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Chesapeake Bay's water quality condition has been recovering: Insights from a multimetric indicator assessment of thirty years of tidal monitoring data

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Abstract

To protect the aquatic living resources of Chesapeake Bay, the Chesapeake Bay Program partnership has developed guidance for state water quality standards, which include ambient water quality criteria to protect designated uses (DUs), and associated assessment procedures for dissolved oxygen (DO), water clarity/underwater bay grasses, and chlorophyll-a. For measuring progress toward meeting the respective states' water quality standards, a multimetric attainment indicator approach was developed to estimate combined standards attainment. We applied this approach to three decades of monitoring data of DO, water clarity/underwater bay grasses, and chlorophyll-a data on annually updated moving 3-year periods to track the progress in all 92 management segments of tidal waters in Chesapeake Bay. In 2014–2016, 40% of tidal water segment-DU-criterion combinations in the Bay ($n = 291$) are estimated to meet thresholds for attainment of their water quality criteria. This index score marks the best 3-year status in the entire record. Since 1985–1987, the indicator has followed a nonlinear trajectory, consistent with impacts from extreme weather events and subsequent recoveries. Over the record (1985–2016), the indicator exhibited a positive and statistically significant trend ($p < 0.05$), indicating that the Bay has been recovering since 1985. Patterns of attainment of individual DUs are variable, but improvements in open water DO, deep channel DO, and water clarity/SAV have combined to drive the improvement in the Baywide indicator in 2014–2016 relative to its long-term median. Finally, the improvement in estimated Baywide attainment was statistically linked to total nitrogen,

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Appendix A. Supplementary Data

Supplementary material related to this article can be found at <http://dx.doi.org/xxx>.

indicating responsiveness of attainment status to the reduction of nutrient load through various management actions since at least the 1980s.

Keywords

Chesapeake Bay; water quality standards; trends; dissolved oxygen; chlorophyll-a; monitoring and assessment

1. Introduction

Like many other estuaries around the world, Chesapeake Bay and its tidal tributaries (the Bay) have suffered from a long history of cultural eutrophication that has resulted in ecological degradation. Key symptoms have included excessive algal growth, poor water clarity, decreased submerged aquatic vegetation (SAV) acreage, and low dissolved oxygen (DO), related to excessive nutrient and sediment inputs from its watershed (Hagy *et al.*, 2004; Kemp *et al.*, 2005; Murphy *et al.*, 2011; Zhang *et al.*, 2015; Zhang and Blomquist, 2018).

In 1983, the first Chesapeake Bay Agreement was developed, through which the U.S. Environmental Protection Agency (USEPA) and four Bay jurisdictions (the states of Maryland, Virginia, Pennsylvania, and the District of Columbia) committed to the protection of water quality and habitat conditions necessary to support the living resources in the Bay ecosystem. In 2003, the Chesapeake Bay Program (CBP) partnership published a guidance framework entitled “*Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll-a for the Chesapeake Bay and Its Tidal Tributaries*” (USEPA, 2003 a). These water quality criteria, applied over a 92-segment management grid (Fig. 1), were adopted into states’ water quality standards to define which waters are impaired under the Clean Water Act (Table S1). In the 2003 framework (USEPA, 2003a), water quality criteria are established for aquatic habitats for open water (OW), deep water (DW), deep channel (DC), migratory spawning and nursery (MSN), and shallow water (SW) designated uses (DUs), which reflect the seasonal nature of water column structure and the life history needs of living resources (Fig. 2; Table S1) (USEPA, 2003b; USEPA, 2004b).

The 2003 framework also sets the foundation of water quality criteria assessment procedures (USEPA, 2003a). The procedures are based on the most recent CBP segmentation scheme, which divides the Bay into 92 segments (USEPA, 2005). Since 2003, the assessment procedures have been periodically refined as new scientific understanding became available, leading to the publication of a series of technical addendums (USEPA, 2003a; USEPA, 2004a; USEPA, 2007a; USEPA, 2007b; USEPA, 2008; USEPA, 2010a; USEPA, 2017). For a summary of these addendums up to 2010, see Tango and Batiuk (2013).

To achieve consistent assessment over time and among jurisdictions, a multimetric indicator was proposed by the CBP partnership to provide a means for measuring progress towards attainment of water quality standards in the Bay (USEPA, 2017). This indicator uses available data - and applies a set of decision rules to account for missing data otherwise required - to perform a complete assessment of all criteria in order to compute an index

score (Table S1). The index score represents a surface-area-weighted estimate of water quality standards attainment that quantifies the fraction of tidal waters estimated to meet all applicable season-specific criteria thresholds for each applicable standard in 3-year moving assessment windows. Due to data limitations, this indicator should not be treated as a full accounting of water quality standards for DO, water clarity/SAV, and chlorophyll-a as stated by state regulations. Also, this indicator does not consider other parameters that may impair water quality including pH, bacteria, or toxics.

The main objective of this work was to apply the multimetric indicator approach to three decades of monitoring data of DO, water clarity/SAV, and chlorophyll-a in the Bay to track the progress in water quality standards attainment for the 92 segments that are listed in the Chesapeake Bay Total Maximum Daily Loads (USEPA, 2010b). For the first time in the scientific literature, the status and trends of Chesapeake Bay water quality standards attainment are documented, which provides essential information to the Bay management and research community. One immediate use of such information is for assessing the effectiveness of management interventions after decades of public investment in the restoration of Chesapeake Bay. This work highlights Chesapeake Bay as an example where a long-term, collaborative monitoring network has allowed for the development, refinement, and implementation of analyses to assess the ecological status of a complex ecosystem. This work can serve as a model for other coastal and inland systems, either for comparison with existing assessments, or for development of similar monitoring and assessment frameworks (Borja *et al.*, 2008; Bricker *et al.*, 2008; Patricio *et al.*, 2016; Schiff *et al.*, 2016; Sherwood *et al.*, 2016; Trowbridge *et al.*, 2016).

