectiveness of best management practices (BMPs) occur.

3. Methods

3.1. Data collection

While the Bay is currently divided into 78 segments for monitoring and management purposes (www.chesapeakebay.net), these were grouped into 15 larger reporting regions in order to simplify regional comparisons (Table 1, Fig. 1). Four metrics (chlorophyll-a, DO, Secchi depth, and SAV) and two indices (P-IBI and B-IBI) with sufficient spatial and temporal coverage were used in the BHI.

Chlorophyll-a, DO and Secchi depth data were combined into a Water Quality Index (WQI). Data for these metrics were collected monthly or bi-monthly (12 to 20 samples annually) for the Maryland and Virginia Chesapeake Bay Program (CBP) monitoring programs at 152 fixed sites (mid-channel, open water) between 1985 and 2007 (Fig. 2). Chlorophyll-a data were from surface samples ($z = 0.5$ m); dissolved oxygen data were from the entire water column at 1 m intervals (US Environmental Protection Agency, 2008). Spring, summer and early fall (March–November) data were used in the analysis and the specific period of interest varied by index or metric (Table 2).

The remaining indices and SAV were combined into a Biotic Index (BI). Phytoplankton samples were collected for the CBP monitoring programs at 27 sites, usually synoptically with the water quality data, and the March–May and July–September data were used to calculate the P-IBI. Collection and analysis protocols for the three water quality metrics and P-IBI are described online at www.chesapeakebay.net (US Environmental Protection Agency, 2008). Benthic macroinvertebrate samples were collected between July 15 and September 30 at 250 stratified random sampling stations (in 2007), and detailed information on the B-IBI can be obtained from the Benthic Monitoring Programs website (www.baybenthos.versar.com/) or in Llansó et al. (2005). Annual measurements by the Virginia Institute of Marine Sciences (VIMS) of the extent of submerged aquatic vegetation were used to calculate the SAV metric. Submersed aquatic vegetation data were collected throughout the late summer and early fall which offer the best visibility of SAV beds during overflights. The source data sets and related data documentation files are located at www.chesapeakebay.net and www.vims.edu/bio/sav.

4. Metric selection

There are a large number of possible metrics that can be included in an ecosystem health index for Chesapeake Bay. For the purposes of the BHI, metrics and biotic indices were used because they had (1) bay-wide coverage that allowed us to discriminate among various reporting regions and (2) defined ecological health-based thresholds that allowed us to discriminate between unimpaired and impaired areas. Thus, for example, although there are metrics of chemical contaminants (e.g., polychlorinated biphenyls – PCBs) and higher trophic level species (e.g., menhanden and blue crabs), these do not currently have the spatial coverage that allowed us to use them in the BHI. Furthermore, nutrient concentration metrics (i.e., N and P), do not currently have viable and defensible ecological health-based thresholds applicable to this system. However, the BHI was designed to allow such metrics to eventually be incorporated when they have both adequate spatial coverage and meaningful ecological health-based thresholds.

The Chesapeake Bay is listed by the US Environmental Protection Agency (2003) as a water body largely impaired by excess nutrient inputs of N and P, as well as high sediment loads that cause poor water clarity. Consequently, all metrics included in the BHI are influenced by nutrient and sediment inputs and were evaluated for their ability to discriminate between unimpaired and impaired conditions and variable flow regimes (i.e., the 2002 and 2003 water years that approximate the extremes of low and high river flow to the Chesapeake Bay, respectively).

The ecological health-based thresholds used to evaluate the BHI metrics and indices have clear associations with conditions that meet the concept of ecosystem health, and can discriminate between degraded and desirable habitat conditions. Consistent achievement of the chlorophyll-a, DO, and Secchi thresholds ensures water quality conditions that are protective of living resources in Chesapeake Bay and its tidal tributaries. The thresholds are listed in Table 2, and their derivations are described in more detail in US Environmental Protection Agency (2003a,b), Lacouture et al. (2006), and Buchanan et al. (2005). The multi-metric P-IBI and B-IBI, and the SAV metric are the three remaining components of the BHI. They represent important ecological groups in Chesapeake Bay that have an adequate level of sampling

Table 1
Reporting regions, bay surface area, the proportion of each reporting region's area to the total bay area, and the total number of stations for the indices used in the analysis. Total population, watershed area, and the percentage of developed (Dev) and combined Dev and Agr (agricultural) land use in the watershed(s) of each reporting region. Submerged aquatic vegetation (SAV) restoration goals are not applicable to the Elizabeth since this is a designated no-grow-zone (NGZ).

Reporting regions	Bay surface area (km^2)	Percent of total reporting area	No. of water quality stations	No. of phyto-plankton stations	No. of benthic stations (2007)	Population (2000)	Watershed area (km^2)	Dev (%)	Dev + Agr (%)	SAV restoration goal (ha)
Choptank R.	430	3.7	4	2	9	82,140	4186	2.3	43.9	5647
Elizabeth R.	47	0.4	16	1	1	594,760	1075	38.8	55.8	NGZ
James R.	640	5.5	13	3	24	2,522,583	43,501	4.5	21.6	1064
Mid Bay	2383	20.4	17	2	13		216,914	3.5	35.4	7461
N East Shore	474	4.1	8	1	12	147,572	5374	2.6	52.1	5207
N West Shore	88	0.8	4	0	9	421,297	2856	8	50.8	1482
Northern Bay	788	6.8	8	2	25	3,399,766	114,613	2.2	31.5	6061
Patapsco R.	110	0.9	2	1	6	1,496,330	2835	27.9	61.5	157
Patuxent R.	126	1.1	10	3	25	590,769	3991	10.7	44.9	791
Potomac R.	1268	10.9	13	3	25	5,243,322	61,209	4.8	36.5	8581
Rappahannock	403	3.5	12	3	25	240,754	11,864	1.8	32.8	1025
S East Shore	1482	12.7	11	0	18	467,542	21,049	2.1	40.7	23,331
S West Shore	100	0.9	5	1	10	224,464	797	18.8	35.1	733
Southern Bay	3019	25.9	21	4	23		276,830	3.6	32.1	14,517
York R.	211	1.8	8	3	25	372,488	13,635	2.3	23.1	1337
Chesapeake	11,569	99.4	152	29	250	15,803,787	276,830	3.6	32.1	77,392

