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Short Communication

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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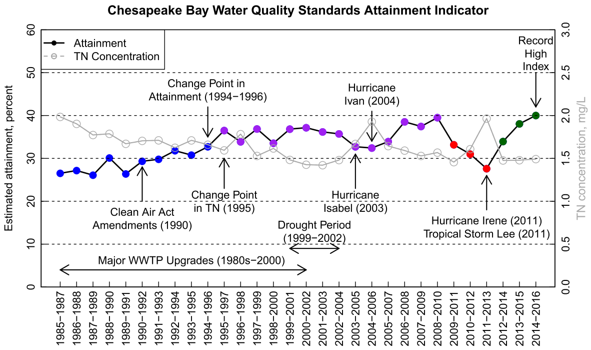
HIGHLIGHTS

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

GRAPHICAL ABSTRACT



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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 period of 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/submerged aquatic vegetation have combined to drive the

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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 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.

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 (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, 2003a). 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 establishes 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 toward 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 provide 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. More broadly, 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; Patrício 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). 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 has been sampled consistently since 1985, with 12–20 times per year and sometimes additional synoptic sampling (USEPA, 2010b; Tango and Batiuk, 2013). 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 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 interpolated 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

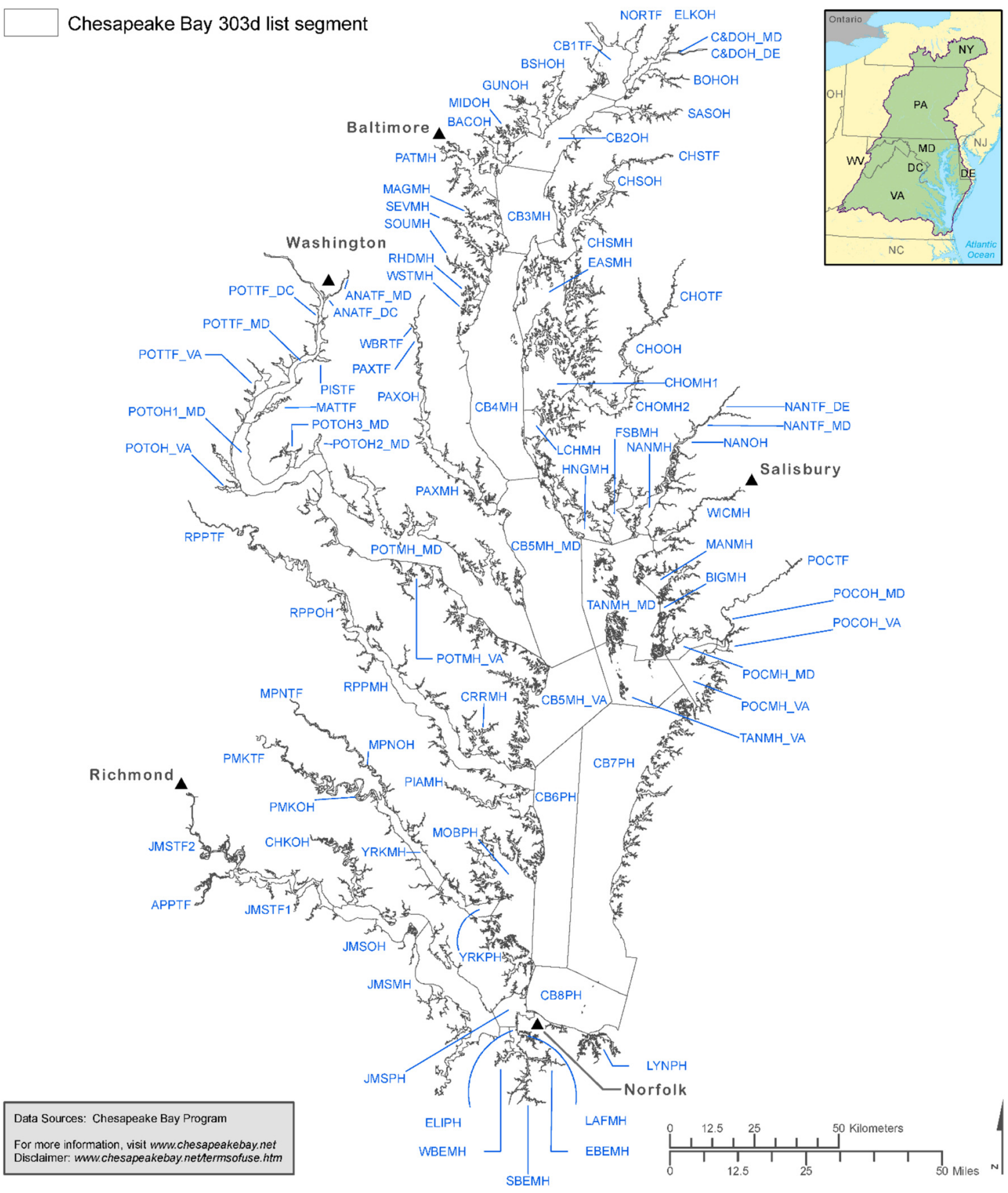

Fig. 1. Segmentation scheme used in the Chesapeake Bay water quality standards assessment (USEPA, 2004b; USEPA, 2005).

Batiuk et al. (2009) and USEPA (2003a) for full details. This methodology was based on the 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 are 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 CBP 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

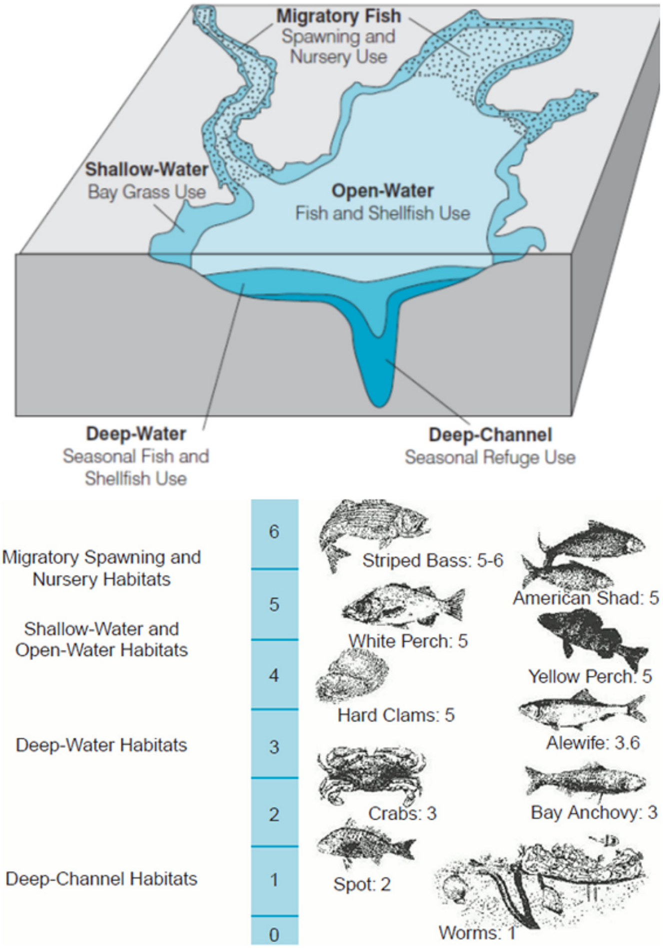

Fig. 2. The five designated uses in the Chesapeake Bay water quality standards attainment assessment. Top: conceptual illustration. Bottom: dissolved oxygen (mg/ L) concentrations required by different Chesapeake Bay species and communities (USEPA, 2003b; USEPA, 2003a; USEPA, 2004b).

