

Maryland Lower Eastern Shore Tributary Summary:
A summary of trends in tidal water quality and
associated factors, 1985-2023.

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Prepared for the Chesapeake Bay Program (CBP) Partnership by the CBP
Integrated Trends Analysis Team (ITAT)



Chesapeake Bay Program

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1. Purpose and Scope

The Lower Eastern Shore Tributary Summary outlines change over time according to a suite of monitored tidal water quality parameters and associated potential drivers of those trends for the period 1985 – 2023, and provides a brief description of the current state of knowledge explaining these observed changes. Water quality parameters described include surface (above pycnocline) total nitrogen (TN), surface total phosphorus (TP), surface water temperature (WTEMP), spring (March-May) and summer (July-September) surface chlorophyll *a*, summer bottom (below pycnocline) dissolved oxygen (DO) concentrations, and Secchi disk depth (a measure of water clarity). Results for annual bottom TP, bottom TN, surface ortho-phosphate (PO₄), surface dissolved inorganic nitrogen (DIN), surface total suspended solids (TSS), and summer surface DO concentrations are provided in an Appendix B. Drivers discussed include physiographic watershed characteristics, changes in TN, TP, and sediment loads from the watershed to tidal waters, expected effects of changing land use, and implementation of nutrient management and natural resource conservation practices. Factors internal to estuarine waters that also play a role as drivers are described including biogeochemical processes, physical forces such as wind-driven mixing of the water column and increase in rainfall intensity and volume, and biological factors such as phytoplankton biomass and the presence of submersed aquatic vegetation. Continuing to track water quality response and investigating these influencing factors are important steps to understanding water quality patterns and changes in the Lower Eastern Shore. The intended audiences for this report include, but are not limited to, 1) technical managers within jurisdictions who use tidal water quality to inform management decisions, 2) local watershed organizations that are trying to understand these analyses and working to connect them to their local area(s), and 3) federal, state, and academic researchers. Figure 1 presents a conceptual model highlighting these intended audiences. The Tributary Summary documents are sources of readily available background for change over time in tidal water quality observed with monitoring data. They help answer questions related to water quality, show how landscape factors drive water-quality changes over time, provide support for management decisions that may alter water quality trends and living resources conditions, and highlight where there may be information or knowledge gaps.

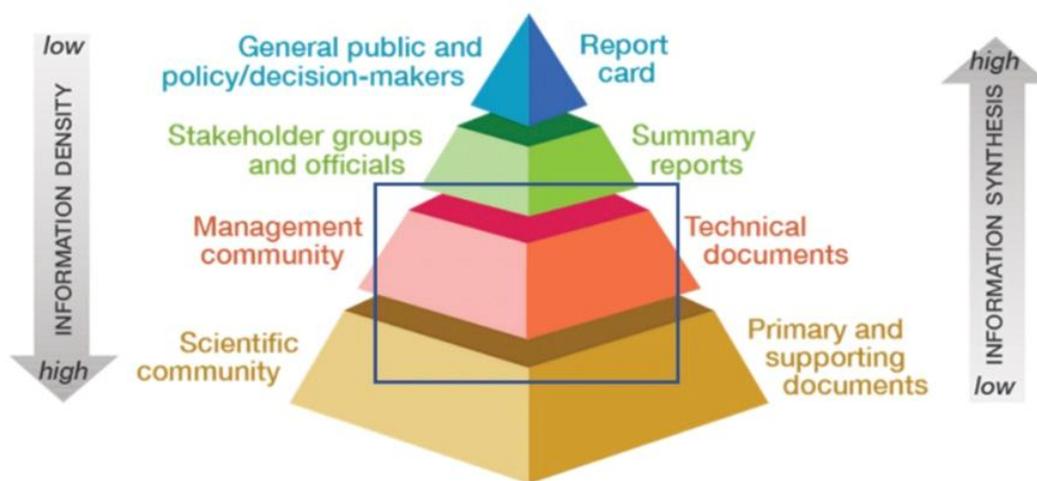


Figure 1: Conceptual model detailing different levels of information density and information synthesis. The intended audiences for the Tributary Summary denoted by the blue box. Figure courtesy of the

University of Maryland Center for Environmental Science Integration and Application Network (<https://ian.umces.edu/https://ian.umces.edu/>).

2. Location

The Lower Eastern Shore watershed is the sixth largest subwatershed in the Chesapeake Bay drainage basin, covering roughly 2.3% of the Chesapeake Bay Watershed. Its watershed is approximately 9,022 km² (Table 1) and spans three states, Delaware, Maryland, and Virginia (Figure 2). Major tributaries to the Lower Eastern Shore include the Nanticoke, Manokin, Wicomico, Big Annemessex, and Pocomoke Rivers, and the Tangier Sound.

Table 1. Watershed areas, which includes tidal wetland area, for each of the 12 tributary or tributary groups for which Tributary Summaries have been produced. Data are from the Chesapeake Assessment Scenario Tool (CAST;

<https://cast.chesapeakebay.net/About/UpgradeHistory><https://cast.chesapeakebay.net/About/UpgradeHistory>, version Phase 6 – 7.6.0). Each of the tributary summaries can be accessed at the following link: <https://cast.chesapeakebay.net/Home/TMDLTracking#tributaryRptsSection>².

Tributary	Tributary Area (km ²)
Virginia Mainstem	165,397
Maryland Mainstem	119,759
Potomac	37,457
James	31,147
York	12,530
Lower Eastern Shore	9,022
Rappahannock	6,729
Maryland Upper Eastern Shore	2,647
Patuxent	2,476
Choptank	1,845
Patapsco-Back	1,647
Maryland Upper Western Shore	1,523
Maryland Lower Western Shore	439

Source: Data are from the Chesapeake Assessment Scenario Tool (CAST)

2.1 Watershed Physiography

The Lower Eastern Shore watershed is entirely located in the Coastal Plain region (Figure 2). This physiography covers lowland, dissected upland, and upland areas. Implications of these physiographies for nutrient and sediment transport are summarized in Section 5.1.1.

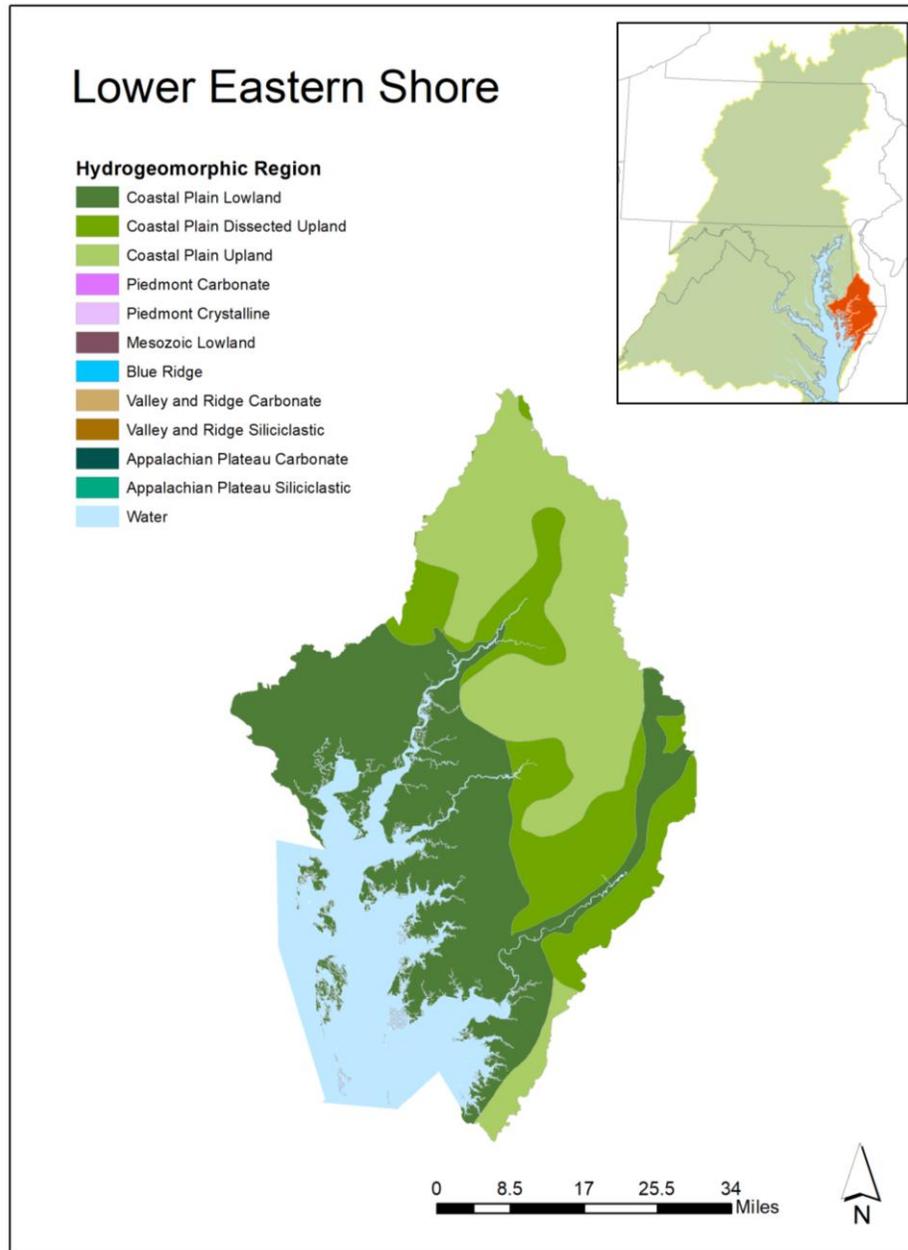


Figure 2. Distribution of physiography in the Lower Eastern Shore watershed, shown in dark orange, bottom right of the inset map. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983. Hydrogeomorphic region data credit to Brakebill and Kelley, 2023.

2.2 Land Use

Land use in the Lower Eastern Shore watershed is dominated (52%) by natural areas. Urban and suburban land areas have increased by 205 square kilometers since 1985, agricultural lands have decreased by 216 square kilometers, and natural lands have increased by 8 square kilometers. Correspondingly, the proportion of urban land in this watershed has increased from 8% in 1985 to 13% in 2023 (Figure 3). Since the 1970s, urban areas have expanded into previously natural and agricultural landscapes (Figure 4). The impacts of land development differ depending on the use from which the

land is converted (Keisman *et al.*, 2019; Ator *et al.*, 2020). Implications of changing land use for nutrient and sediment transport are summarized in Section 5.1.3.