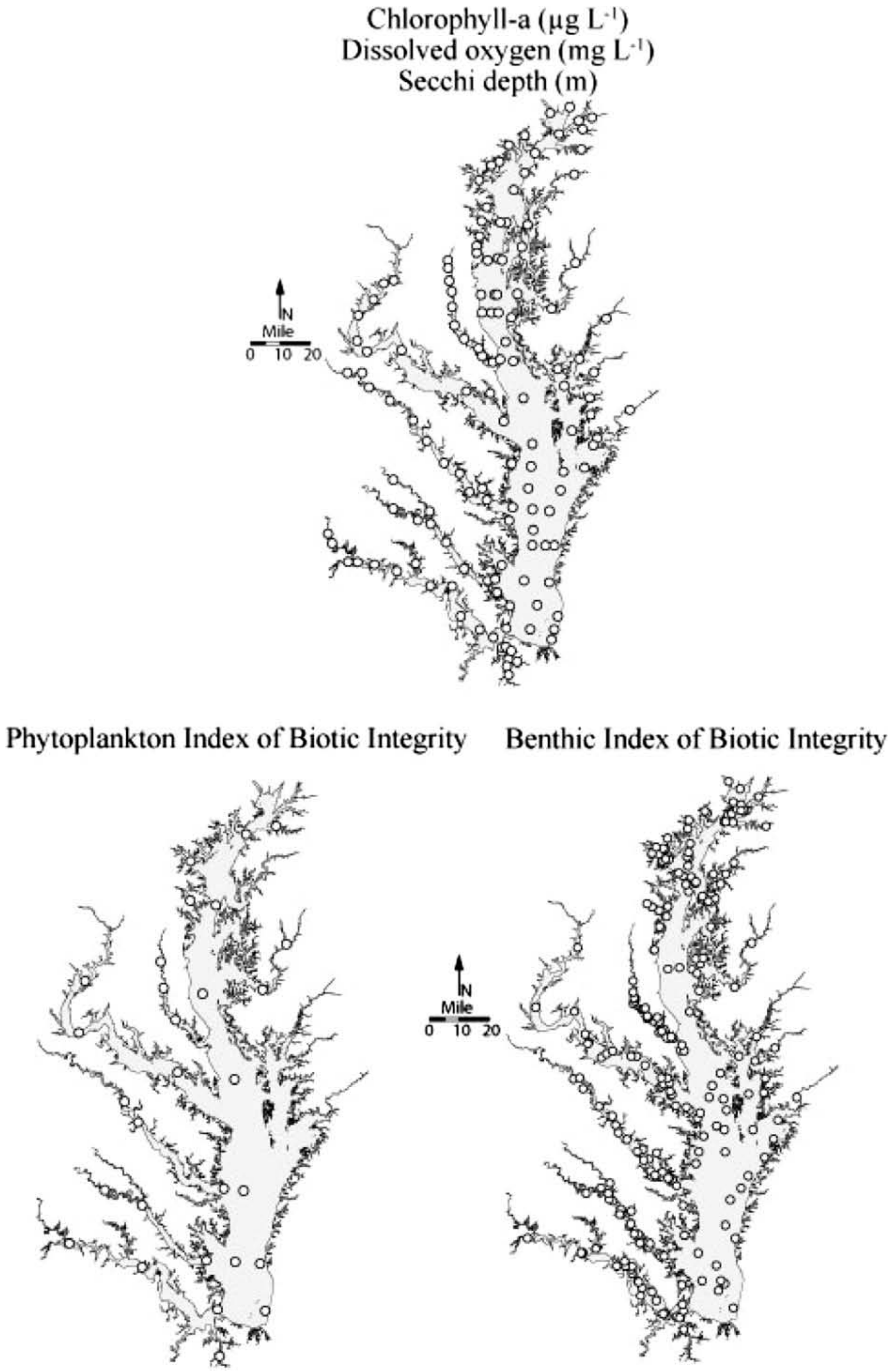

Fig. 2. Locations of fixed, mid-channel sampling stations used for the collection of water quality data (i.e., chlorophyll-a, dissolved oxygen, and Secchi depth,), Benthic Monitoring Program probability-based stations (Benthic Index of Biotic Integrity, B-IBI; example from 2006), and phytoplankton monitoring survey stations (Phytoplankton Index of Biotic Integrity, P-IBI). P-IBI sampling stations for the South Western Shore and North Eastern Shore were added in 2007.

in most or all reporting regions and allow us to conduct a spatially-explicit analysis. The selection process for the metrics used in the P-IBI is described in detail in Lacouture et al. (2006); for the B-IBI, refer to Weisberg et al. (1997), Alden et al. (2002) and Llansó (2008). Both of the indices are on a scale of 1–5, with 3 considered to be the lower boundary of the distribution of index values found in naturally occurring "reference" communities. Measurements of SAV coverage are compared to segment-specific historical coverages, which are considered representative of a healthy Chesapeake Bay and have been adopted as CBP restoration goals (US Environmental Protection Agency, 2004). Annual SAV results are expressed as segment-specific percentages of the restoration goals.

4.1. Metric scoring procedure

All the metrics and indices in the BHI, excluding SAV, were scored by calculating the proportion of observations meeting or exceeding a specific threshold (Table 2) or index value (3) within a Bay segment. For SAV, the score was the SAV coverage in each segment as a percent of its restoration goal coverage. This proce-

Table 2
Thresholds used for each metric of the Water Quality Index (WQI). Metrics are labeled as: "Chl-a" for chlorophyll-a, "Secchi" for Secchi depth, and "DO" for dissolved oxygen. Designated uses are defined as: open water = above pycnocline, deep water = between top and bottom of pycnocline, and deep channel = below pycnocline.

Chl-a salinity regime	Chl-a season	Chl-a reference community thresholds (μg L^{-1})[a]	Secchi salinity regime	Secchi season	Secchi relative status thresholds (m)[b]	DO designated use	DO season	DO criteria thresholds (mg L^{-1})[c]
Tidal fresh	March-mid June	⩽13.98	Tidal Fresh	April October	⩾0.85	Open Water	June September	⩾5.0
Oligohaline	March-mid June	⩽20.93	Oligohaline	April October	⩾0.65	Deep Water	June September	⩾3.0
Mesohaline	March-mid June	⩽6.17	Mesohaline	April October	⩾1.63	Deep Channel	June September	⩾1.0
Polyhaline	March-mid June	⩽2.80	Polyhaline	March November	⩾2.0			
Tidal Fresh	mid June – September	⩽12.00						
Oligohaline	mid June – September	⩽9.47						
Mesohaline	mid June – September	⩽7.70						
Polyhaline	mid June – September	⩽4.52						

[a] Lacouture et al. (2006).
[b] Buchanan et al. (2005).
[c] US Environmental Protection Agency (2003a).

dure puts the scores for each BHI component on a common scale of 0% (impaired) to 100% (unimpaired), where higher index values represent more ecologically robust conditions. The resulting percentages for the six components were weighted by segment area and then summed to obtain results for each reporting region. The chlorophyll-a, DO, and Secchi depth percentages were averaged to obtain the WQI; the P-IBI, B-IBI, and SAV percentages averaged to obtain the BI; and the WQI and BI were averaged to obtain the BHI (details below).