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 assessment of the OW DO attainment status. 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 the 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 to 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 input 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} (*data not shown*) and has a longer series. Like the attainment indicator, the TN_{FWC} time series was also examined using the change-point analysis. Finally, we fit three generalized least squares models (GLS) to 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 was not known a priori, we chose to fit three models with different assumptions on the error structure:

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

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

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

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

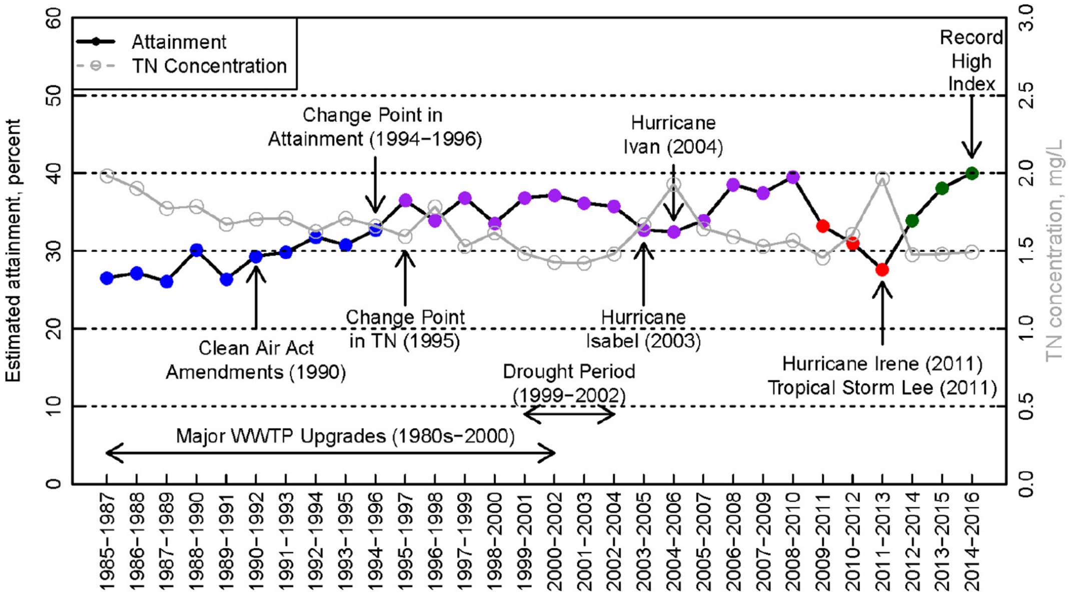

Fig. 3. Time series of the multimetric indicator score for estimated Chesapeake Bay water quality standards attainment across the thirty 3-year assessment periods. Time series of flow-weighted TN concentration is shown on a separate y-axis. Key weather events, management actions, and change points are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

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

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. Significance levels: $p < 0.05$ (***), $0.05 < p < 0.1$ (*), and $p > 0.1$ ($^{-}$).

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 ***

[a] The 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.

(0.33%/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 DUs' 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 periods 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%/yr; $p < 0.05$). DW-DO has a change point at 1993–1995 ($p = 0.14$) and a positive long-term trend (+0.10%/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 the 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.