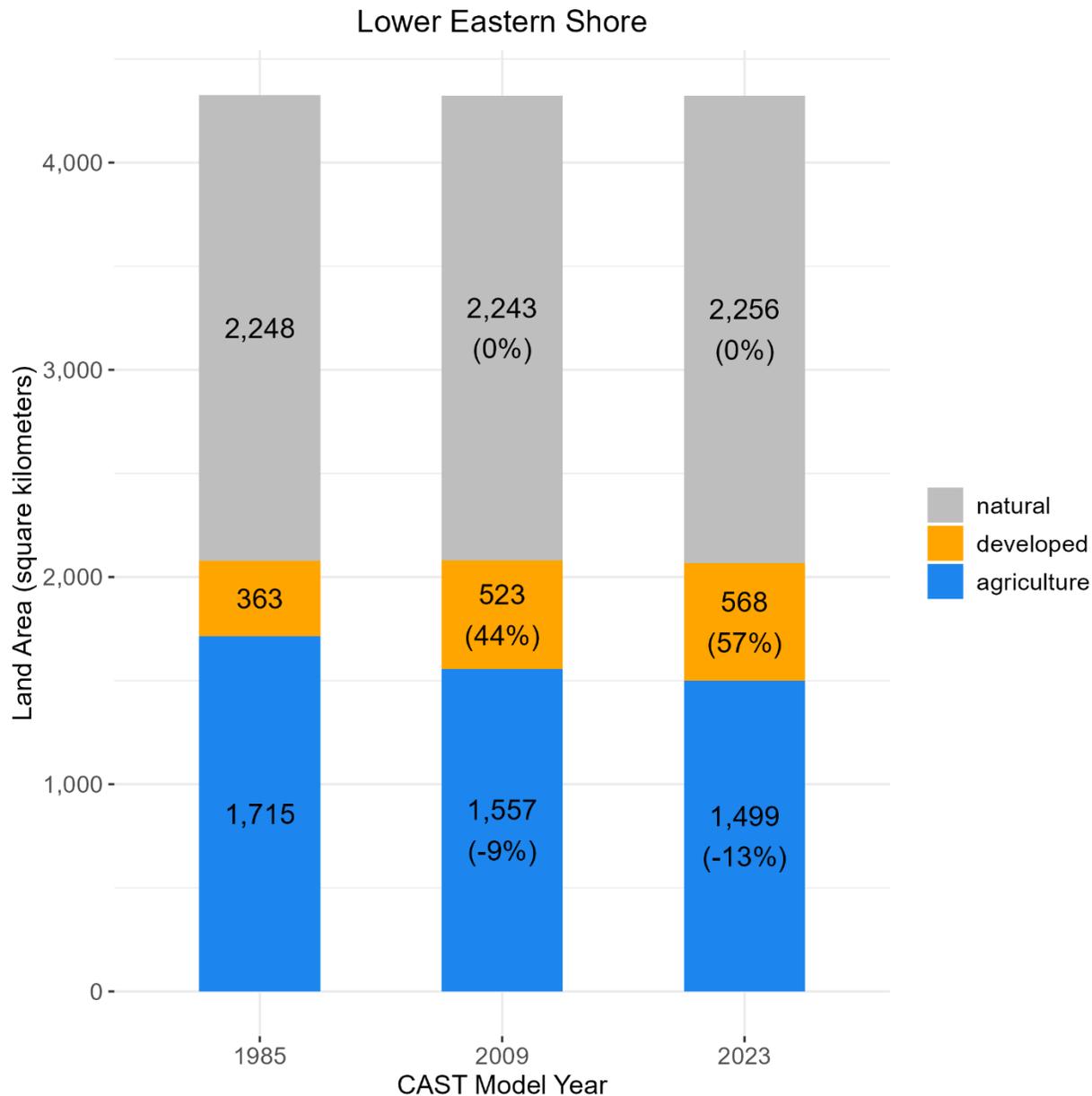


Figure 3. Distribution of land uses in the Lower Eastern Shore watershed. Percentages are the percent change from 1985 for each source sector. Data are from the Chesapeake Assessment Scenario Tool (CAST, 2023).

In general, prior to 1980, developed lands within the Lower Eastern Shore were mainly located around Salisbury municipality area which held 23.89% of contiguously developed and semi-developed areas. Smaller developed pockets were also present around Seaford and Laurel, DE. Since 1980, most development has occurred around Salisbury (Figure 4), with less concentrated development occurring around the other areas (Figure 4). Implications of changing land use for nutrient and sediment transport are summarized in Section 5.1.3.

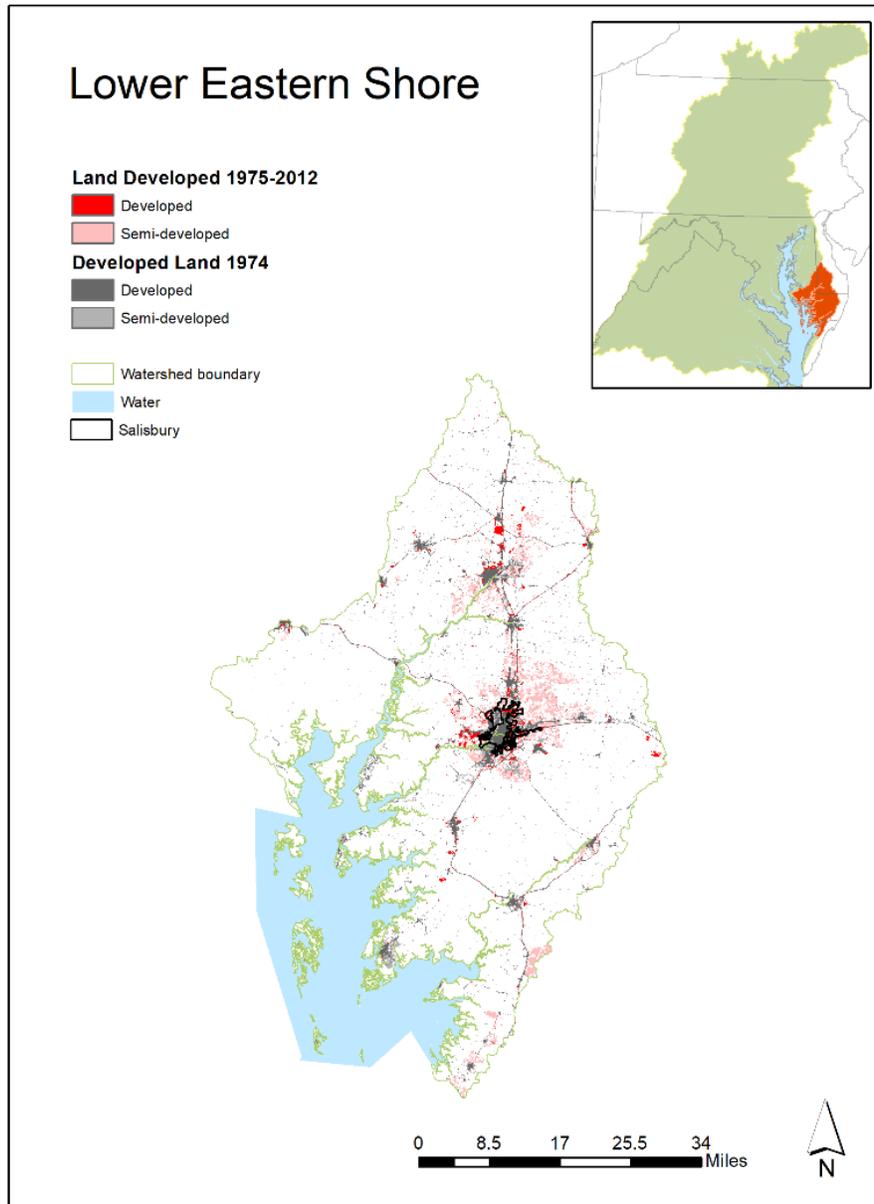


Figure 4. Distribution of developed land in the Lower Eastern Shore watershed, shown in dark orange on the inset map. Derived from Falcone (2015). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

2.3 Tidal Waters and Stations

For the purposes of water quality standards assessment and reporting, the tidal waters associated with the Lower Eastern Shore Tributaries are divided into 15 split segments across three states (USEPA, 2004). The Tidal Fresh Nanticoke River is split between Delaware (NANTF_DE) and Maryland (NANTF_MD). Other segments in Maryland include Mesohaline Fishing Bay (FSBMH), Oligohaline and Mesohaline Nanticoke River (NANOH, NANMH), Mesohaline Wicomico River (WICMH), Manokin River

(MANMH), and Big Annessex River (BIGMH); the Tidal Fresh, Oligohaline and Mesohaline Pocomoke River (POCTF, POCOH_MD, POCMH_MD); and the Maryland portion of the Mesohaline Tangier Sound (TANMH_MD). Segments in Virginia include Oligohaline and Mesohaline Pocomoke River (POCOH_VA, POCMH_VA) and the Virginia portion of the Mesohaline Tangier Sound (TANMH_VA).

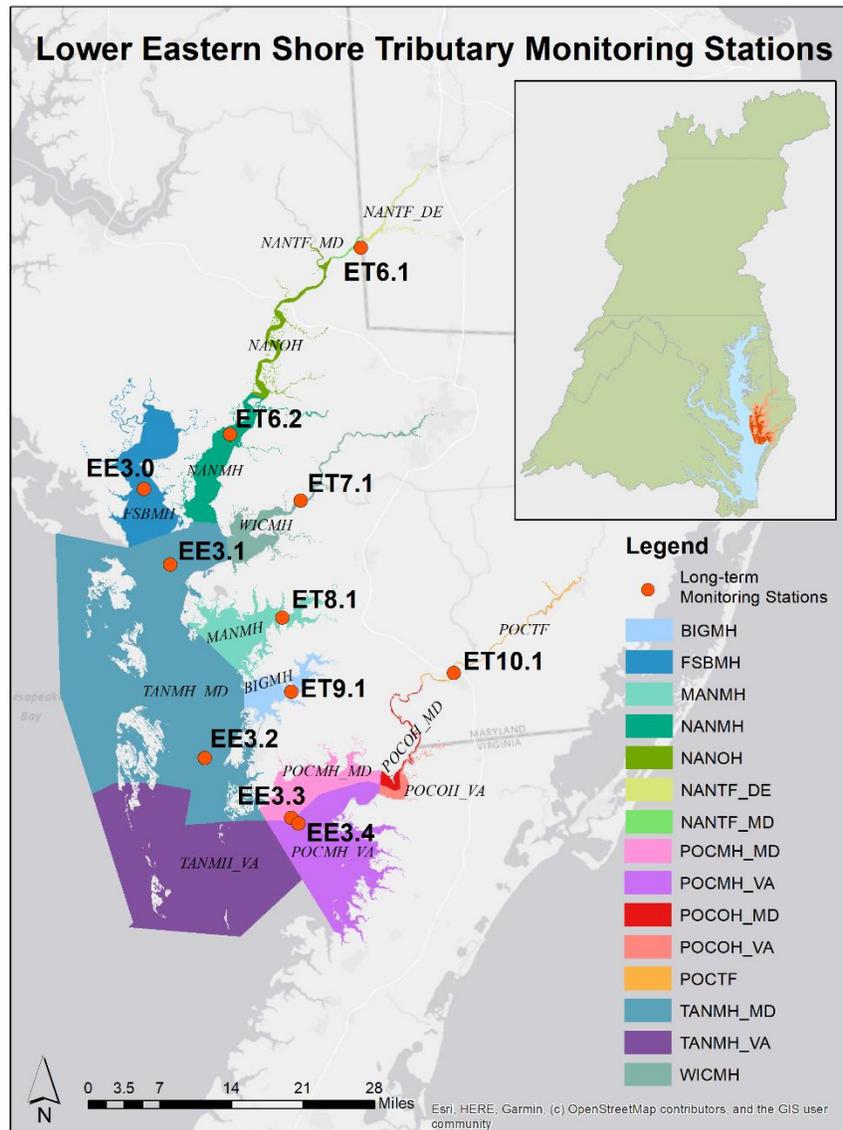


Figure 5. Map of tidal Lower Eastern Shore River segments and long-term monitoring stations. Base map credit Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community, World Geodetic System 1984.