2. Methods

2.1. Monitoring data

To compute the multimetric indicator, data on DO concentrations, chlorophyll-a concentrations, water clarity, SAV acreage, water temperature, and salinity are required. SAV acreage has been measured by the Virginia Institute of Marine Science in collaboration with the CBP, and is available via <http://web.vims.edu/bio/sav/StateSegmentAreaTable.htm>. Data for all the other parameters were obtained from the CBP Water Quality Database (http://www.chesapeakebay.net/data/downloads/cbp_water_quality_database_1984_present). These data have been routinely reported to the CBP by the Maryland Department of Natural Resources, Virginia Department of Environmental Quality, Old Dominion University, Virginia Institute of Marine Science, and citizen/volunteer monitoring initiatives. The Chesapeake Bay water quality monitoring program uses a fixed station profiling strategy with sites distributed along the mid-channel waters of the Bay, its tidal tributaries, and embayments. A set of over 100 stations have been sampled consistently since 1985, with 12–20 times per year and sometimes additional synoptic sampling (USEPA, 2010b; Tango and Batiuk, 2013). The sampling and analytical methods are described in detail in an EPA-approved quality assurance project plan (https://www.chesapeakebay.net/what/programs/chesapeake_bay_quality_assurance_program/quality_assurance_tidal_water_quality_monitoring).

2.2. Criteria attainment assessment procedures

The current water quality standards attainment assessment procedures evaluate observed exceedances of the DO, water clarity/SAV, and chlorophyll-a criteria using the CBP quality-assured monitoring data listed in Section 2.1 (USEPA, 2003a; USEPA, 2004a; USEPA, 2007a; USEPA, 2007b; USEPA, 2008; USEPA, 2010a; USEPA, 2017). Station-level DO and chlorophyll-a data are spatially interpolated in three dimensions. Salinity and water temperature data are used to compute the vertical density structure of the water column, which is translated into layers of OW, DW, and DC designated uses. To assess criteria exceedance rates, water quality criteria thresholds are applied to monitoring data according to designated use. Criteria attainment is then determined by comparing exceedance rates over a 3-year period to a reference cumulative frequency distribution (CFD) that represents the extent of allowable exceedance (Fig. S1) – refer to Batiuk *et al.* (2009) and USEPA (2003a) for full details. This methodology was based on best scientific knowledge available for assessment of the Bay’s water quality criteria (Chesapeake Bay Program Scientific and Technical Advisory Committee, 2006). For water clarity/SAV criterion assessment, acreage comparisons were made with segment-specific goals for each 3-year period -- refer to USEPA (2003a); Batiuk *et al.* (2009); USEPA (2017) for details. These assessment procedures have resulted in attainment status of each applicable segment-DU-criterion combination ($n = 291$) for each 3-year assessment period from 1985–1987 to 2014–2016. Such three-year periods have been used for water quality status assessment by the Chesapeake Bay Program partners because these periods can include some natural year-to-year variability largely due to climatic events and also addresses residual effects of one year’s conditions on succeeding years (USEPA, 2003a).

2.3. The multimetric water quality standards attainment indicator

The above procedures can generate “pass/fail” results for all applicable segment-DU-criterion combinations ($n = 291$), which can then be integrated in a Baywide assessment. On this basis, we calculated a multimetric indicator to quantify the fraction of segment-DU-criterion combinations that meet all applicable season-specific thresholds for each 3-year assessment period from 1985–1987 to 2014–2016 (30 periods in total). For each 3-year assessment period, all applicable segment-DU-criterion combinations were evaluated in a binomial fashion and scored 1 for “in attainment” and 0 for “nonattainment”. The classified status of each segment-DU-criterion combination was weighted via segments’ surface area and summed to obtain the multimetric index score. This weighting scheme was adopted for two reasons: (1) segments vary in size over four orders of magnitude, and (2) surface area of each segment does not change with time or DUs, unlike seasonally variable habitat volume or bottom water area (USEPA, 2017). For more details, readers are referred to Chapter IV “Development of a Multi-metric Chesapeake Bay Water Quality Indicator for Tracking Progress toward Chesapeake Bay Water Quality Standards Achievement” of the “2017 Technical Addendum” report (USEPA, 2017).

This indicator provides temporally and spatially consistent assessments of the long-term, quality-assured CBP water quality monitoring records. The indicator uses data applied to a subset of the full suite of criteria necessary for a complete accounting of water quality standards attainment assessments. For example, to be in full attainment for OW DO in a

segment, three conditions need to be met simultaneously: a 30-day mean condition, a 7-day mean condition, and an instantaneous condition (see Table S1). For the period examined, we only interpret the OW summer 30-day mean for attainment of the OW DO assessment. A decision rule has been established based on model analyses to suggest that the 7-day and instantaneous criteria are met if the 30-day mean criterion is met (USEPA, 2010a; Chesapeake Bay Program Scientific and Technical Advisory Committee, 2012). A complete set of rules is documented in USEPA (2017), which were used to compute an index score that provides a measure of estimated water quality standards attainment. This indicator time series is presented in Table S2.