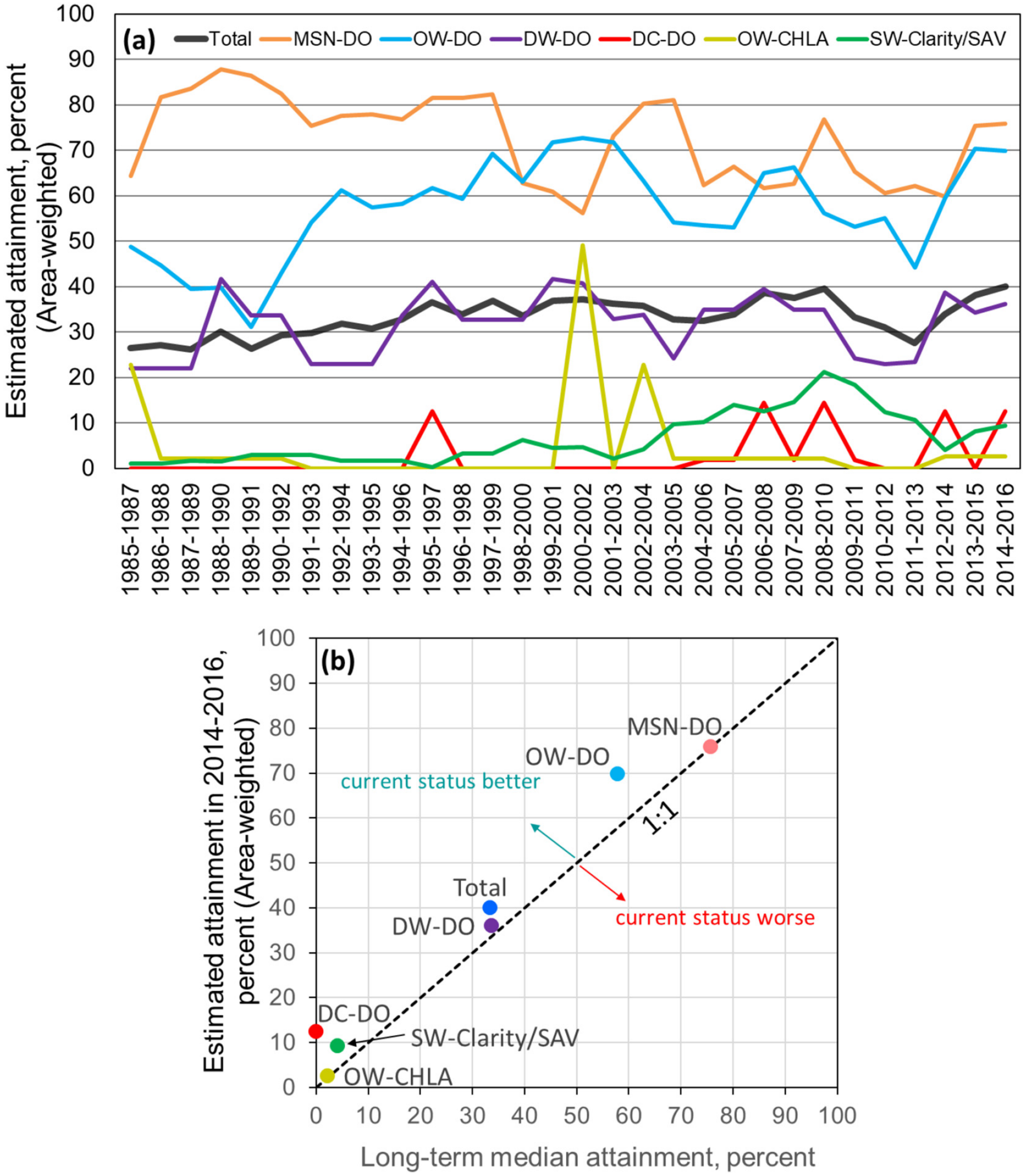

Fig. 4. Area-weighted estimated attainment results for the six designated uses (DUs). (a) Time series of DU-specific attainment scores between 1985–1987 and 2014–2016. (b) Comparison between the current attainment status (i.e., 2014–2016) and the long-term median for each DU.

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%/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 current status, 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%) and DC-DO (13% vs. 0%) and moderately better in SW-Clarity/SAV (9% vs. 4%). These improvements have contributed to the Baywide indicator's higher 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. 4a). 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 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 a 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; Chanat et al., 2016; Moyer et al., 2017). It has been understood that the early-year decline in TN is largely related to the decline in atmospheric deposition since the establishment of Clean Air Act Amendments in 1990 (Eshleman et al., 2013; Linker et al., 2013), 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., 2013; 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 the 1990s (Litke, 1999; Boynton et al., 2008; Lyerly et al., 2014) may have also contributed to a positive Bay response detected as 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 discussed above, 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 response 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 to 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 Baywide 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. In this regard, 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.05.025.