Long-term trends in water quality are analyzed by both the Maryland Department of Natural Resources and the Virginia Department of Environmental Quality at 11 stations throughout these tributaries (Figure 5). Water quality data at these stations are also used to assess attainment of DO water quality

criteria. All tidal water quality data analyzed for this report are available from the Chesapeake Bay Program Data Hub (Chesapeake Bay Program, 2024). Other shallow-water monitoring has been conducted in these waters, but it is not included in the long-term trend graphics in subsequent sections because of its shorter duration. For additional information please refer to [Maryland Department of Natural Resources Eyes on the Bay](#) (EOTB) website (MDNR, 2025) and the [Chesapeake Monitoring Cooperative \(CMC\) Data Explorer](#) (CMC, 2025), which together serve up much of the extensive additional monitoring data that has been collected in the MD mainstem. Those observations are not included in subsequent trend graphics which focus on the long-term monitoring at fixed stations.

3. Tidal Water Quality Status

The Lower Eastern Shore provides a direct example of the relevance of long-term water quality monitoring and the evaluation of long-term trends relative to environmental management goals. Multiple water quality standards were developed for the tidal waters of Chesapeake Bay to protect aquatic living resources (U.S. Environmental Protection Agency, 2003; Tango and Batiuk, 2013). These standards include specific criteria for DO, chlorophyll-a, and water clarity/underwater bay grasses. A record of the evaluation results indicating whether different segments of this system have attained DO criteria over time (Zhang et al., 2018a; Zhang et al., 2018b; Hernandez Cordero et al., 2020) are shown below (Figure 6). These results provide context for the importance of understanding water quality trends and the underlying drivers. More specifically, trends in the water quality parameters summarized in this report directly affect environmental management goals implemented by stakeholders within the watershed. For more information on water quality standards, criteria, and standards attainment, visit the CBP's "Chesapeake Progress" website at www.chesapeakeprogress.com.

Attainment deficit is an approach used to document whether a particular criterion is met in a certain period, and if not, how far the segment is from meeting it. If the attainment deficit was zero, the criterion was fully met; a negative attainment deficit indicates how far the segment and designated use was from meeting the criterion during that period. The graphics in Figure 6 show that the Open Water (OW) criterion was at or near zero from the start of monitoring to the most recent assessment period covered by this report (2020-2022) in eight segments, namely, BIGMH, FSBMH, MANMH, NANMH, POCMH_MD, POCMH_VA, TANMH_MD, and TANMH_VA. In contrast, the other segments showed a high degree of variability with four segments (NANO, NANTF_DE, NANTF_MD, WICMH) attaining the criterion in some assessment periods and three segments (POCOH_MD, POCOH_VA, POCTF) never achieving that status. Notably, five segments (NANO, NANTF_DE, NANTF_MD, POCOH_MD, POCOH_VA) consistently reached their minimum values of attainment deficit around the 2001-2003 assessment period and then recovered to levels at or close to full attainment in the most recent assessment period. Mann-Kendall trend results for 1985 – 2022 indicated four statistically significant trends in OW-DO, i.e., long-term improvements in POCOH_MD and POCOH_VA and long-term declines in POCTF and WICMH (Figure 6). The 30-day mean OW summer DO criterion status is mixed in this region, with some segments meeting the criterion and some not. Most of the stations show no long-term trend in surface DO. This example shows the importance of establishing criteria and monitoring water quality conditions relative to established goals for those criteria. It also demonstrates the relevance of trend results in relation to criteria assessments.

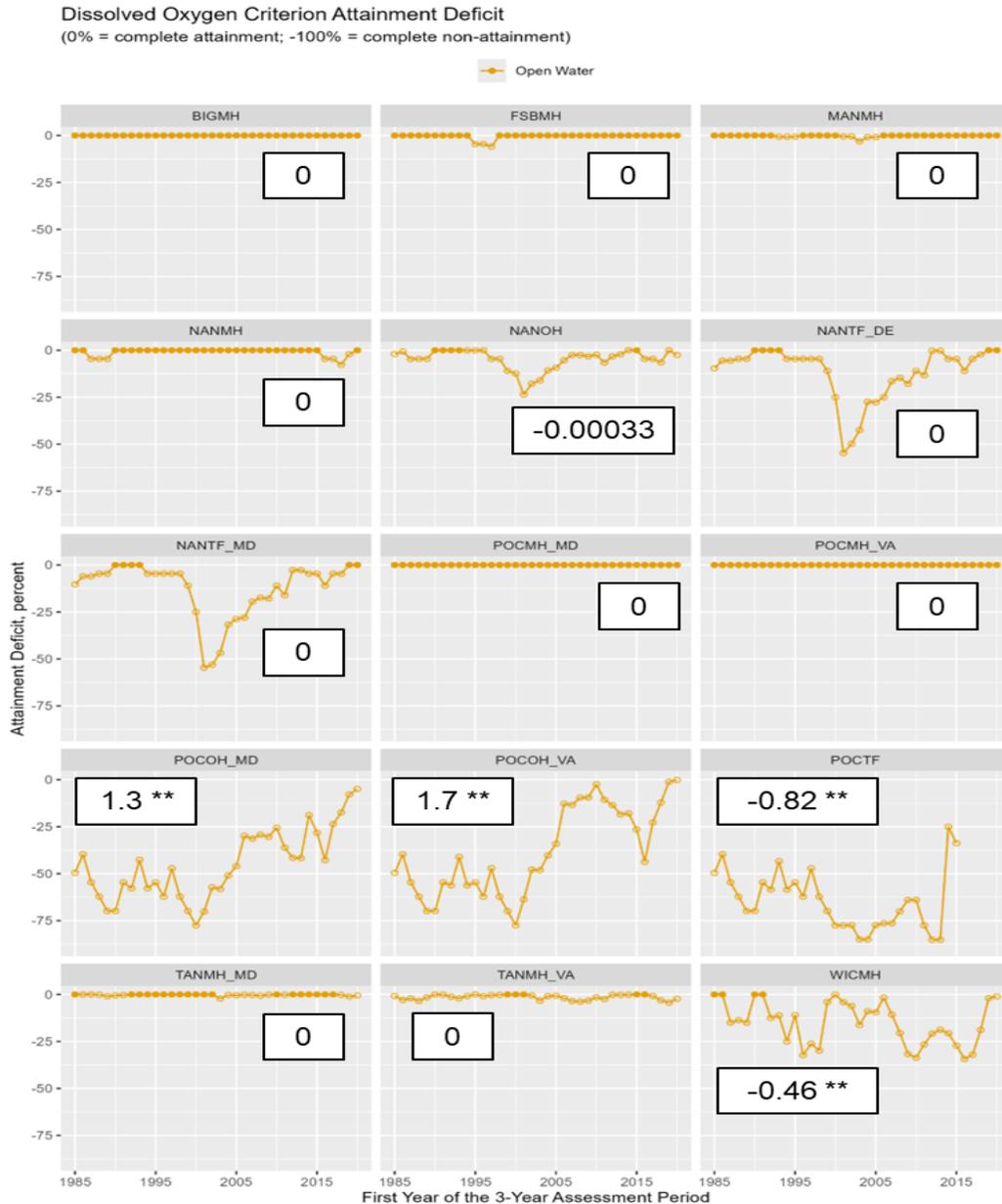


Figure 6. Attainment deficit for Open Water (30-day mean; June-September) dissolved oxygen criteria for three-year assessment periods from the start of monitoring (1985) through the current (2020-2022) assessment period. A value of 0% indicates full attainment for a given criterion, while negative values indicate percent non-attainment (deficit) for the segment and criterion being plotted. Numbers associated with a given line are the Sen Slope estimates. Trends significant at $p < 0.05$ are indicated by ** or at $p < 0.1$ by *.

Comparing trends in station-level DO concentrations to the computed DO criterion status for a recent assessment period can reveal whether progress is being made towards attainment in a segment that is

not meeting the water quality criteria, or conversely, the possibility that conditions are degrading even if the criteria are currently being met. To illustrate this, the 2020-2022 attainment status for the OW summer DO criteria based on passed/failed assessment are overlain with the 1985-2022 change in summer surface DO concentration (Figure 7). In this region, a distinct spatial pattern appears, with the more upstream segments in the Nanticoke, Wicomico, and Pocomoke Rivers not meeting the 30-day mean OW summer DO criterion and having degrading oxygen concentrations. All other mesohaline segments, including Fishing Bay, Tangier Sound, Manokin, Big Annemessex, and mesohaline Pocomoke segments, are meeting the criterion and have improving or no trend in oxygen.