2.4. Statistical analyses

The time series of the multimetric indicator was analyzed using two statistical approaches in R (R Core Team, 2014). A change-point analysis was conducted to test for a shift in the central tendency of the indicator time series. The non-parametric Pettitt test was adopted (Pettitt, 1979), which was implemented using the “pettitt.test” function in the R-package “trend” (Pohlert, 2018). In addition, trend analysis was conducted on the indicator time series to determine if Chesapeake Bay’s attainment status has improved over time. We adopted a modified version of the Mann-Kendall (MK) test that can account for autocorrelation in the series (Hamed and Rao, 1998). This non-parametric test was chosen because the indicator time series is not expected to follow any specific distribution and the values are bounded between zero and 100%. An autocorrelation correction was needed because the assessment was conducted on monitoring data in running 3-year periods, resulting in spurious autocorrelation and hence false inference on trend significance. The Sen slope was computed as well to generate an estimate of change over time (Sen, 1968). The modified Mann Kendall and the Sen slope tests were implemented through the “mkTrend” function in the R-package “fume” (Santander Meteorology Group, 2012) to calculate significance and slope for both a long-term trend (30-year; 1985–1987 to 2014–2016) and a short-term trend (10-year; 2005–2007 to 2014–2016). The alpha level was set to 0.05 as a cutoff for a likely or unlikely trend. Furthermore, surface-area-weighted attainment status was quantified individually for each of the six DUs from 1985–1987 to 2014–2016 – see Table S2. These DU-specific time series were also examined using the change-point analysis and modified MK analysis.

To investigate whether the indicator variability has been driven by nutrient input that in turn reflects effects of management interventions in the Bay watershed, we calculated the annual flow-weighted concentration of total nitrogen (TN_{FWC}) from 1985–2015 for nine major tributaries to Chesapeake Bay, which have been monitored by the US Geological Survey (Moyer *et al.*, 2017). The TN_{FWC} provides a measure of the TN that is not as dramatically impacted by fluctuations in flow as other measures (e.g., annual TN load), because it is annual load divided by annual flow. This proxy enables a fair comparison with the attainment indicator, because the latter is aggregated over 3-year cycles and hence removes some year-to-year variability that is driven by annual flow fluctuations. Although the selected TN_{FWC} does not account for the flow and TN input from the tidal watershed, it shows a decadal pattern similar to the total-watershed-based TN_{FWC} and has a longer series (*data not shown*). Like the attainment indicator, the TN_{FWC} time series was also examined

using the change-point analysis. We fit three generalized least squares models (GLS) to both the attainment indicator and TN_{FWC} to investigate their relationship, which was done using the “gls” function in R-package “nlme” (Pinheiro *et al.*, 2018). Because the attainment time series was found to have serial autocorrelation, the structure of which is not known a priori, we chose to fit three models with different assumptions on the error structure:

GLS_0 : Attainment = $\beta_0 + \beta_1 * TN_{FWC}$ (subject to uncorrelated errors).

GLS_1 : Attainment = $\beta_0 + \beta_1 * TN_{FWC}$ (subject to autoregressive errors with an order of 1).

GLS_2 : Attainment = $\beta_0 + \beta_1 * TN_{FWC}$ (subject to autoregressive errors with an order of 2).

The best model was selected based on the Akaike information criterion (AIC).

3. Results & Discussion

3.1. Status and trends of the estimated Baywide attainment

The multimetric indicator provides an integrated measure of Chesapeake Bay’s water quality condition (Table S2). Overall, this indicator has followed a nonlinear trajectory over the thirty 3-year assessment periods that can be broadly divided into four stages, as illustrated with varying colors in Fig. 3:

- (1) Steady improvement in the first 11 periods, when it increased from 26.5% (1985–1987) to 36.5% (1995–1997).
- (2) Slight improvement with a great deal of variability from 1995–1997 to 2008–2010, with the latter marking the second highest score (39.5%) in the entire record. This part of the record covered a prolonged drought period of 1999–2002, which corresponds to the best scores in the assessment cycles before 2006–2008.
- (3) Sharp decline in the three consecutive assessment periods that involved 2011 – the year Hurricane Irene and Tropical Storm Lee affected the region. The index declined to 27.6% in 2011–2013, the lowest score since 1990.
- (4) Steady and rapid recovery in the last three assessment periods; it reached 40.0% - the highest score in the entire 30-year record - in 2014–2016. This current status (2014–2016) indicates that 40% of the Bay’s tidal water segment-DU-criterion combinations are estimated to have reached their respective water quality criteria.

For this time series, a change point was identified at 1994–1996 ($p < 0.05$) (Table 1). Prior to the change point, the indicator had improved steadily over time. Later than the change point, however, the indicator was more variable with periods of improvement and decline that appear to have corresponded to extreme weather events in the region, including a drought period (1999–2002), Hurricane Isabel (2003), Hurricane Ivan (2004), and Hurricane Irene and Tropical Storm Lee (2011). Particularly, the indicator dropped to low points in the several assessment periods that involve 2003, 2004, and 2011, followed by periods of improvement. This pattern suggests that the Bay ecosystem is responsive to extreme weather

events, but within this period of record for these metrics, its recovery has been relatively quick.