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Supplementary Materials for

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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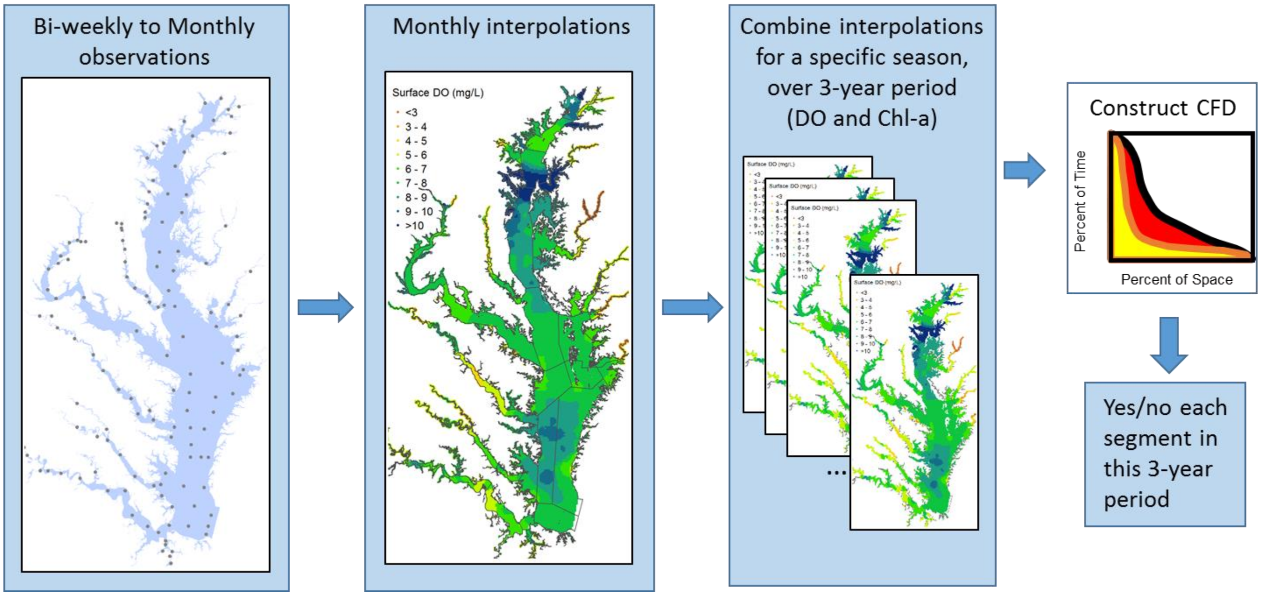

Fig. S1. Overview of the water quality standards assessment for dissolved oxygen and chlorophyll-a criteria. (Abbreviations: DO = dissolved oxygen; Chl-a = chlorophyll-a; CFD = cumulative frequency distribution.)

Table S1. Water quality standards criteria for dissolved oxygen, water clarity/underwater bay grasses, and chlorophyll-a and the designated uses (USEPA, 2003b; USEPA, 2003a; USEPA, 2004b). Criterion thresholds that were used in the water quality standards attainment procedures are shown in blue color.

Criterion	Designated Use	Season	Threshold	Critical Value	Applicable Segments	Designation in this paper
Dissolved Oxygen (DO)	Migratory fish spawning and nursery (MSN)	February 1 - May 31	30-day mean [a]	6 mg L^{-1}	73	MSN-DO
		February 1 - May 31	7-day mean	6 mg L^{-1}		
		February 1 - May 31	Instantaneous	5 mg L^{-1}		
		June 1 - January 31	*OW criteria apply*			
	Open-water fish and shellfish (OW)	Year-round	30-day mean [b]	5.5 mg L^{-1} in very low salinity; 5 mg L^{-1} otherwise	92	OW-DO
			7-day mean	4 mg L^{-1}		
			Instantaneous	3.2 mg L^{-1}		
	Deep-water seasonal fish and shellfish (DW)	June 1 - September 30	30-day mean	3 mg L^{-1}	18	DW-DO
		June 1 - September 30	1-day mean	2.3 mg L^{-1}		
		June 1 - September 30	Instantaneous	1.7 mg L^{-1}		
		October 1 - May 31	*OW criteria apply*			
	Deep-channel seasonal refuge (DC)	June 1 - September 30	Instantaneous	1 mg L^{-1}	10	DC-DO
		October 1 - May 31	*OW criteria apply*			
	Shallow-water bay grass (SW)	June 1 - September 30	*Dependent upon OW attainment assessment*		79	-
Chlorophyll-a (CHLA)	Open-water fish and shellfish (OW)	Spring (March 1 - May 31)	10 to 15 µg L^{-1} (salinity based)		7	OW-CHLA
		Summer (July 1 - September 30)	10 to 25 µg L^{-1} (salinity based)			
SAV and/or Water Clarity	Shallow-water bay grass (SW)	SAV season	Segment specific water clarity and bay grass acreage goals		79	SW-Clarity/SAV