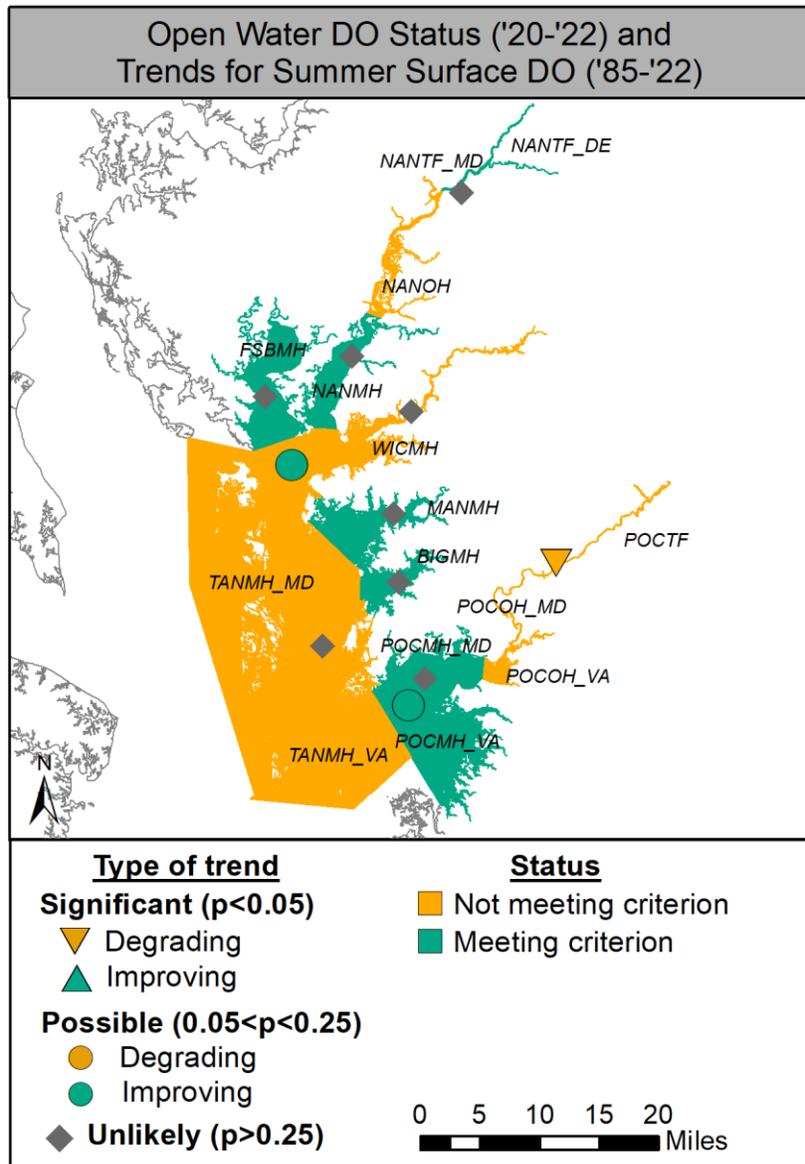


Figure 7. Pass-fail DO criterion status for 30-day OW summer DO designated use in Lower Eastern Shore segments along with long-term trends in DO concentrations. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

4. Tidal Water Quality Trends

Tidal water quality trends were computed by fitting generalized additive models (GAMs) to the water quality observations that have been collected one or two times per month since the 1980s at the 11 Lower Eastern Shore tidal stations labeled in Figure 5. For more details on the GAM implementation that is applied each year by MD Department of Natural Resources and VA Department of Environmental Quality for these stations in collaboration with the Chesapeake Bay Program, refer to Murphy et al. (2019).

Results shown below in each set of maps (Figure 8) include those generated using two different GAM fits to each station-parameter combination. The first approach involves fitting a GAM to the raw observations to generate a mean estimate of change over time, as observed in the estuary. The second approach involves including monitored river flow or *in situ* salinity (as an aggregated measure of multiple river flows) in the GAM to explain some of the variation in the water quality parameter. From the results of this second approach, it is possible to estimate the “flow-adjusted” change over time, which gives a mean estimate of what the water quality parameter trend would have been if average river flows had been observed over the period of record. Note that depending on station and parameter, gaged river flow or salinity is used for this adjustment, but we refer to all these results as “flow-adjusted” for simplicity.

To determine if there has been a change over time (i.e., a trend) at a particular station for a given parameter, we compute a percent change between the estimates at the beginning and end of a period of interest. For each percent change computation, the level of statistical significance is computed and indicated on the maps. Change is called significant if $p < 0.05$ and possible if the p -value is up to 0.25. That upper limit is higher than usually reported for statistical tests but allows us to provide a more complete picture of the results, identifying locations where change might be starting to occur and could be further investigated (Murphy et al., 2019). In addition to the maps of trends, for each parameter, there is a set of graphs (e.g., Figure 9) that include the raw observations (dots on the graphs) and lines representing the mean annual or seasonal GAM estimates, without flow adjustment. Each set of graphs corresponds to the top left map of the preceding figure, showing long-term data without flow adjustment, grouped by segments designated in Figure 5. The flow-adjusted GAM line graphs are not shown so that figures better represent what living resources (e.g., fish species, SAV, blue crabs) experience.

To view tidal water quality trends across the Chesapeake Bay watershed and compare trends between tributaries, please refer to the Integrated Trends Analysis Team project webpage: [Integrated Trends Analysis Team Projects](#) (CBP, 2025). To view an interactive map of tidal water quality trends across the Chesapeake Bay watershed and compare mean parameter measurements between tributaries, please visit the [baytrendsmat interactive tool](#) (Chesapeake Bay Program and U.S. Geological Survey, n.d).

4.1 Surface Total Nitrogen

Annual total nitrogen (TN) trends are improving at most of the Lower Eastern Shore stations over the long term, with and without flow adjustment (Figure 8). Station ET6.1, in the Nanticoke River stands out in this region as having possible degrading and no trends in TN in the flow-adjusted and non-flow-adjusted, respectively. Over the short term, most of the stations are possibly or significantly improving, with ET6.1, ET3.2, ET9.1 showing an unlikely trend for non-flow-adjusted, and ET3.3 showing an unlikely trend for the flow-adjusted (Figure 8).

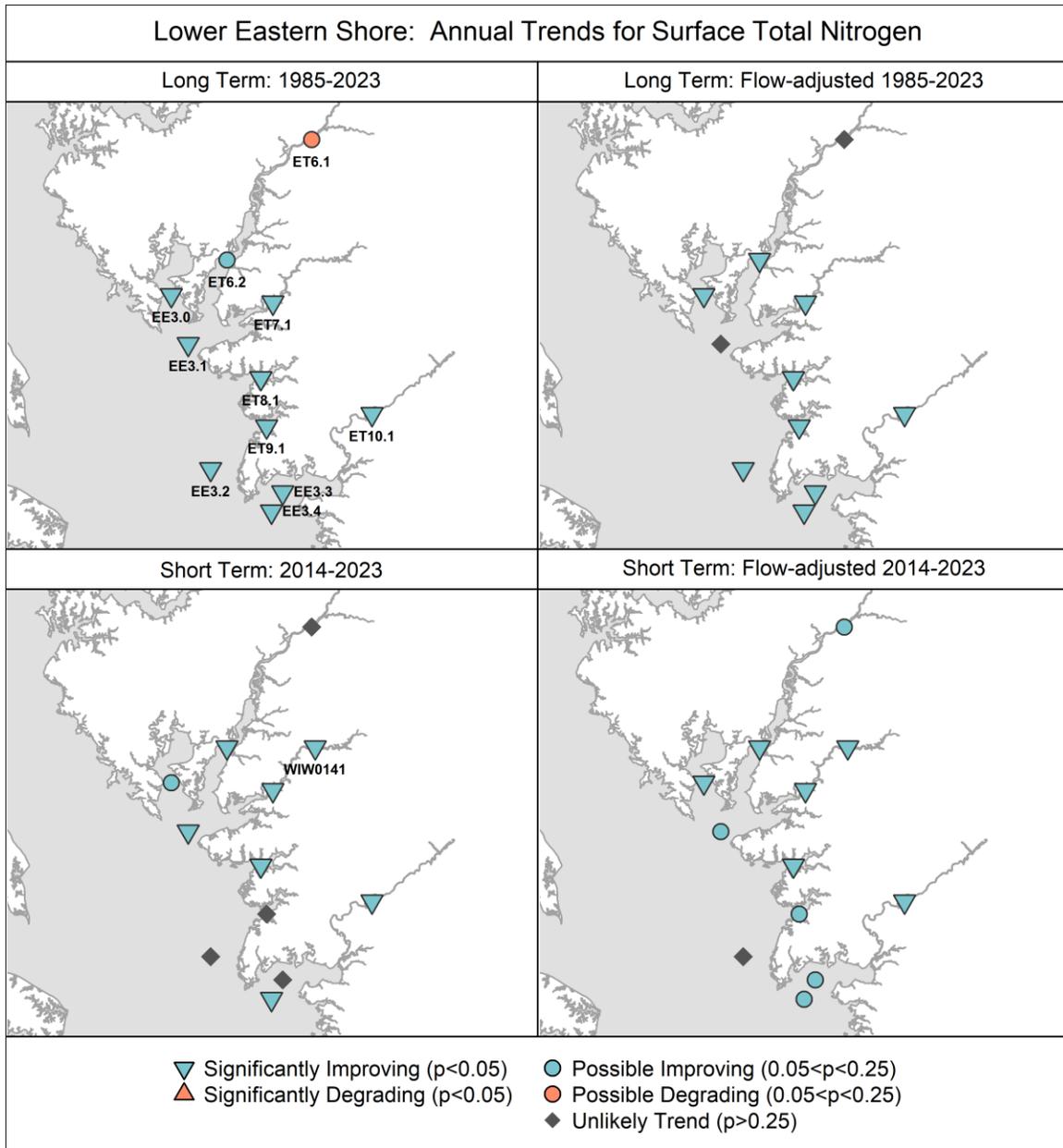


Figure 8. Surface TN trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983. For more information on the tidal stations and Chesapeake Bay tidal water quality monitoring, refer to <https://www.chesapeakebay.net/what/programs/quality-assurance/tidal-water-quality-monitoring>.

The TN mean annual GAM estimates fluctuate year-to-year (Figure 9), likely due to variability in freshwater flow. The two tidal fresh stations in this group (ET6.1 and ET10.1), and WW0141 have higher TN concentrations than the remaining mesohaline stations (Figure 9). Other long-term trends are difficult to discern, likely because of a method change in 1998 that caused a shift in the data values. Vertical blue dotted lines represent this laboratory and method change (May 1, 1998) that was tested for its impact on data values. A statistical intervention test within the GAM models showed that these changes were significant at most stations. This is evident by the vertical jump in the mean annual GAM

estimates shown with the lines. With this technique, we can estimate long-term change after accounting for the artificial jump from the method change (Murphy et al., 2019). Each station (with the exception of ET6.1) shows significant improvement as indicated by the downward trend for each of the plotted lines, especially in the short term.