For the recent 10-year timespan (i.e., 2005–2007 to 2014–2016), the MK trend has a negative slope that is not statistically significant (Table 1). This insignificance reflects the large variability in the time series over the last ten periods, which in turn reflects the effects of extreme weather events discussed above. Over the long-term timespan (i.e., 1985–1987 to 2014–2016), the MK trend has a positive slope (0.33 percent/year) that is statistically significant ($p < 0.05$). This improvement has been largely driven by the steady rise in the early part of the record, as revealed by the change-point analysis.

Overall, these results demonstrate that the Bay's water quality has generally been recovering since the beginning of the record, when concerted restoration efforts began. While there is still progress to be made -- and the Bay's status in any future year can deviate from this general path should extreme weather events occur -- the Bay's health is demonstrated to be on a positive trajectory.

3.2. Exploration of estimated attainment scores by designated uses

To better understand the estimated Baywide attainment time series pattern, it is useful to delve into designated uses specific results (Table S2). The six DU-specific attainment time series are plotted in Fig. 4a and the associated change-point and trend results are provided in Table 1.

MSN-DO experienced a sharp spike in the attainment time series in the first few years but generally degraded after the 1997–1999 change point. OW-DO experienced a sharp rise in the early 1990s and became variable thereafter. It has a change point at 1991–1993 ($p < 0.1$) and a positive long-term trend (+0.61 percent/yr; $p < 0.05$). DW-DO has a change point at 1993–1995 ($p = 0.14$) and a positive long-term trend (+0.10 percent/yr; $p < 0.05$). DC-DO never exceeded 15% and has many zero values. This DU exhibited several spikes -- one in the 1990s and four in the post-2005 years. Correspondingly, this DU has a change point at 2003–2005 ($p < 0.05$). The recent increased frequency of non-zero results in the DC-DO pattern may suggest that the mainstem Bay's summer hypoxic zone has begun to show some level of ecosystem recovery after decades of nutrient load reduction in the watershed.

OW-CHLA, which has only been applied in the Potomac and James Rivers (7 segments), shows near zero attainment in most periods except 1985–1987, 2000–2002 and 2002–2004. The latter two periods were associated with the most regionally significant drought and among lowest TN concentrations in the 30-year record (Fig. 3). Similarly, 1985–1987 annual river flows were among the lowest in this period of record.

SW-Clarity/SAV shows a steady rise in the 2000s, a sharp decline in the early 2010s, and a steady recovery thereafter. The latter two aspects signify the effects of the 2011 extreme weather events (Hurricane Ivan and Tropical Storm Lee) and the subsequent resurgence of bay grasses (Gurbisz and Kemp, 2014; Lefcheck *et al.*, 2018). For this time series, 1997–1999 was identified to be the change point ($p < 0.05$), before which the indicator value was almost always zero and after which it ranged in ~5–20%. Consequently, this DU shows a

positive long-term trend (+0.42 percent/yr; $p < 0.05$). Such an improvement in Chesapeake Bay SAV abundance is consistent with observations in other studies, which have attributed it to the reduction of anthropogenic nutrient inputs (Ruhl and Rybicki, 2010; Lefcheck *et al.*, 2018). However, the short-term trend in SAV attainment is negative ($p < 0.05$), owing to the effects associated with the 2011 extreme events. This short-term trend may be reversed if the post-2011 recovery continues in the coming years.

Estimated water quality standards attainment index scores of the six DUs are more directly compared in Fig. 4b, which plots the current estimated attainment status (2014–2016) against the long-term median for each DU. In terms of long-term median, the six DUs show the following ranking: *MSN-DO* (76%) > *OW-DO* (70%) > *Total* (40%) > *DW-DO* (36%) > *DC-DO* (13%) > *SW-Clarity/SAV* (9%) > *OW-CHLA* (3%). In other words, MSN-DO and OW-DO are the only DUs that are on average better than the Baywide average status. In addition, DUs related to the DO criterion have higher attainment values than DUs related to the other two criteria. Compared with respective long-term medians, the current attainment status is much better in OW-DO (70% in 2014–2016 vs. long-term median of 58%), DC-DO (13% vs. 0%), and moderately better in SW-Clarity/SAV (9% vs. 4%). These improvements have contributed to the Baywide indicator's current status (40% in 2014–2016) compared to its long-term median (33%).

3.3. Exploration of change points and drivers

The estimated Baywide attainment showed a steady rise in the years leading to its change point at 1994–1996 (Table 1; Fig. 3). The rise between 1989–1991 and 1995–1997 appeared to be related to improvements in OW-DO and DW-DO, with OW-DO contributing to the first four periods and DW-DO to the last three periods (Fig. 3a). In fact, both OW-DO and DW-DO were detected to have change points in the early 1990s. For OW-DO, it had a substantial jump from ~30% in 1989–1991 to ~60% in 1992–1994. Examining the OW-DO results for each segment revealed that the ~1990 jump in OW-DO attainment status appears to be a system-wide response that is relevant to many salinity zones and many mainstem/tributary systems (*data not shown*).