4.2. Water Quality Index

The established growing season or the season of interest varied by metric: (a) chlorophyll-a was March 1 – September 30, (b) dissolved oxygen was June 1 – September 30, and (c) Secchi depth was April 1 – October 31 in the tidal fresh (TF), oligohaline (OH) and mesohaline (MH) zones and March 1 – November 30 in the polyhaline (PH) zone. Salinity zones in Chesapeake Bay are commonly represented by the following PSU values: TF (⩽0.5), OH (>0.5–5.0), MH (>5.0–18), and PH (>18.0).

To calculate the WQI, data of chlorophyll-a, DO and Secchi depth over the appropriate growing season indicated above were downloaded from the Chesapeake Bay Information Management System (CIMS) data hub (www.chesapeakebay.net). Subsequently, the frequency that each parameter at each sampling station met or exceeded their threshold values (i.e., ratio of n samples that pass threshold to the total number of samples collected; Table 2) was calculated as indicated below.

The available surface chlorophyll-a data collected each year over the period from March – September at each fixed station of the Bay were compared to the appropriate season- and salinity-specific threshold (Table 2). Those samples with chlorophyll-a concentrations lower than the threshold concentrations passed, whereas those with higher concentrations failed, and the frequency of passing scores over the growing season was applied to that station.

Dissolved oxygen concentration data at 1 m depth intervals from June – September were first categorized as "open water," "deep water," or "deep channel" designated uses as defined by the US Environmental Protection Agency (2003b) and then compared to the threshold concentration applicable to the designated use (Table 2). DO concentrations higher than the applicable threshold passed whereas those with lower concentrations failed. The frequency of passing scores in each designated use was weighted by the proportion of samples collected in that designated use at that station. The weighted percentages for each designated use were then summed to obtain the station frequency of passing dissolved oxygen measurements.

Secchi depth data from April to October (TF, OH and MH zones) and March–November (PH zone) at each fixed station were compared to the applicable Secchi depth threshold (Table 2). Sampling events with Secchi depths deeper than the applicable threshold passed, whereas those with shallower depths (i.e., more turbid) failed. The frequency of passing Secchi depths over the growing season was applied to that station.

An annual WQI was generated for each station by averaging the frequencies of passing scores for the three water quality metrics. Next, all the station WQIs within a segment were averaged. Then, segment WQIs within a reporting region were weighted by the areal proportion of each segment relative to the reporting region and summed to obtain a WQI for the reporting region.

4.3. Biotic index

The BI combined the frequencies of passing scores for submerged aquatic grasses (SAV), the Benthic Index of Biotic Integrity (B-IBI) and the Phytoplankton Index of Biotic Integrity (P-IBI). Similar to the WQI, a BI was calculated for each segment by averaging the passing frequencies of the three components. BIs for the several segments in a reporting region were weighted by each segment's areal proportion of the reporting region and summed to obtain a BI for the reporting region.

Estimates of SAV cover for each CBP segment were obtained from the annual aerial surveys of SAV done by the VIMS (Orth et al., 2005; www.vims.edu/bio/sav/). SAV restoration goals have been developed for most of the Bay segments, and were published in a Technical Support Document (US Environmental Protection Agency, 2004, www.chesapeakebay.net/content/publications/cbp_13270.pdf). However, restoration goals adopted by VA and MD differ slightly from those published in this document, so the acreages used in this analysis were updated (refer to Maryland Department of the Environment document COMAR26.08.02.03-3WQ_Criteria_052405.pdf and Virginia Department of Environmental Quality document 9 VAC 25-260, August 2005). The restoration goal for each reporting region was determined by summing the restoration goals of all segments located within the reporting region (Table 1).

To obtain the SAV passing frequency for a reporting region, the sum of SAV acreages observed in all the segments of a reporting region was divided by the sum of all SAV restoration goal acreages for the region. In cases where an existing SAV acreage exceeded the restoration goal acreage, that segment's SAV acreage was reduced to equal the restoration goal acreage. Although this occurred in only 15% of all segments used in this analysis, doing so prevented artificially inflating SAV passing frequencies for some reporting regions.

The Chesapeake Bay B-IBI was developed to assess benthic community health and environmental quality. 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. The B-IBI is therefore a measure of deviation from reference conditions. The B-IBI is calculated by scoring each of several attributes of benthic community structure and function (abundance, biomass, Shannon diversity, etc.) according to thresholds established from reference data distributions. The scores (on a 1 to 5 scale) are then averaged across attributes to calculate an index value. Samples with index values of $\geqslant 3.0$ are considered to have good benthic condition and are indicative of good habitat quality.

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

The CBP benthic monitoring program contains two elements: a fixed station monitoring effort designed to identify temporal trends and a probability-based sampling effort intended to assess the areal extent of degraded benthic community conditions (Fig. 2). Only probability-based samples are used in this assessment.

Development of the multi-metric Phytoplankton Index of Biotic Integrity (P-IBI) for Chesapeake Bay is described in Lacouture et al. (2006). Typically, only one phytoplankton monitoring station is located in a segment. Each station is assumed to represent the segment in which it is located because each segment has a characteristic salinity and hydrography. Not all segments have a monitoring station, so it was also assumed that the total area of segments with biomonitoring stations (8364 km^2) is representative of the total area of Bay tidal waters (11,666 km^2). P-IBI scores are calculated for each station-date sampling event during a six-month index period: March, April, and May (spring) and July, August, and September (summer). The highest P-IBI scores are associated with desirable water quality conditions that are not impaired by excess dissolved inorganic nitrogen (DIN), excess ortho-phosphate (PO_4), or inadequate (stressful) light levels for phytoplankton photosynthesis (Lacouture et al., 2006).

Individual P-IBI scores are evaluated against a threshold criterion of 3.0 on a scale of 1.0–5.0. Scores $\geqslant 3.0$ pass; scores <3.0 fail. The annual frequency of passing scores in each CBP segment is weighted by the segment's areal proportion of the reporting region in which it is located. Area-weighted frequencies are then summed to obtain an overall frequency of passing P-IBI scores in each reporting region.