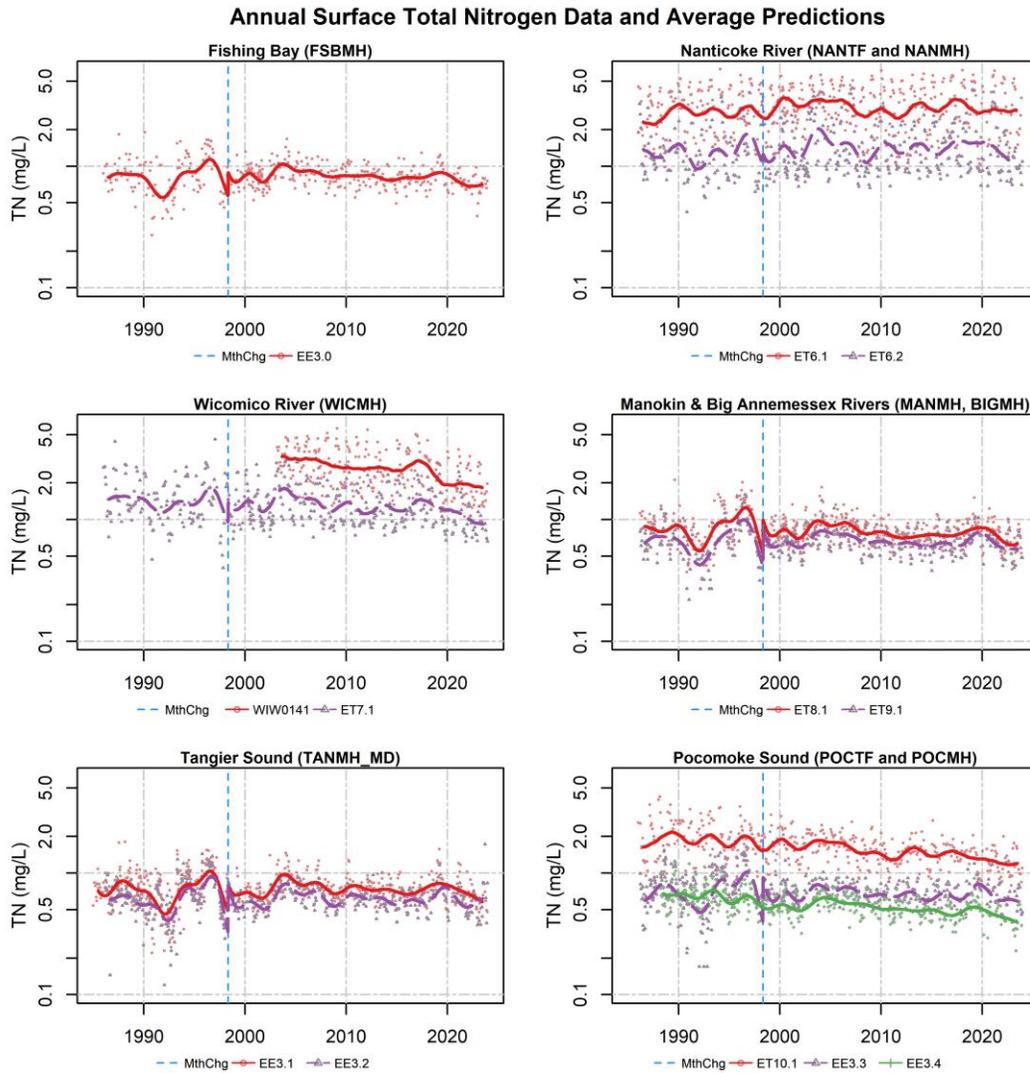


Figure 9. Surface TN data (dots) and average long-term pattern generated from non-flow adjusted Generalized Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations. Vertical blue dotted lines (MthChg) represent timing of changes in laboratory and/or sampling methods.

4.2 Surface Total Phosphorus

Surface total phosphorus (TP) trends are improving at most stations over the long term, both with and without flow adjustment (Figure 10). EE3.4 shows only a possible improvement for flow-adjusted trends. However, short-term flow-adjusted trends show a mix of no-trend, possibly degrading and degrading conditions (Figure 10).

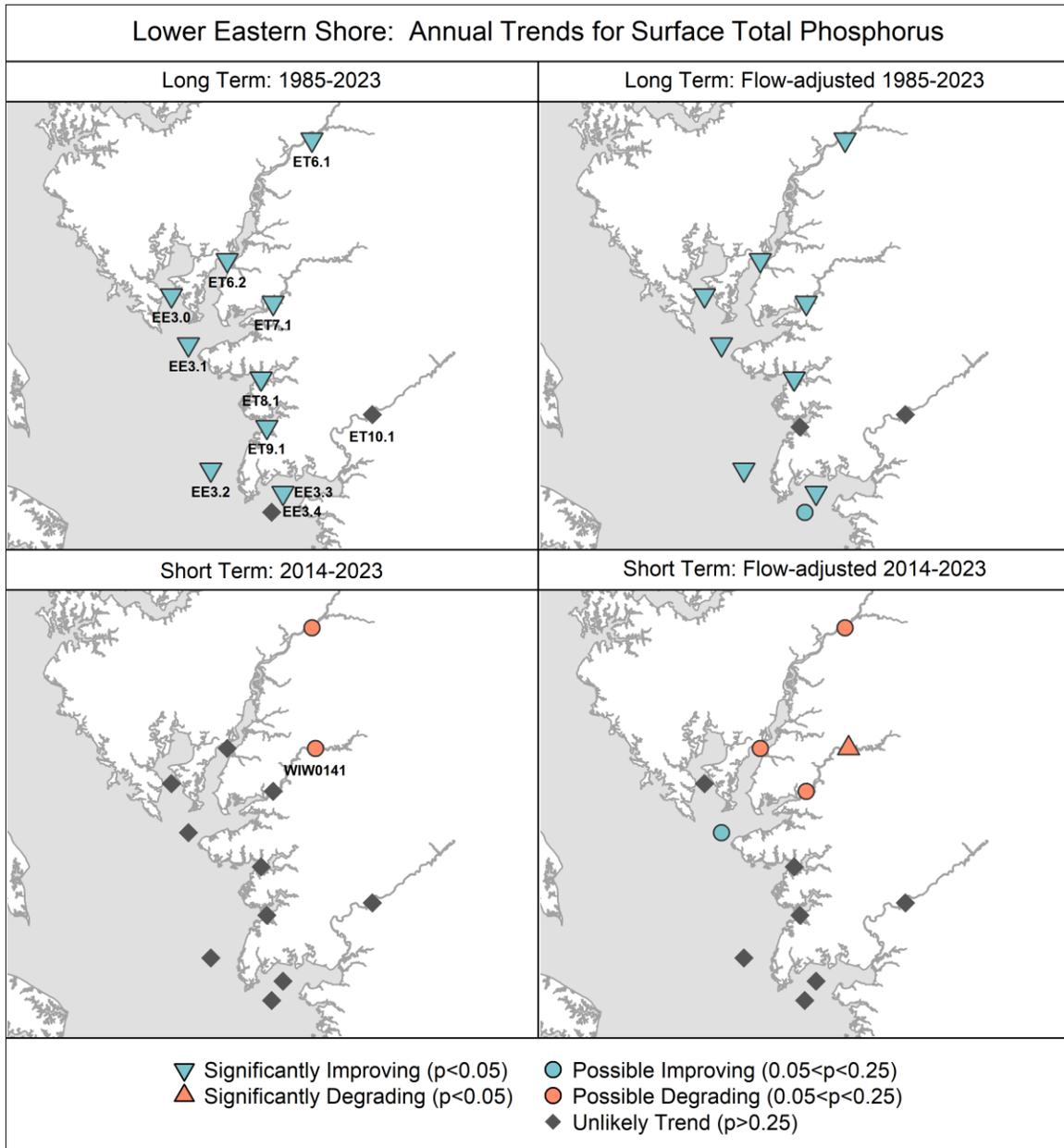


Figure 10. Surface TP trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983. For more information on the tidal stations and Chesapeake Bay tidal water quality monitoring, refer to <https://www.chesapeakebay.net/what/programs/quality-assurance/tidal-water-quality-monitoring>.

The long-term improvements at most of the Lower Eastern Shore stations are evident in the data values and mean annual GAM estimates (Figure 11). Many of the decreases are in the first decade of the record, and concentrations level-out in the second half of the record. The upswing from 2010 to 2020 has begun to taper downwards over the past three years for stations within the bay, while stations closer to tidal freshwater are showing more consistent concentrations.

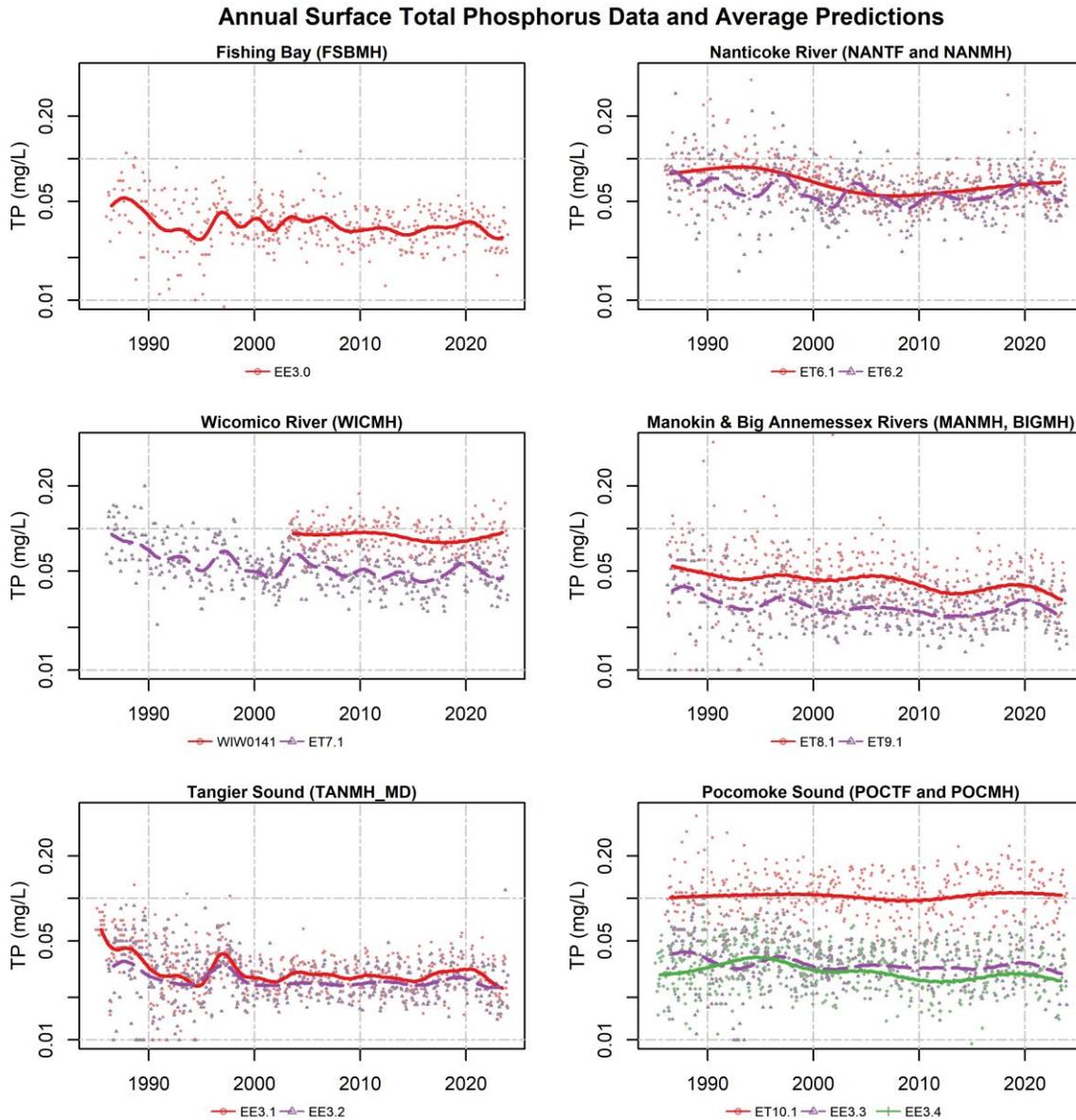


Figure 11. Surface TP data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent data corresponding to the monitoring station indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