[a] USEPA (2003) does not have a 30-day mean February-May threshold for MSN. The decision for indicator used a 30-day mean of 6 mg L^{-1} as February-May threshold, same as the 7-day mean threshold.

[b] June-September (as opposed to the entire year) is evaluated for the 30-day mean criterion for OW in the attainment assessment procedures.

Table S2. Time series of the estimated attainment scores (in percent) for the Baywide attainment indicator ("Total") and each of the six designated uses (DUs). Refer to Table S1 or the main text for details of the DUs.

Assessment Period	Total ("Indicator")	MSN-DO	OW-DO	DW-DO	DC-DO	OW-CHLA	SW-Clarity/SAV
1985-1987	26.5	64.3	48.7	21.9	0.0	22.7	1.0
1986-1988	27.2	81.6	44.7	21.9	0.0	2.1	1.0
1987-1989	26.1	83.6	39.4	21.9	0.0	2.1	1.7
1988-1990	30.1	87.8	39.8	41.6	0.0	2.1	1.6
1989-1991	26.4	86.4	31.0	33.6	0.0	2.1	2.9
1990-1992	29.3	82.4	42.9	33.6	0.0	2.1	2.9
1991-1993	29.8	75.3	54.0	22.9	0.0	0.0	2.9
1992-1994	31.8	77.5	61.1	22.9	0.0	0.0	1.7
1993-1995	30.8	77.9	57.5	22.9	0.0	0.0	1.7
1994-1996	32.7	76.8	58.2	33.6	0.0	0.0	1.7
1995-1997	36.5	81.6	61.6	41.1	12.6	0.0	0.2
1996-1998	33.9	81.6	59.2	32.7	0.0	0.0	3.3
1997-1999	36.9	82.4	69.2	32.7	0.0	0.0	3.3
1998-2000	33.5	62.8	63.1	32.7	0.0	0.0	6.2
1999-2001	36.8	60.8	71.7	41.6	0.0	0.0	4.5
2000-2002	37.2	56.1	72.6	40.8	0.0	49.0	4.6
2001-2003	36.2	73.1	71.8	32.8	0.0	0.0	2.2
2002-2004	35.7	80.3	63.3	33.9	0.0	22.7	4.2
2003-2005	32.7	81.0	54.1	24.1	0.0	2.1	9.7
2004-2006	32.4	62.3	53.5	34.9	1.9	2.1	10.1
2005-2007	33.9	66.4	53.0	34.9	1.9	2.1	14.0
2006-2008	38.5	61.6	64.9	39.5	14.5	2.1	12.5
2007-2009	37.4	62.6	66.2	34.9	1.9	2.1	14.6
2008-2010	39.5	76.7	56.1	34.9	14.5	2.1	21.2
2009-2011	33.2	65.3	53.2	24.3	1.9	0.0	18.3
2010-2012	31.0	60.6	55.1	22.9	0.0	0.0	12.3
2011-2013	27.6	62.1	44.3	23.3	0.0	0.0	10.6
2012-2014	33.9	59.8	59.5	38.7	12.6	2.7	4.1
2013-2015	38.1	75.4	70.4	34.2	0.0	2.7	8.2
2014-2016	40.0	75.9	69.8	36.1	12.6	2.7	9.4