What caused the steady rise in the estimated Baywide attainment in the 1990s? While we acknowledge the importance of many possible factors, e.g., external physical forcing (Scully, 2010; Du and Shen, 2015; Li *et al.*, 2016; Scully, 2016), internal biogeochemical processes (Kemp *et al.*, 2005; Irby *et al.*, 2016; Testa *et al.*, 2017), climate change (Boesch *et al.*, 2001; Najjar *et al.*, 2010; Harding Jr. *et al.*, 2016), and phosphorus loads (Litke, 1999; Boynton *et al.*, 2008; Lyerly *et al.*, 2014), we have focused on the hypothesis that changes in TN_{FWC} (i.e., riverine load divided by river discharge) was a primary driver, as similarly hypothesized in prior studies of Bay hypoxia (Hagy *et al.*, 2004; Murphy *et al.*, 2011; Testa *et al.*, 2014). For the time series of TN_{FWC} (Fig. 3), 1995 was identified as the change point ($p < 0.05$), which is within the 3-year change point (1994–1996) of the estimated Baywide attainment. Such shift in TN_{FWC} is consistent with TN loading trend that has been documented elsewhere (Moyer *et al.*, 2012; Zhang *et al.*, 2013; Zhang *et al.*, 2015; Chanut *et al.*, 2016; Moyer *et al.*, 2017). It has been understood that the early-year decline in total nitrogen is largely related to decline in atmospheric deposition since the establishment of Clean Air Act

Amendments in 1990 (Eshleman *et al.*, 2013; Linker *et al.*, 2013b), decline in discharges of many wastewater treatment plants (WWTPs) with the “biological nutrient removal technology” upgrade that spanned many years since the 1980s (Boynton *et al.*, 2008), and decline in fertilizer applications in agricultural areas (Linker *et al.*, 2013a; Shenk and Linker, 2013; Zhang *et al.*, 2016; Keisman *et al.*, in press). Although not explicitly established here, reductions in watershed phosphorus load owing to phosphorus detergent ban that began in the 1970s and continued through 1990s (Litke, 1999; Boynton *et al.*, 2008; Lyerly *et al.*, 2014) may have also contributed to the early-year rise in the Baywide attainment score.

Estimated Baywide attainment and TN_{FWC} are negatively correlated (Fig. 3), with a correlation coefficient of -0.75 . The fitted GLS models allowed us to more rigorously test their statistical relationship. Model performance gets progressively better from GLS_0 (AIC = 145.6) to GLS_1 (AIC = 139.3) to GLS_2 (AIC = 139.2), which follows our expectation for the autocorrelation effect. For the best model (GLS_2), β_1 estimate is -12.1 ($p < 0.05$), implying that a reduction of TN_{FWC} by 0.1 mg/L could result in an improvement in the estimated Baywide attainment of 1.2%. This statistical relationship, coupled with the proximity of their change points, indicate that Chesapeake Bay’s water quality condition has been recovering in response to the reduction of nitrogen load through various management actions since at least the 1980s. This conclusion lends further support to prior findings regarding the response of Bay hypoxia to TN load reduction (Hagy *et al.*, 2004; Murphy *et al.*, 2011; Testa *et al.*, 2014) and Bay SAV to TN load reduction (Ruhl and Rybicki, 2010; Lefcheck *et al.*, 2018).

4. Conclusions

The multimetric water quality standards attainment indicator tracks the status and trends of Chesapeake Bay’s water quality condition across three decades of monitoring data. On a surface-area-weighted basis, 40% of all tidal water segment-DU-criterion combinations ($n = 291$) in the Bay are estimated have met or exceeded applicable water quality criteria thresholds in 2014–2016, which marks the best 3-year status since 1985–1987. The indicator is responsive to extreme weather events and can recover afterwards. Its positive and statistically significant trend from 1985 to 2016 indicates that the Bay has been recovering since 1985, when concerted restoration efforts began. Patterns of attainment of individual DUs are variable, but improvements in open water DO, deep channel DO, and water clarity/SAV have combined to drive the improvement in the Baywide indicator in 2014–2016 relative to its long-term median. Finally, the improvement in estimated attainment was statistically linked to the decline of total nitrogen, indicating responsiveness of attainment status to the reduction of nutrient load through various management actions since at least the 1980s. While there is still progress to be made and the Bay’s status in any future year can deviate from this general path should extreme weather events occur, our results demonstrate that Chesapeake Bay is on a positive trajectory toward recovery. Continued Baywide monitoring and assessment will provide timely insights to inform adaptive management. Future analysis efforts that delve into the segment level results will provide managers with more detailed information about how estuarine water quality changes in space, time, and across different DUs. Further understanding of spatial and temporal patterns can inform

managers of progress in water quality improvement at various locations and areas in need of more targeted actions to meet water quality standards.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Highlights

1. Chesapeake Bay's water quality history was assessed by using an indicator framework.
2. The indicator has a positive long-term trend ($p < 0.05$) and reached its peak in 2014–2016.
3. The indicator was responsive to extreme weather events but can recover afterwards.
4. Improvement of 2014–2016 over long-term average was driven by open water and deep channel dissolved oxygen.
5. The improvement in attainment has been linked to the decline of total nitrogen.