4.3 Surface Chlorophyll *a*: Spring (March-May)

Trends for chlorophyll *a* are split into spring and summer to analyze chlorophyll *a* during the two seasons when phytoplankton blooms are commonly observed in different parts of Chesapeake Bay (Smith and Kemp, 1995; Harding and Perry, 1997). Spring long-term chlorophyll *a* trends are degrading or show an unlikely trend at most stations with and without flow adjustment (Figure 12). EE3.4 is significantly improving for both long term non- and flow-adjusted. ET8.1 shows significant improvement for flow-adjusted, and possible improvement for ET10.1 for non-flow-adjusted. Over the short-term, ET6.1 and ET6.2 show significantly degrading trends with and without flow adjustment, and ET7.1 shows possible degrading without flow adjustment (Figure 12). EE3.0, EE3.1, and ET8.1 show significantly improving trends across both short-term non-flow-adjusted and flow-adjusted trends.

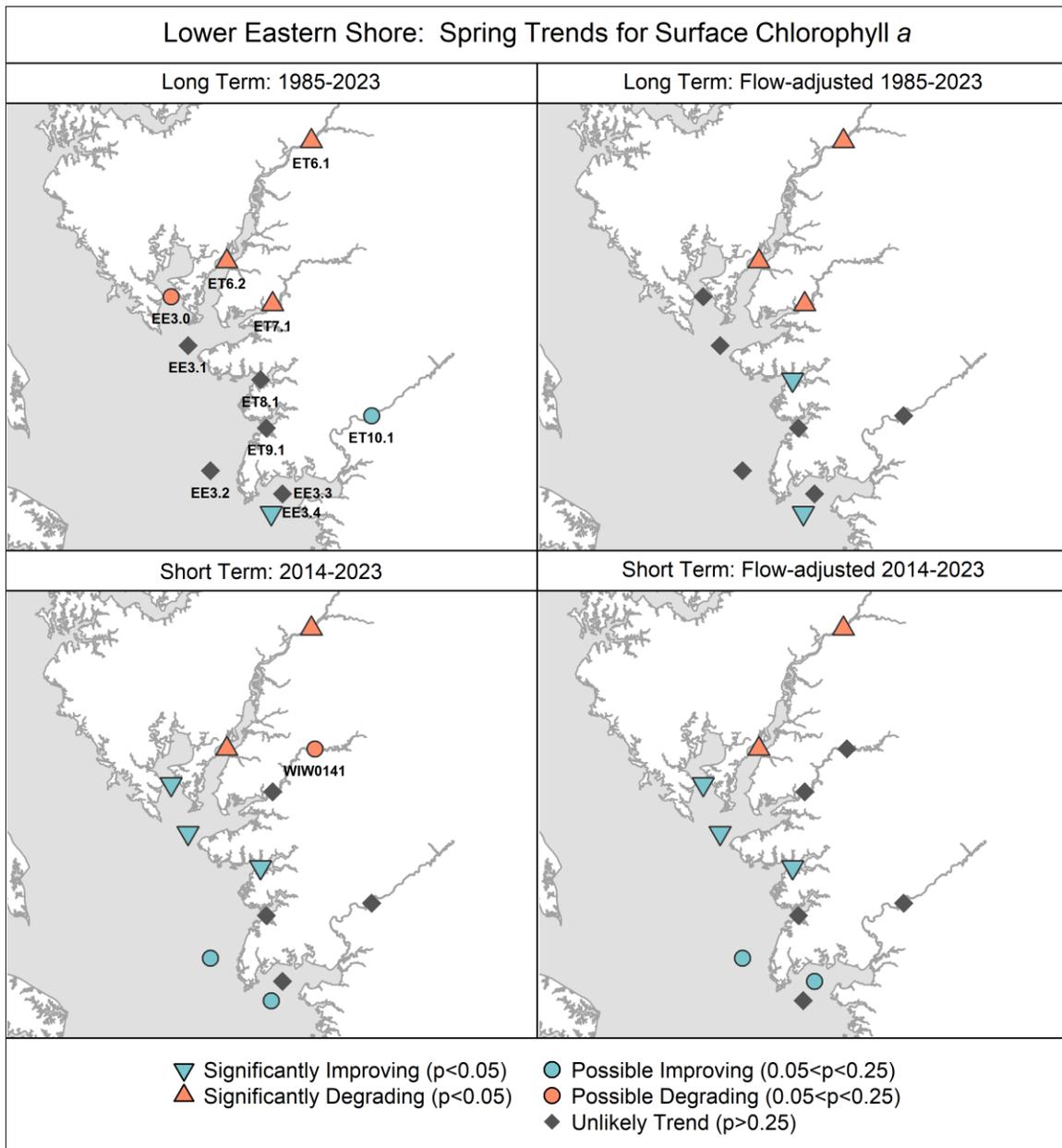


Figure 12. Surface spring (March-May) chlorophyll *a* trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983. For more information on the tidal stations and Chesapeake Bay tidal water quality monitoring, refer to <https://www.chesapeakebay.net/what/programs/quality-assurance/tidal-water-quality-monitoring>.

A variety of patterns in spring chlorophyll *a* concentrations and seasonal mean GAM estimates exist (Figure 13). Long-term increases in the Nanticoke River (ET6.1 and ET6.2) and Potomoke Sound (ET10.1) all take on very different shapes. There have been short-term decreases in EE3.2, EE8.1, EE3.1, and EE3.0.

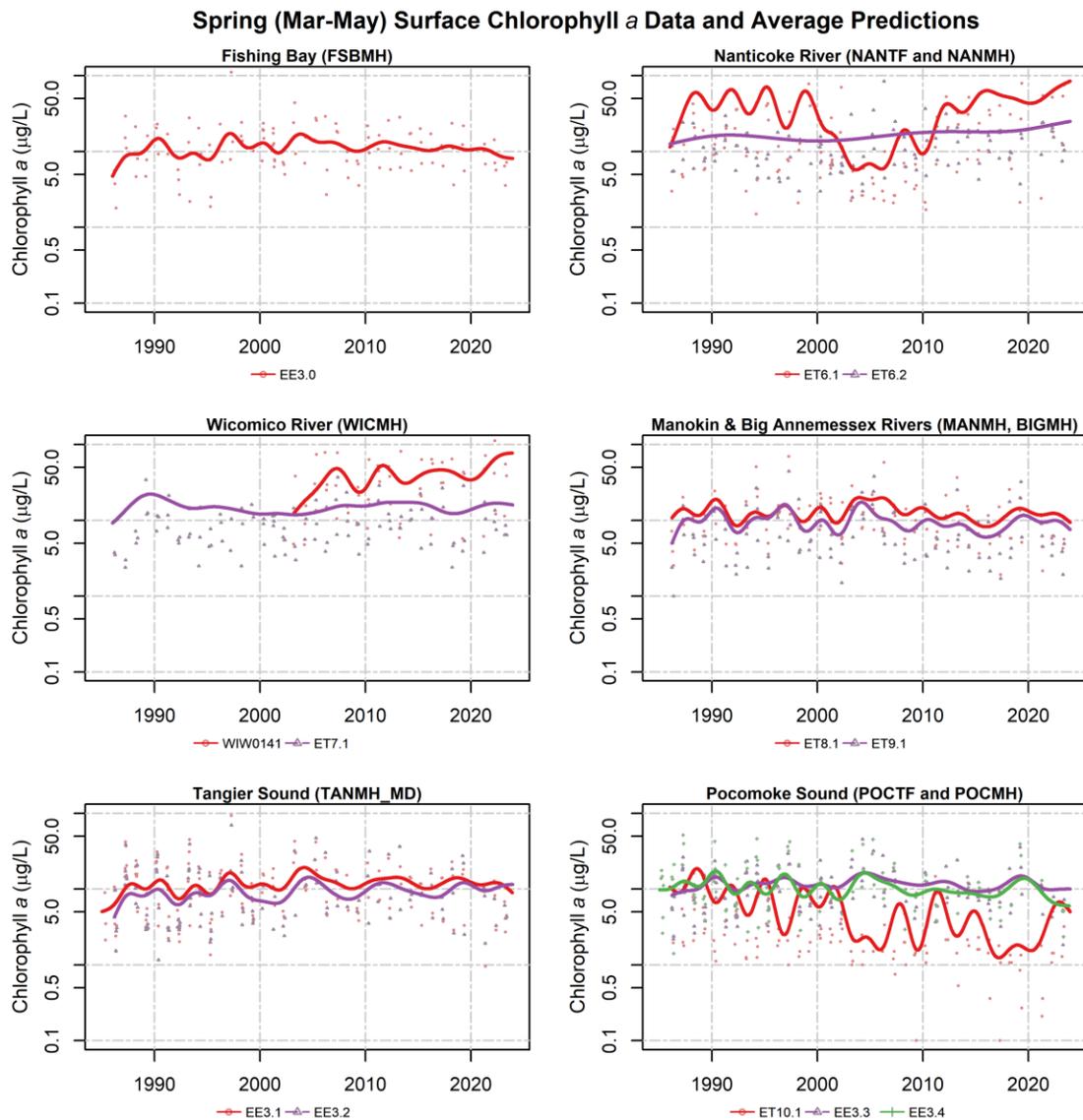


Figure 13. Surface spring chlorophyll *a* data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent March-May data corresponding to the monitoring station

indicated in the legend; colored lines represent mean spring GAM estimates for the noted monitoring stations.

4.4 Surface Chlorophyll *a*: Summer (July-September)

Summer long-term chlorophyll *a* trends (Figure 14) are relatively similar to spring with an exception there being no significant improvement for the station EE3.4 for non-flow adjusted trends. Short-term trends show notably more significant and possible degrading trends for both non-flow-adjusted and flow-adjusted trends in the summer versus the spring (Figure 13 and Figure 14).