4.4. Bay Health Index

The water quality and biotic indices, both expressed as the average of the percent attainment of their component metrics and biotic indices, were averaged to obtain the BHI. We used a simple averaging technique for the WQI and BI that assumes these indices are of equal weight in representing ecosystem health based on the rationale that there is no manner in which a weighting scheme can be objectively determined and therefore justified. Although the three metrics in each of the water quality and biotic indices are equally weighted in their current configuration, new metrics eventually incorporated into these indices could create an unequal weighting scheme amongst the individual metrics. For example, if nitrogen were added to the WQI, then there would be a total of four metrics and each of these would account for 25% of the total WQI value, in contrast to a total of three metrics and sub-indices that each would account for 33% of the total BI value.

The BHI of each reporting region (Table 1) was graded according to the following equally divided ranges: 0–20% (grade = F), 21–40% (grade = D), 41–60% (grade = C), 61–80% (grade = B), 81–100% (grade = A). Positive and negative qualifiers (i.e., + and −) were used to designate the upper and lower quartiles of each category. Grades similar to those commonly used in academic report cards were chosen because they serve as a communication tool that has broad appeal to and can be easily understood by the general public.

5. Sensitivity to extreme flow regimes

The low- and high-flow periods of 2002 and 2003 were years of relatively good and poor water quality in Chesapeake Bay, respectively. Moreover, these years approximate the extremes of low and high nutrient loads and flows to the Bay over the period of record by the USGS (va.water.usgs.gov/chesbay/RIMP/). The calendar year of 2002 approximated the $81(10)^6$ and $5.8(10)^6$ kg restoration loading goals of N and P (www.chesapeakebay.net/caploads.htm), respectively, whereas the 2003 loads were roughly 3 and 8 times larger, respectively, than these goals. The WQI and BI components in 2002 and 2003 were compared to test and ensure that there were distinct differences between 2002 and 2003.

5.1. Relationships of index values and land use

Important drivers responsible for nutrient and sediment loading include developed and agricultural land use in the Chesapeake Bay watershed (Officer et al., 1984; Fisher et al., 2006). Consequently, the reporting regions used in the spatially-explicit analysis of the BHI and accompanying report card were evaluated to determine whether they have some relationship with land use characteristics. Land use was characterized for each reporting region using a Landsat 7 ETM + image from 2001 by assigning all land use possibilities into one of 6 different categories: developed (Dev), agriculture (Agr), forest (For), open water (OW), wetland (Wet) and barren (Bar). Because nutrient and sediment loadings to receiving waters are commonly associated with developed and agricultural (DevAgr) land use (Williams et al., 2005, 2006), these categories were combined and used in the regression analysis.

Open water area was included in the total basin area for the DevAgr land use versus BHI calculation in order to normalize the data for the various reporting regions. For instance, in cases where there is a small watershed with a very large open water (OW) area (small watershed area to OW area ratio), the DevAgr land use would have a very small effect on water quality, even if the DevAgr land use total of watershed area approached 100%. By contrast, in cases where there is a very large watershed area and a small OW area (i.e., a large ratio), the total DevAgr land use would likely have an overwhelming effect on the water body. Consequently, the relationship between DevAgr land use and the WQI or BHI is weakened when using the DevAgr land use in the watershed (without the OW area included) because this is influencing a proportionally larger water body in some reporting regions than in others. By including the OW area in the calculation, this partially removes the artifact associated with variable watershed to OW area ratios.

The proportion of OW to watershed area in the reporting regions used in the BHI ranged from 1 to over 30%.

6. Results

6.1. Bay Health Index

Time series of the metrics and indices, as well as the overarching BHI, indicated that values from 1985 to 2007 commonly ranged from 30 to 60 (Fig. 3). Using the assessment protocol described above, the overall BHI status in the Chesapeake Bay in 2007 was 42, and ranged from 34 to 54 from 1985 to 2007. The trend in SAV increased from 1985 to 2002 ($r^2 = 0.53$, $p = 0.0001$), whereas that of the WQI decreased from 1992 to 2007 ($r^2 = 0.26$, $p = 0.02$). Overall, the BHI had no significant trend over the period of record, although there are several periods of missing data from the BHI time series. For instance, there were no B-IBI data until 1996 for the entire Bay, no P-IBI data for 4 regions of the Bay until 2007 (including the South Eastern Shore that has a relatively large surface area), and no SAV data for the Elizabeth River region because this is a designated no-grow-zone (i.e., an area that cannot support the growth of SAV).

Frequency distributions of all the WQI and overarching BHI values for the 23-year period were normal (Fig. 4). Although the P-IBI and B-IBI frequency distributions were normal, that of SAV was skewed and this resulted in a frequency distribution for the BI that was slightly bi-modal and skewed. The range of the frequency distributions varied from 15–70, 0–80, and 5–85 for the WQI, BI and BHI, respectively, and the normal frequency distribution of the BHI indicated that there was good alignment (i.e., the ranges of values were similar) of most of the metrics and indices used.

6.2. Evaluation analyses

6.2.1. Comparison of extreme flow years

Most metrics and indices used in the BHI had strong differences in attainment between 2002 (dry year) and 2003 (wet year). Of all the metrics used, B-IBI and SAV were the least responsive to the large increase in flow that occurred from 2002 to 2003 (Fig. 3). BHI values for different reporting regions ranged from 12 to 66 in 2002 and from 18 to 45 in 2003. All reporting regions had higher BHI values in 2002 than in 2003, except for the Elizabeth, Patapsco, and South Western Shore (Fig. 5). Given the high sensitivity of the metrics and indices to variable flow regimes, there were significant negative correlations with total flow (water year) to the Chesapeake Bay from 1985 to 2007; the WQI and P-IBI had the highest coefficients among BHI metrics (Tables 3a and 3b). Pearson correlation coefficients of flow with total nitrogen, total phosphorus, and total suspended sediments were all positive and significant ($r = 0.88$, $p < 0.0001$; $r = 0.75$, $p < 0.0001$; $r = 0.51$, $p = 0.015$, respectively).

6.2.2. Relationships to land use

The metric and index values typically had moderate inverse relationships with the % of developed and agricultural (DevAgr) land use (2001) for each reporting region in individual years. Although the average of the 1985–2007 BHI and DevAgr land use had a moderate relationship (Fig. 6a), removing the James and York rivers, and South Western Shore reporting regions from the analysis substantially improved the coefficients of determination (r^2). Without these regions, the relationship determined in Fig. 6b was highly significant ($r^2 = 0.62$, $p = 0.0013$).