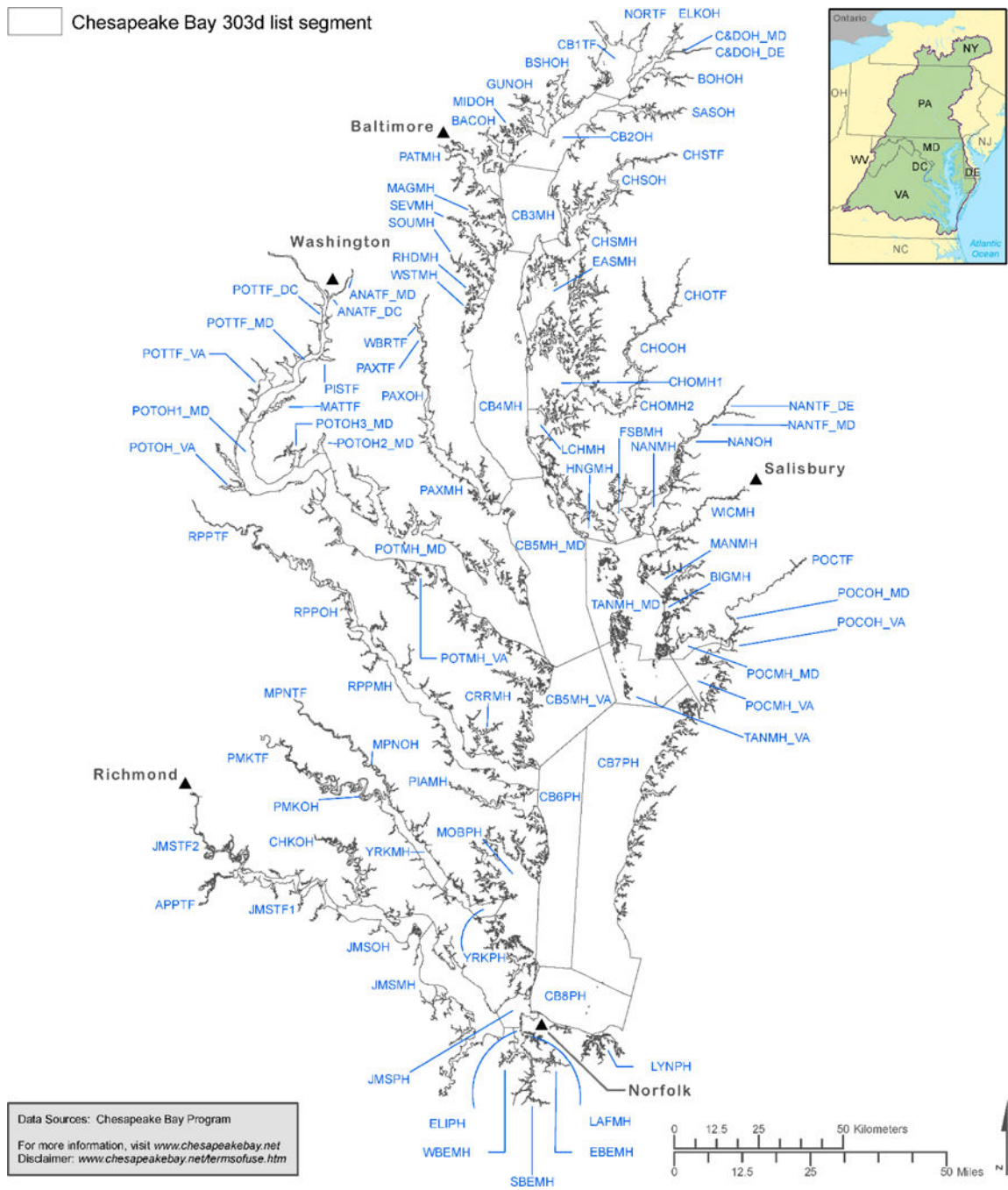


Fig. 1. Segmentation scheme used in the Chesapeake Bay water quality standards assessment (USEPA, 2004).