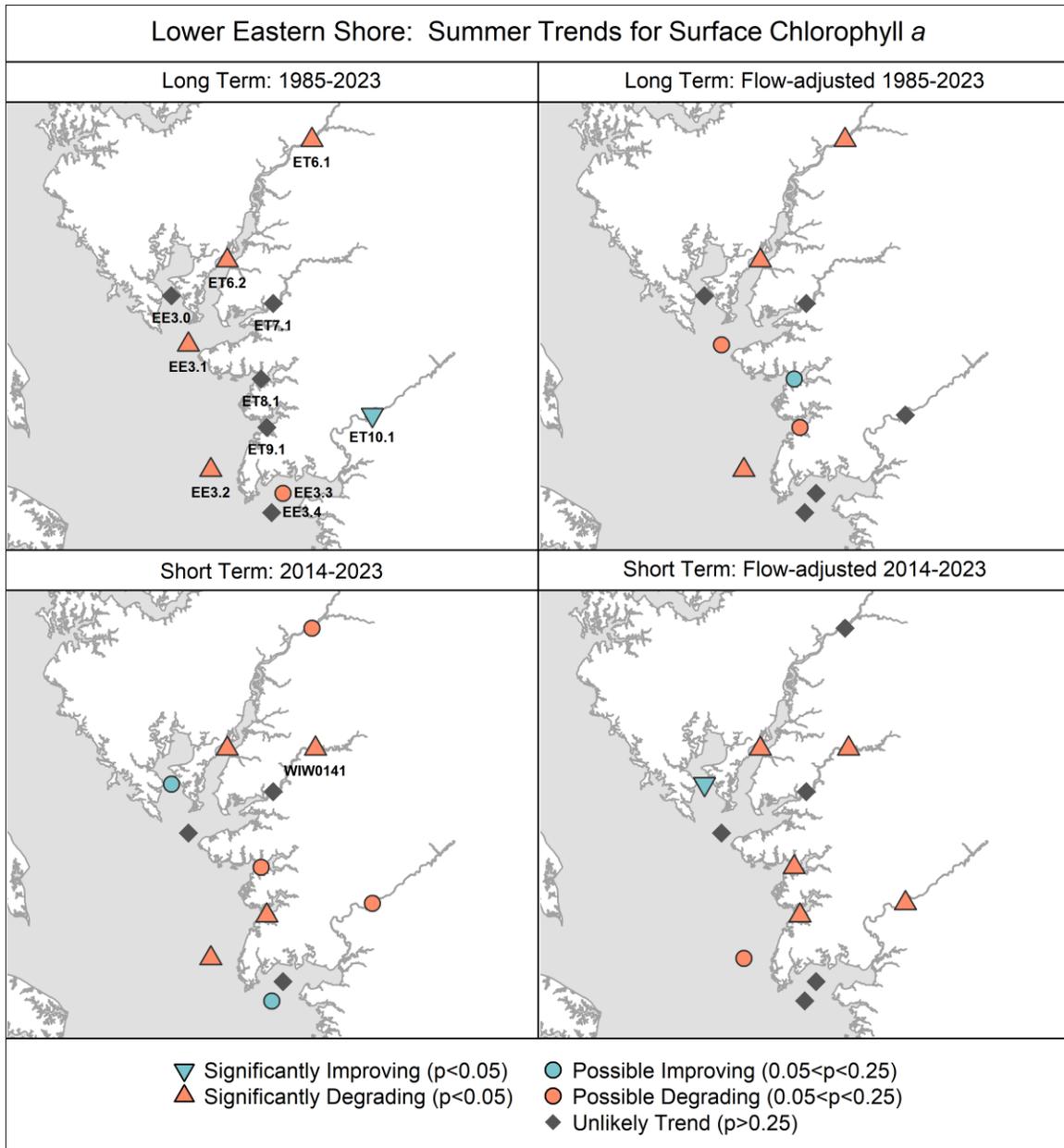


Figure 14. Surface summer (July-September) chlorophyll *a* trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983. For more information on the tidal stations and

Chesapeake Bay tidal water quality monitoring, refer to <https://www.chesapeakebay.net/what/programs/quality-assurance/tidal-water-quality-monitoring>.

The patterns in the summer chlorophyll *a* mean GAM estimates (Figure 15) are similar to patterns in the spring (Figure 13). Patterns at most of the stations are gradually increasing over time, with short periods of decreases particularly visible in stations EE3.0 and EE3.4 (Figure 14).

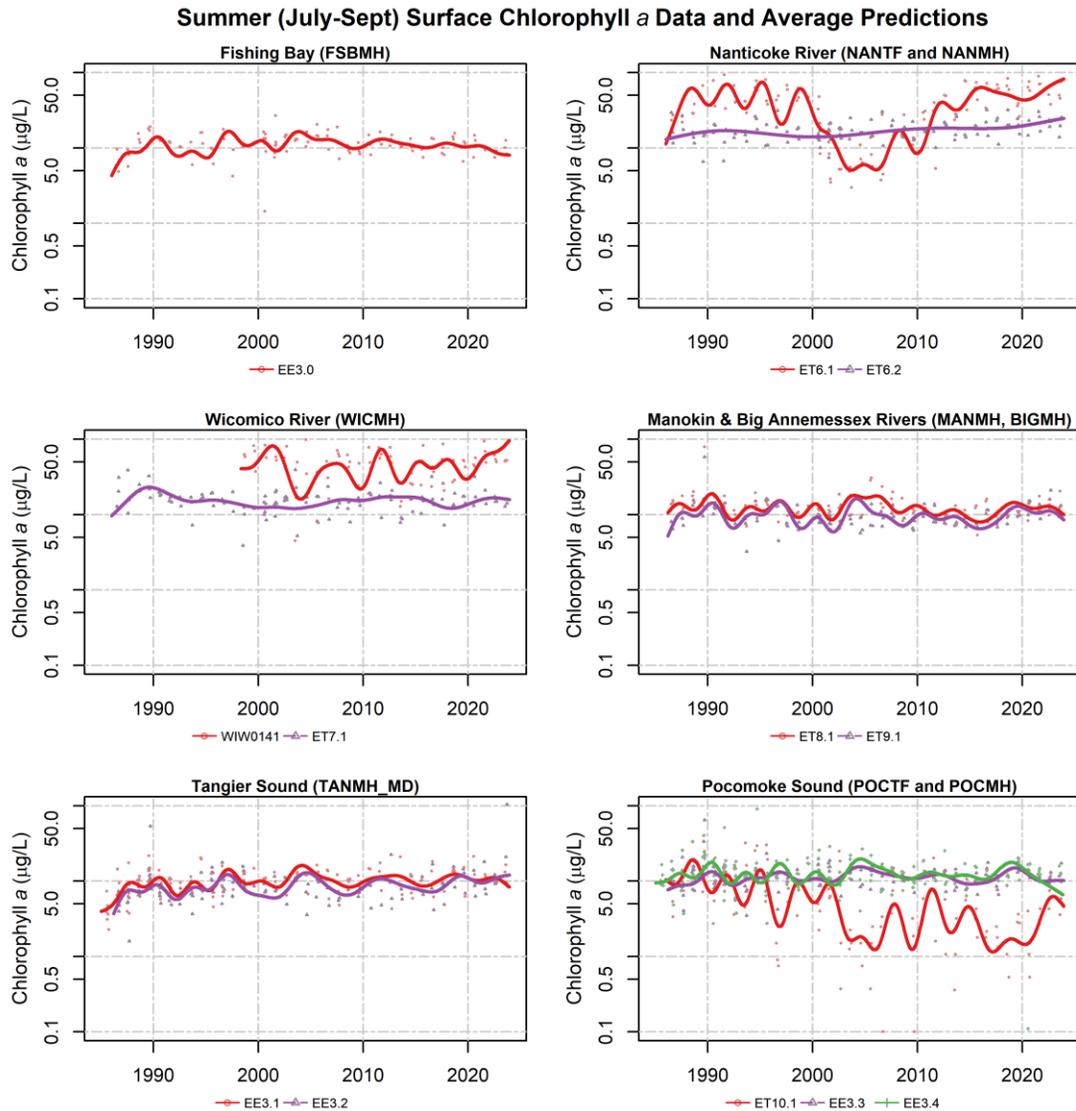


Figure 15. Surface summer chlorophyll *a* data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent July-September data corresponding to the monitoring station indicated in the legend; colored lines represent mean summer GAM estimates for the noted monitoring stations.

4.5 Secchi Disk Depth

Trends in Secchi disk depth, a measure of visibility through the water column, are degrading at most of these Lower Eastern Shore stations over the long-term with and without flow adjustment (Figure 16).

ET7.1, ET8.1, and ET10.1 are the only stations that show an unlikely long-term trend rather than a degrading one. Over the short term, three of the flow-adjusted stations show possible or significant improvements, while four show improvements for non-flow-adjusted trends. The station ET9.1 shows a significant degradation across non- and flow-adjusted trends in the short term.