Improvements in the land use relationships were common using sub-indices of the BHI, particularly in individual years. For example, the WQI and DevAgr in 1995 was highly significant ($r^2 = 0.86$, $p < 0.001$) when the South Western Shore and the York River regions were removed from the analysis. The highest r^2 for the WQI occurred when the York River, North Western Shore and South Western Shore reporting regions were omitted (mean $r^2 = 0.39$ and 0.54 with and without all reporting regions included, respectively; $p \leqslant 0.05$). Strong relationships of DevAgr land use and P-IBI were common in the 23-year data record, but again there was significant improvement with the York and James rivers and North Western Shore reporting regions omitted. Land use relationships were usually weaker for B-IBI (mean $r^2 = 0.12$ for 1996–2007) and SAV (mean $r^2 = 0.32$) than for the WQI and P-IBI, although there were strong relationships with every index in individual years. The strongest land use relationships of any year for the WQI, BI and BHI had r^2 values of 0.86, 0.54 and 0.68, respectively.

6.3. Example of BHI results from 2007

Summarizing regional results from the 2007 calendar year (average flow) among the 15 separate reporting regions in Chesapeake Bay, overall BHI values were highest for the North Western

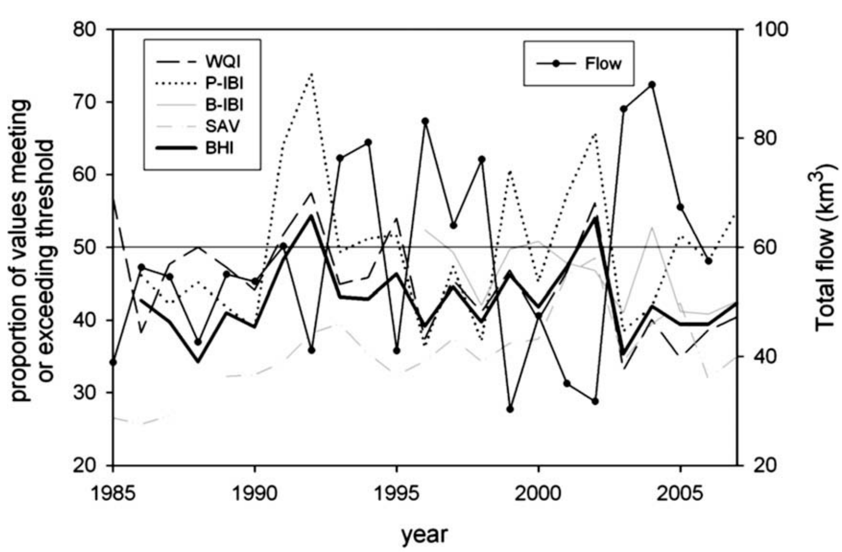

Fig. 3. Time series of the Water Quality Index (WQI), Phytoplankton Index of Biotic Integrity (P-IBI), Benthic Index of Biotic Integrity (B-IBI), Submerged Aquatic Vegetation (SAV), the Bay Health Index (BHI) and total flow to the Chesapeake Bay (1985–2007). Not including flow, values are area-weighted means of the proportion of values meeting or exceeding assessment thresholds for each of the 15 reporting regions. Note that Bay-wide B-IBI data were first available in 1996.

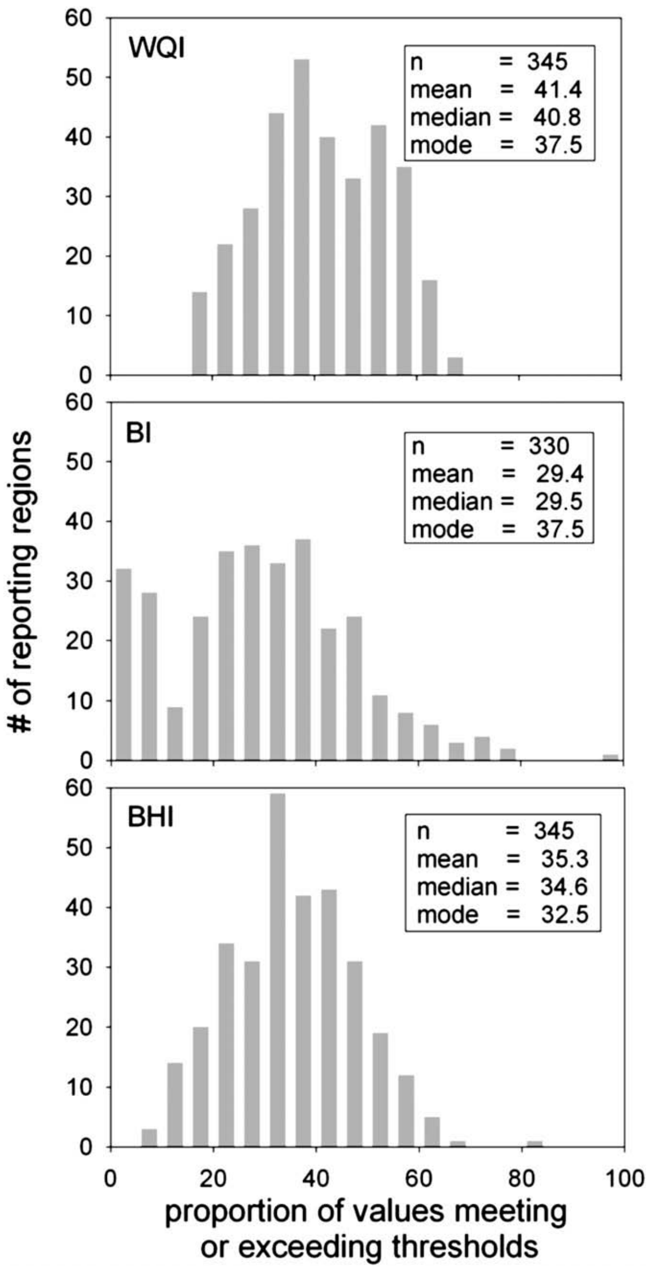

Fig. 4. Frequency distributions of the Water Quality Index (WQI), Biotic Index (BI) and Bay Health Index (BHI) for all reporting regions from 1985 to 2007.

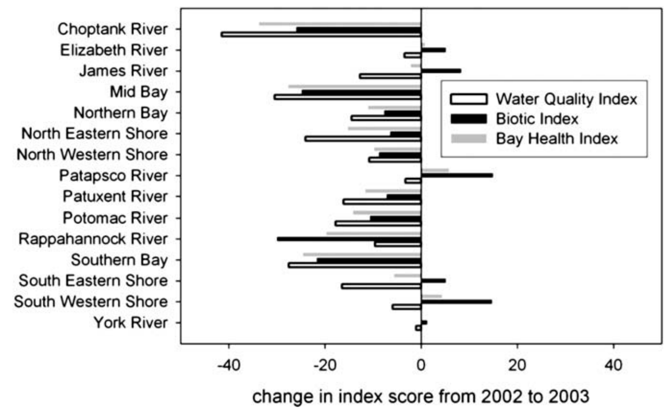

Fig. 5. Comparison of the Water Quality Index (WQI), Biotic Index (BI) and Bay Health Index (BHI) values for 2002 and 2003 in each reporting region.