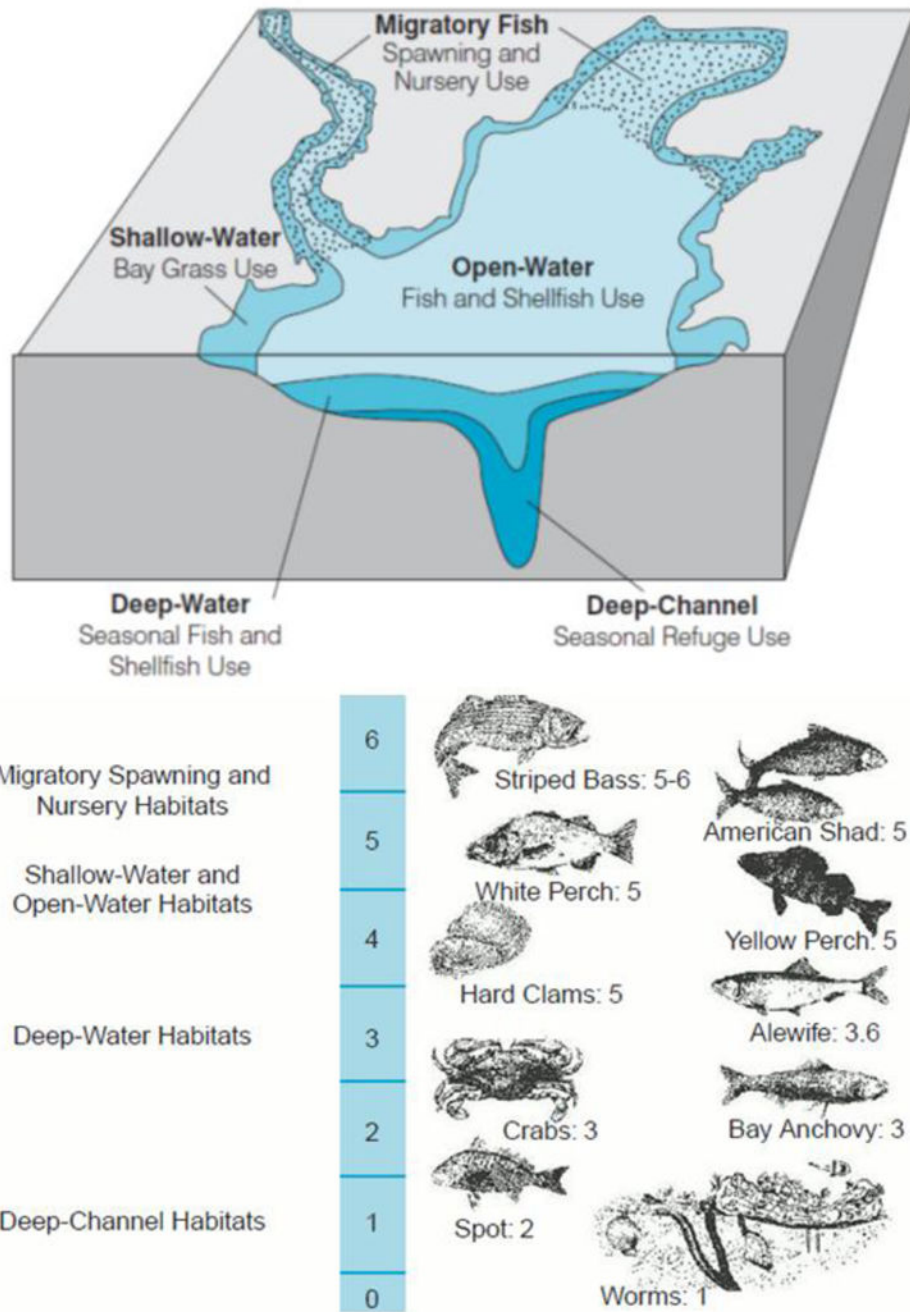


Fig. 2. The five designated uses in the water quality standards attainment assessment. Top: conceptual illustration. Bottom: dissolved oxygen (mg L^{-1}) concentrations required by different Chesapeake Bay species and communities (USEPA, 2003b; USEPA, 2003a; USEPA, 2004b).

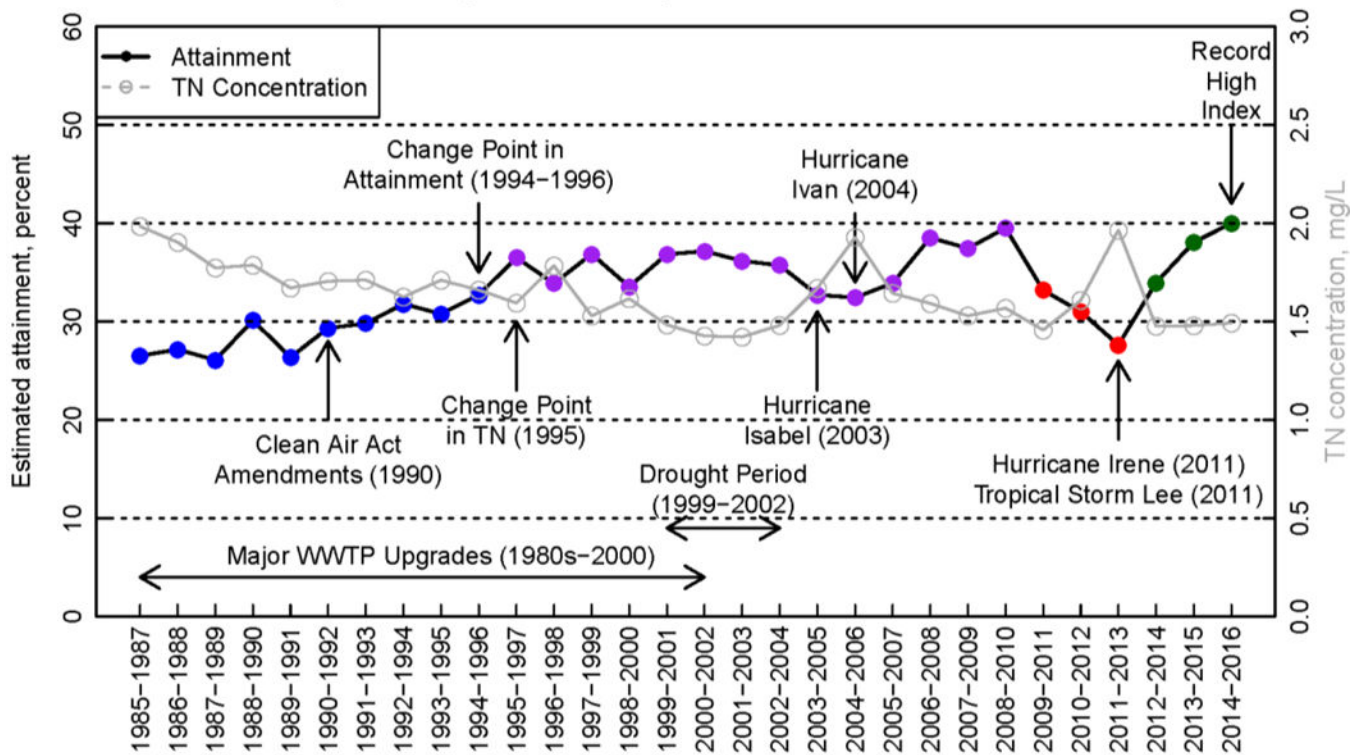


Fig. 3. Time series of the multimetric indicator score for estimated Chesapeake Bay water quality standards attainment across the thirty 3-year assessment periods. Time series of flow-weighted TN concentration is shown on a separate y-axis. Key weather events, management actions, and change points are labeled with arrows.