Table 3a
Pearson correlation coefficients of metrics, indices and total annual flow to the Chesapeake Bay (1985 to 2006). Statistical significance is indicated by asterisks (0.05 ⩾ * > 0.01, 0.01 ⩾ ** > 0.001, 0.001 ⩾ ***).

	WQI	P-IBI	SAV	BHI	Flow
WQI	–				
P-IBI	0.71***	–			
SAV	0.05	0.50**	–		
BHI	0.72***	0.88***	0.50**	-	
Flow	−0.64***	−0.57***	−0.15	−0.49**	–

Table 3b
Pearson correlation coefficients of metrics, indices and total annual flow to the Chesapeake Bay (1996 to 2006). Statistical significance is indicated by asterisks (0.05 ⩾ * ⩾ 0.01, 0.01 ⩾ ** ⩾ 0.001, 0.001 ⩾ ***).

	WQI	P-IBI	B-IBI	SAV	BHI	Flow
WQI	–					
P-IBI	0.75***	–				
B-IBI	0.32	0.23	–			
SAV	0.64**	0.83***	0.16	–		
BHI	0.96***	0.88***	0.40	0.80***	–	
Flow	−0.72**	−0.80***	−0.06	−0.58*	−0.74***	–

Shore (grade = B) and lowest (grade = D-) for the Patuxent and York rivers, and the South Western Shore (Fig. 7). Whereas the Northern and Southern Bay main stem, and James River had average grades (C− to C+), all other regional breakouts had grades in the D range (D− to D+) and no region attained an overall grade above that of a B. These results, in addition to sub-index values, are in Table 4 and available in more detail at www.eco-check.org/reportcard/chesapeake.

7. Discussion

7.1. Factors regulating the BHI

Chesapeake Bay is responsive to terrestrial loadings of N, P and sediments and, therefore, the BHI was designed to accurately indicate areas impaired by excess nutrients and poor water clarity. Indeed, much of the Chesapeake Bay is influenced by highly variable freshwater runoff patterns, particularly in the spring (Sprague et al., 2000). Water quality problems during low-flow years tend to be more prevalent in the tidal fresh and oligohaline zones due in part to the large human populations located near these zones, along the Piedmont fall-line (e.g., Richmond, VA; Washington, DC, Baltimore, MD). In contrast, water quality problems during high flow years are shifted to larger mesohaline and polyhaline segments that represent proportionally more surface area of the Bay. Therefore, flow regimes that result in large differences in nutrient and sediment inputs (as well as chemical contaminants) not only influence BHI values but also create variable distributions of water quality problems in the Bay. Such variations are apparent in the comparison of the 2002 and 2003 flow years that were drier and wetter than average, respectively (Fig. 3) and in our correlation analysis (Tables 3a and 3b). Moreover, in the 2002 and 2003 comparison, there is high variability in the responsiveness of various reporting regions, with the York, James, South Western Shore, Patapsco and Elizabeth being the least responsive and the Choptank River being the most responsive (Fig. 3). This analysis also indicates that the BI tends to show improvement in the least responsive reporting regions during wetter than average years, which is somewhat counterintuitive but which may be explainable in terms of

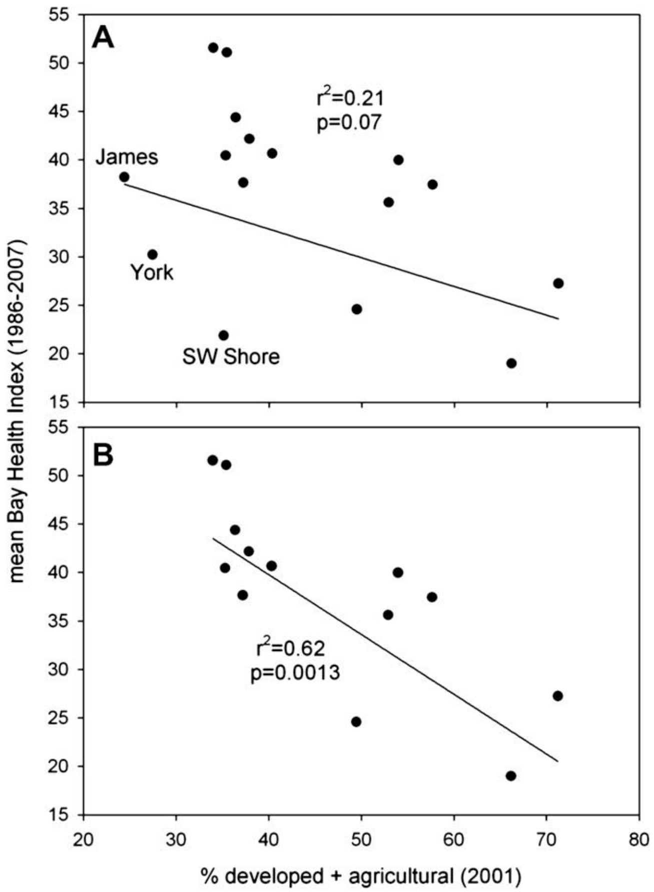

Fig. 6. The total of developed and agricultural land use (2001) (as % of total area in each reporting region) versus the mean Bay Health Index from 1985 to 2007 using all reporting regions (panel A) and without the James, York and SW tributary regions included (panel B).

factors such as a stronger oceanic influence (i.e., James and York rivers), main stem influence (South Western Shore), and relatively short water residence times during high flows (Patapsco and Elizabeth rivers). These results also suggest that B-IBI and SAV values are less responsive to immediate changes in water quality and are likely to require successive years of good water quality conditions to show improvement and eventually meet restoration goals because they take longer to recover from impairments than either the WQI or P-IBI.

In addition to the high sensitivity of the BHI and most of its component metrics and indices to variable flow regimes, our evaluation analyses indicate that these, for most reporting regions, have strong relationships with the total of developed and agricultural land use in their watersheds in most years. Considering the numerous factors that can affect these relationships (i.e., regional bathymetry, nutrient inputs from the main stem to the bottom waters of sub-estuaries, land use classification errors, types of agriculture in each reporting region, the proximity of developed and agricultural land to the water body, and etc.), our results highlight the importance of land use in regulating the water quality and health conditions of Chesapeake Bay. Nevertheless, these analyses indicate that several reporting regions are frequent outliers (i.e., South Western Shore, York and James rivers). These outlier regions have either high-density residential land use on the shoreline (i.e., tributaries such as the Magothy, Severn and South rivers of the South Western Shore) or, as in the case of a large tributary such as the James River, have urban and industrial centers near their mouths. Therefore, we speculate that WQI and BHI values for these regions are consistently lower than what we would predict given the relationships generated with the other reporting regions (Fig. 6) in part because a larger proportion of their developed and agricultural land use is in closer proximity to the water body (i.e., they do not have the same buffering effects that are provided by a more even distribution of developed and agricultural land use throughout their watersheds). And although a preliminary analysis evaluating this hypothesis using a 500 m buffer around the shoreline of each reporting region did not show higher densities of developed and agricultural land use in these outlier regions compared to the others, further analysis using other buffer sizes (i.e., 100 m, 1 km, etc.) located in specific areas of each reporting region (i.e., at the mouths of these tributaries) needs to be done to evaluate this hypothesis.

Our time series of the component metrics and indices, as well as the overarching BHI, indicate that the health status and conditions of Chesapeake Bay have been highly variable between 1985 and 2007, in large part due to variations in hydrology and changes in land use. This variability is characteristic of a heavily stressed system such as the Chesapeake Bay that has received highly elevated nutrient loads from most major tributaries for the better part of 5 decades (Benitez and Fisher, 2004). The high sensitivity of the BHI and most of its indices (i.e., B-IBI is less sensitive than the others) to variable flows is accentuated by decreasing populations of ecologically important phytoplankton grazers. For instance, Atlantic menhaden, *Brevoortia tyrannus*, American oysters, *Crassostrea virginica* (Newell, 1988), and mesozooplankton (Virginia Department of Environmental Quality, 2002) tend to buffer increases in phytoplankton biomass and decreases in water clarity thereby supporting healthy water quality conditions, and with fewer of these grazers present the concentrations of chlorophyll-a would likely be higher during high flow years than if there were more grazers present. Indeed, one of our ultimate objectives is to incorporate higher trophic level metrics into the BHI that can account for decreasing grazer populations. Concurrently, there have been decreases in a variety of benthic macroinvertebrates (Walter Boynton – CBL, pers. comm.) that likely reduced the biogeochemical efficiency (e.g., the extent to which the benthos processes nitrogen namely via denitrification) of the Bay (Kemp et al., 2005).

8. BHI evaluation

One of the clear strengths of the BHI method is that it quantifies the level of impairment of a particular location based on ecological health-based thresholds. It is therefore implicit in the BHI that higher values indicate that the area of interest is healthier than those areas that have lower values, at least in terms of those metrics that we have been able to use in the BHI thus far. Moreover, the values generated for the reporting regions are highly correlated with flow and N, P and sediment loading, and the relationships of BHI values with developed and agricultural land use confirm the strong linkage between human activities in the watershed and their deleterious effects on receiving waters. Moreover, the relative ranking of BHI values for the reporting regions makes sense in that the regions with commonly lower values (e.g., Patuxent, South Western Shore, and Patapsco) are those generally considered to be more polluted than the regions with higher values (e.g., North Western Shore and Northern Bay) that are generally considered to be improving. Thus, BHI values appear to be accurately reflecting ecological conditions in Chesapeake Bay.

Traditional validation procedures (e.g., Karr, 1981; Karydis and Tsirtsis, 1996; Paul, 2003) to determine the robustness of the BHI and its metrics and sub-indices are not possible. First, the data currently used for the BHI are derived from and applied to the entire Chesapeake Bay, and a separate validation data set was not withheld. A traditional validation analysis would require applying the

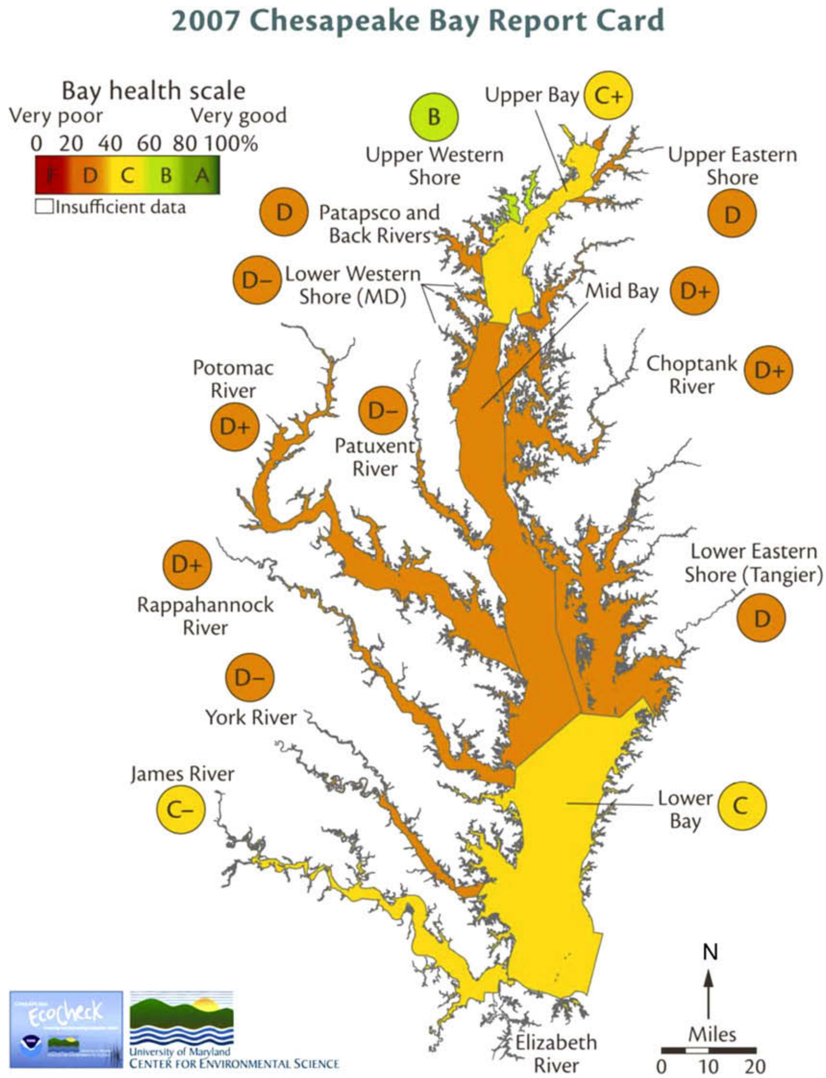

Fig. 7. Map of grades for each reporting region determined from BHI values (BHI values can be found in Table 4). This map was used in the 2007 Bay Health Report Card (www.eco-check.org). For the purposes of the report card, "Upper" and "Lower" represent Northern and Southern reaches of the bay, respectively; "MD" designates the state of Maryland for the Lower Western Shore reporting region, and "Tangier" designates Tangier Sound that is a part of the Lower Eastern Shore reporting region.