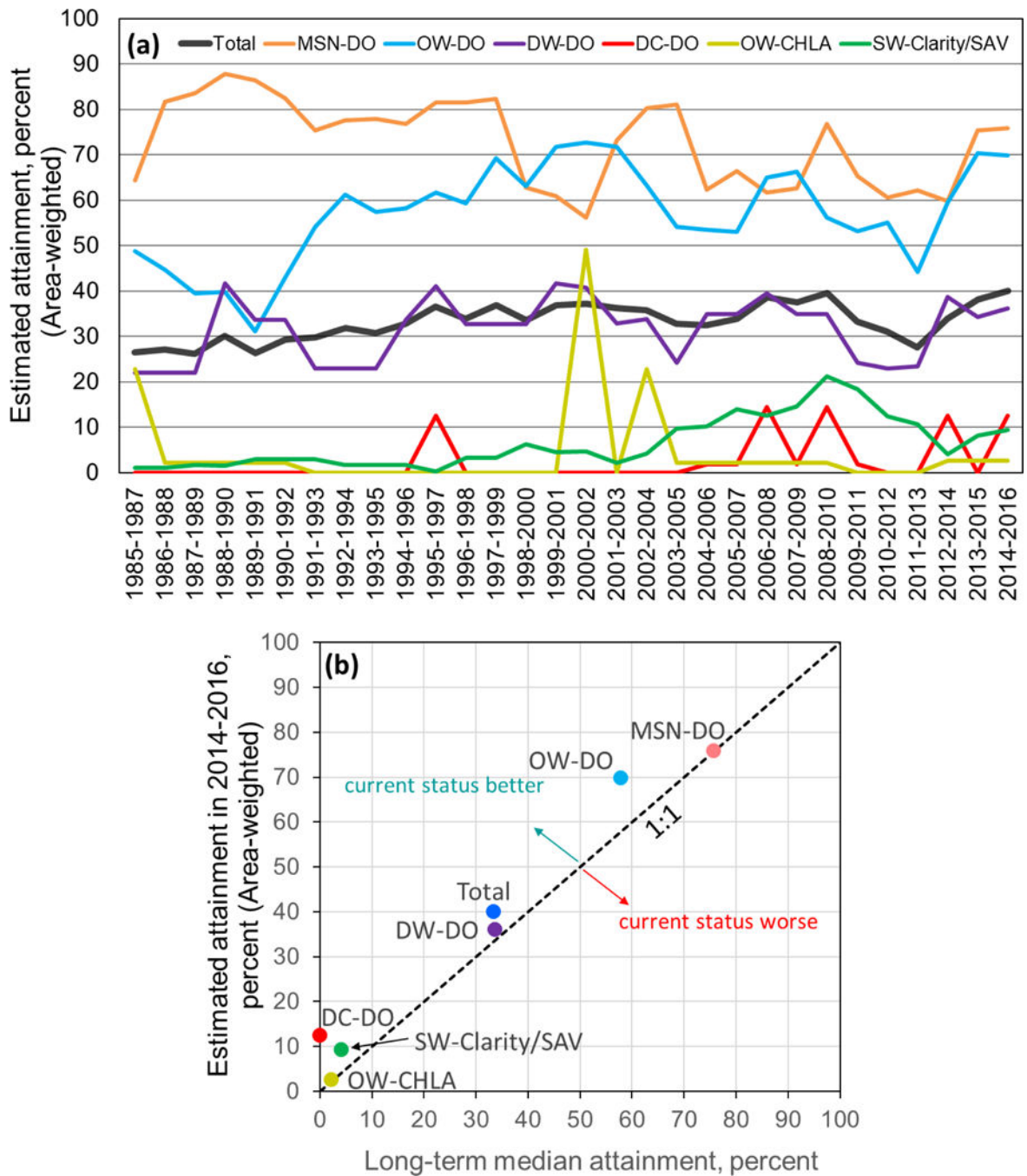


Fig. 4. Area-weighted estimated attainment results for the six designated uses (DUs). (a) Time series of DU-specific attainment scores between 1985–1987 and 2014–2016. (b) Comparison between the current attainment status (i.e., 2014–2016) and the long-term median for each DU.

Table 1.

Estimated attainment results (current and long-term median) for the Baywide indicator (“Total”) and each of the six designated uses (DUs) as well as results from the change point analysis and modified Mann-Kendall (MK) trend analysis.

Designated use	Index score in 2014–2016, percent	Long-term median of index score, percent	Change point (3-year period)	30-year trend ^a , percent/yr	10-year trend ^a , percent/yr
Baywide					
Total	40.0	33.4	1994–1996 ***	0.33 ***	-0.18 -
Designated uses					
MSN-DO	75.9	75.6	1997–1999 ***	-0.66 ***	-0.11 -
OW-DO	69.8	57.8	1991–1993 ***	0.61 *	0.69 -
DW-DO	36.1	33.6	1993–1995 -	0.10 ***	-0.13 -
DC-DO	12.6	0.0	2003–2005 ***	0.00 ***	-0.32 -
OW-CHLA	2.7	2.1	1999–2001 -	0.00 -	0.00 -
SW-Clarity/SAV	9.4	4.1	1997–1999 ***	0.42 ***	-1.08 ***

^aThe numeric Sen slope is presented along with significance levels generated from MK test. A zero Sen slope can happen with a significant MK test if the time series has many instances of the same value.

Significance levels:

(***) $p < 0.05$

(*) $0.05 < p < 0.1$

(-) and $p > 0.1$.