Table 4
Table from the 2007 Chesapeake Bay Report Card with BHI values for each reporting region ranked in ascending order from left to right. For the purposes of the report card, "Upper" and "Lower" represent Northern and Southern reaches of the bay, respectively; "MD" designates the state of Maryland for the Lower Western Shore reporting region, and "Tangier" designates Tangier Sound that is a part of the Lower Eastern Shore reporting region.

Water Quality Index, Biotic Index, and Bay Health Index Scores

	Patuxent River	Lower Western Shore (MD)	York River	Patapsco and Back Rivers	Upper Eastern Shore	Lower Eastern Shore (Tangier)	Rappahannock River	Mid Bay	Choptank River	Potomac River	James River	Lower Bay	Upper Bay	Upper Western Shore	Elizabeth River*
Water Quality Index	27	23	27	19	41	42	38	39	49	42	51	37	52	55	30
Biotic Index	13	18	22	32	24	26	33	33	25	35	36	55	67	75	0
Bay Health Index	**20**	**20**	**24**	**26**	**33**	**34**	**36**	**36**	**37**	**39**	**44**	**46**	**59**	**65**	**23***

(*score based on average of 4 indicators)

BHI method to a different estuarine system, which could be problematic since chlorophyll-a, P-IBI, and Secchi thresholds were determined from Chesapeake Bay "reference" data sets (Lacouture et al., 2006, Buchanan et al., 2005) and may not be transferable to other systems.

Simulation techniques used to validate the robustness of the BHI metric and sub-index scoring thresholds (e.g., Monte Carlo simulations, jackknife, and bootstrapping procedures) are problematic because two BHI metrics are scored against thresholds determined *a priori* (i.e., physiological thresholds for dissolved oxygen, restoration goal for SAV) and not based on the distributions of metric or index values in existing reference communities. Estimates of % total error have been determined with a jackknife-with-replacement procedure for the chlorophyll-a and P-IBI components (Lacouture et al., 2006) and with a bootstrap procedure for the B-IBI component (Alden et al., 2002). Both of these procedures can be used to estimate the precision of metric threshold values and establish confidence estimates around individual metrics or a multi-metric index (Snedecor and Cochran, 1989). Total error (%) for the chlorophyll-a metric threshold in eight salinity- and season-specific pelagic habitat types ranged from 0% (polyhaline spring) to 27.7% (oligohaline spring). Total error (%) for the P-IBI scores of the eight reference communities ranged from 3.1% (mesohaline spring) to 12.6% (tidal fresh and oligohaline spring). Confidence intervals around B-IBI grand medians in the reference communities of each of the seven bottom habitat types ranged 4.0–5.0 (polyhaline sand) to 3.0–4.6 (oligohaline and low salinity mesohaline). The standard error (%) for the B-IBI is commonly <12% (Weisberg et al., 1997).

Considering the limitations of conducting more traditional validation analyses, we have taken a different approach to evaluating the robustness of the BHI. In the scientific literature pertaining to the Chesapeake Bay, it is commonly acknowledged that nutrient and sediment inputs from human activities in the watershed are responsible in large part for the degraded environmental health of the ecosystem (Dauer et al., 2000; Kemp et al., 2005; Li et al., 2007). Indeed, the Atlantic Slope Consortium, which includes more than 50 scientists from six different institutions, identified indicators that connect the amount of development, proximity of streams and patterns of land use to ecological metrics such as marsh bird diversity, abundance of SAV, and PCB levels in white perch (Atlantic Slope Consortium, 2007). Similarly, the significant relationships we observe for BHI values and the total amount of developed and agricultural land use in most of the reporting regions is indicative of a link between these land use types (representing those affected by human activities) and water quality that has a direct impact on the health of important aquatic habitats.

The combination of indices and metrics chosen for predicting habitat health with the BHI strongly relate water quality and biotic conditions to flow and land use. SAV and B-IBI had weaker relationships than the WQI and P-IBI, albeit the former are less responsive to changes in water quality and are strongly influenced by other important drivers. For instance, the growth and distribution of many SAV species are strongly regulated by changes in salinity and water temperature. Nevertheless, our evaluation of the BHI in this context indicates that it is a functional tool to help understand and manage the natural resources of Chesapeake Bay, and the strength of the BHI lies not only in the final score for a particular reporting region but also in the interpretation of the individual metric and sub-index scores that provide specific spatial and temporal characterizations of habitat condition.

Water quality and biotic metrics of the BHI act in concert to provide a quantitative signal of the response to environmental stressors, making the BHI more holistic and therefore robust than their individual metrics. Considering the elevated nutrient, sediment and pollutant loadings that have deleteriously affected the Bay for decades, BHI values in the range of 35 to 55 in our analyses are realistic. And although the range of BHI values can be much higher for individual reporting regions, the highest BHI rating from 1985 to 2007 is likely the best attainable level of ecosystem integrity in any given year that is currently possible in Chesapeake Bay as a whole. However, we assume that BHI values will increase once BMPs (e.g., cover crops, riparian buffers, etc.) are sufficiently implemented and nutrient loadings decrease to levels that improve water quality and habitat conditions, thereby allowing a concomitant recovery of biogeochemical efficiency (Kemp et al., 2005) and progress towards a restored Chesapeake Bay.

8.1. Further development and potential improvements

The BHI was designed in such a manner that it can be easily modified. For example, modifications of the current indices could occur by changing threshold values or by the addition of higher trophic level (e.g., blue crab or menhaden), chemical contaminant (PCBs) and health-related metrics (e.g., enterococci). However, because the BHI is currently configured in such a way that it has considerable robustness as a health index based on its (1) sensitivity to different flow regimes and (2) strong relationships of BHI values for most reporting regions with the sum of developed and agricultural land use in their watersheds, modifications that maintain this robustness will likely change the absolute scores among the reporting regions more than the relative differences of their scores. Nevertheless, there are several reporting regions that are less sensitive to changes in flow and commonly have lower BHI values than what is expected given the total DevAgr land use in their watersheds (i.e., the York and James rivers and South Western Shore), and more analysis is needed to determine what factors are responsible for these anomalies. Insights from such analyses may result in subtle improvements in the robustness of the BHI and conceivably allow it to be used in an even broader context as an assessment tool by the Chesapeake Bay community in the future.

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