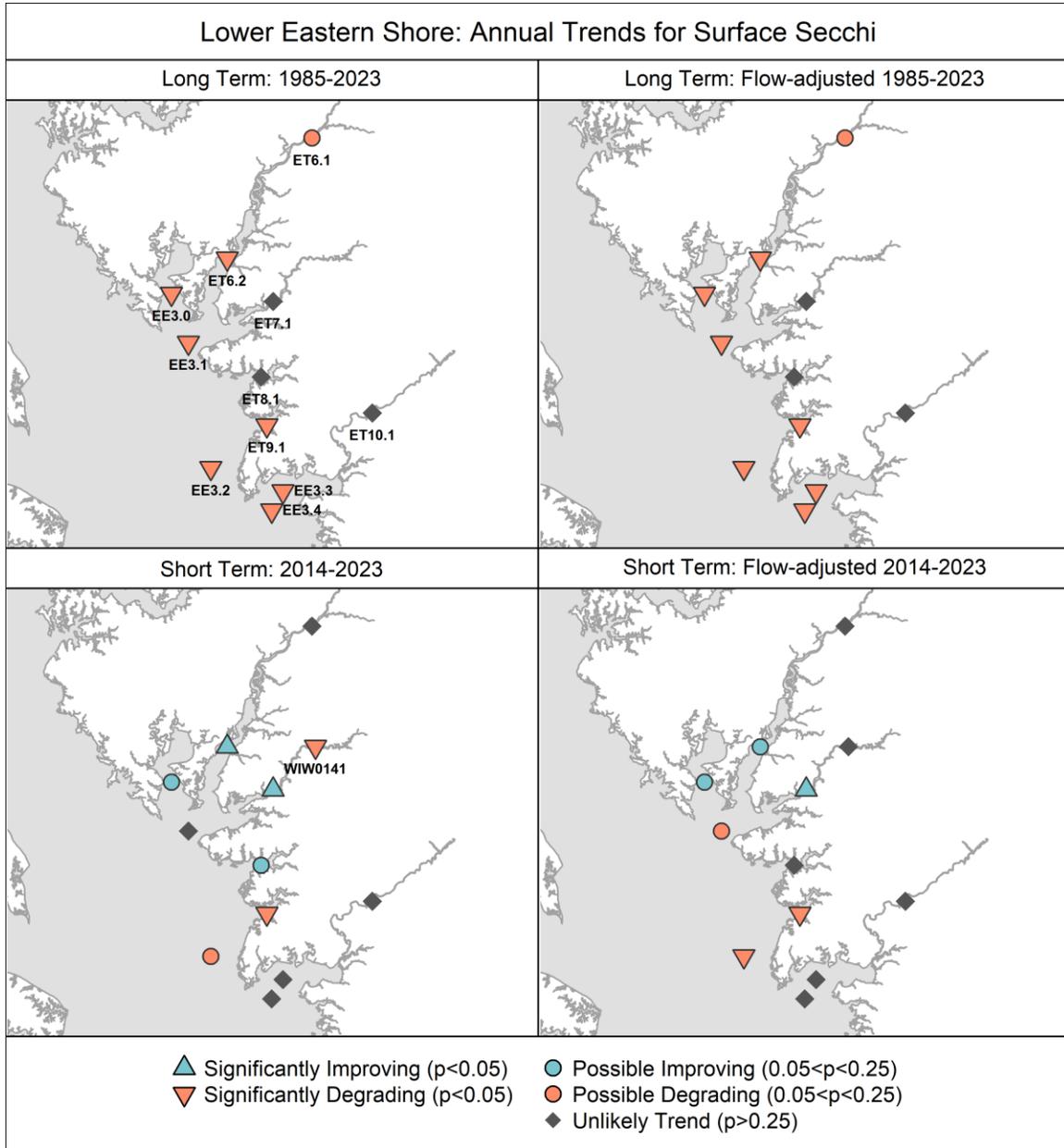


Figure 16. Surface Secchi depth trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983. For more information on the tidal stations and Chesapeake Bay tidal water quality monitoring, refer to <https://www.chesapeakebay.net/what/programs/quality-assurance/tidal-water-quality-monitoring>.

The long-term degrading trends in Secchi depth are apparent in the data and mean annual GAM estimates for most of the stations (Figure 17). Station ET10.1 has no long-term trend, as demonstrated by the low, constant Secchi pattern seen over time. Many stations are beginning to increase in the short term, namely EE3.0, EE6.2, EE7.1, and EE8.1 (Figure 17).

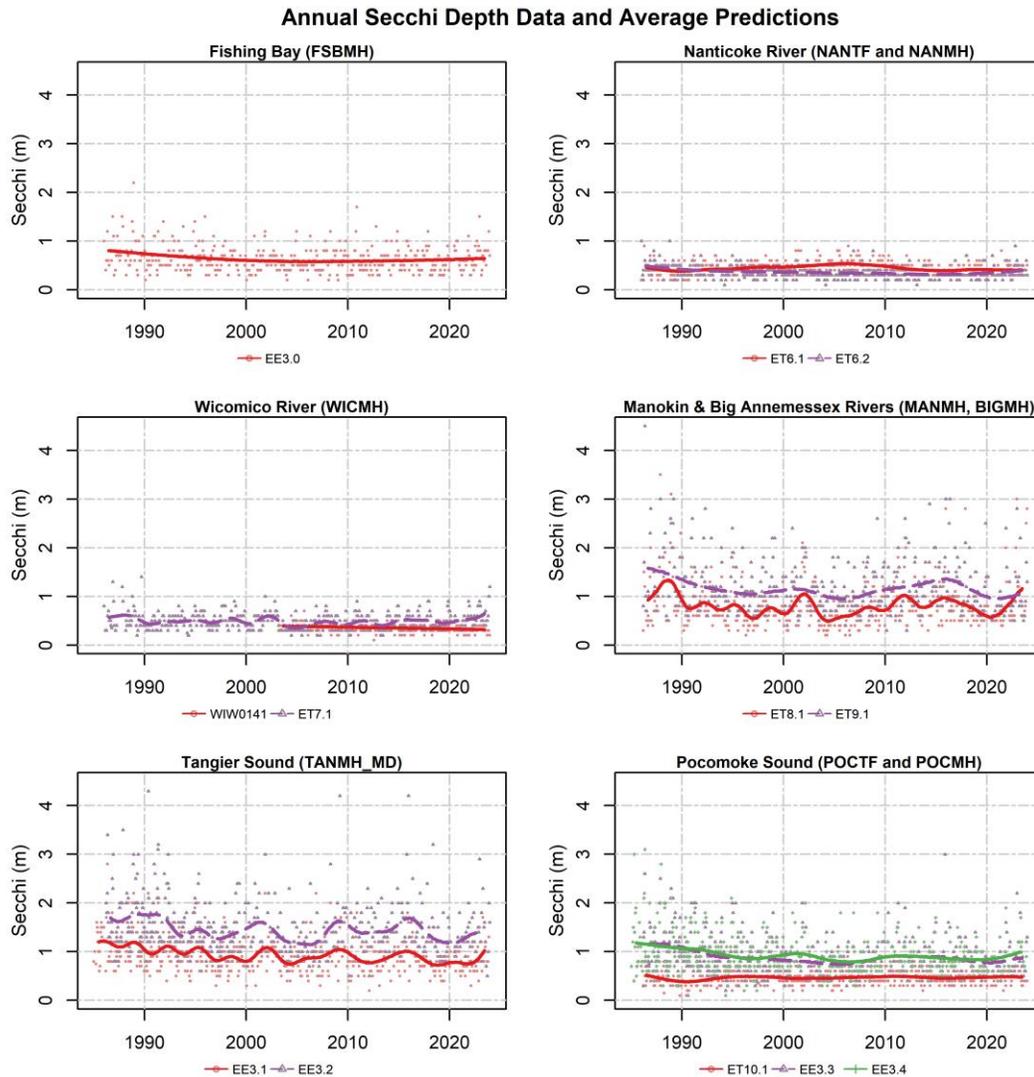


Figure 17. Annual Secchi depth data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

4.6 Summer Bottom Dissolved Oxygen (June-September)

Summer bottom DO concentrations generally show degrading or unlikely trend conditions (Figure 18). Flow-adjusted short-term trends shows less of a degrading trend as a whole.

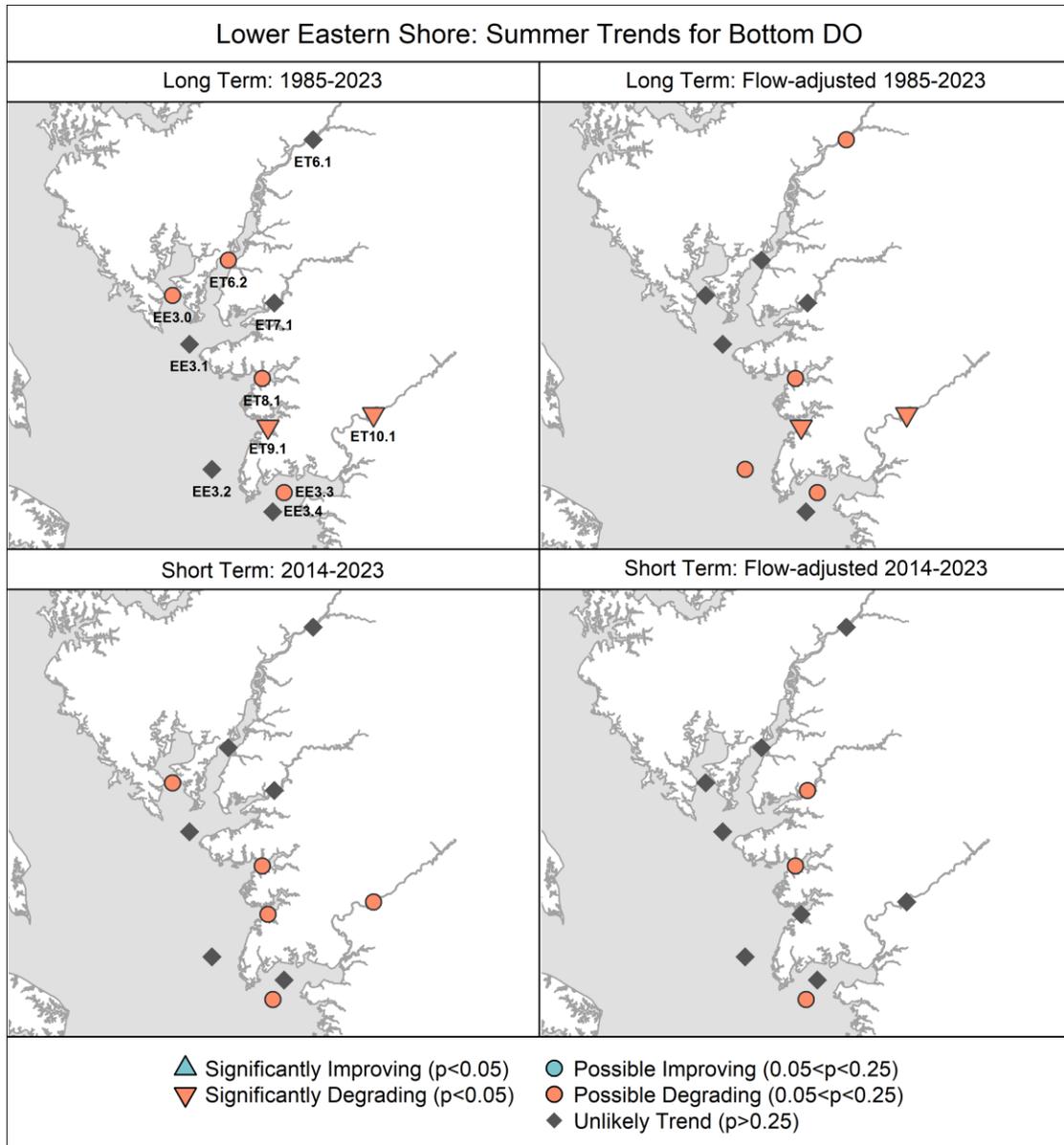


Figure 18. Summer (June-September) bottom DO trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983. For more information on the tidal stations and Chesapeake Bay tidal water quality monitoring, refer to <https://www.chesapeakebay.net/what/programs/quality-assurance/tidal-water-quality-monitoring>.

Summer bottom DO concentrations are relatively high in this region compared to other parts of the Chesapeake Bay, although concentrations less than 3 mg/L occur throughout the record sporadically at the Tangier Sound stations (mostly EE3.2) and Pocomoke Sound stations (ET10.1) (Figure 19). There were recently increases observed in many of the stations, followed by a gradual decrease over the past three years in most stations, leading to the unlikely trends represented in Figure 18.

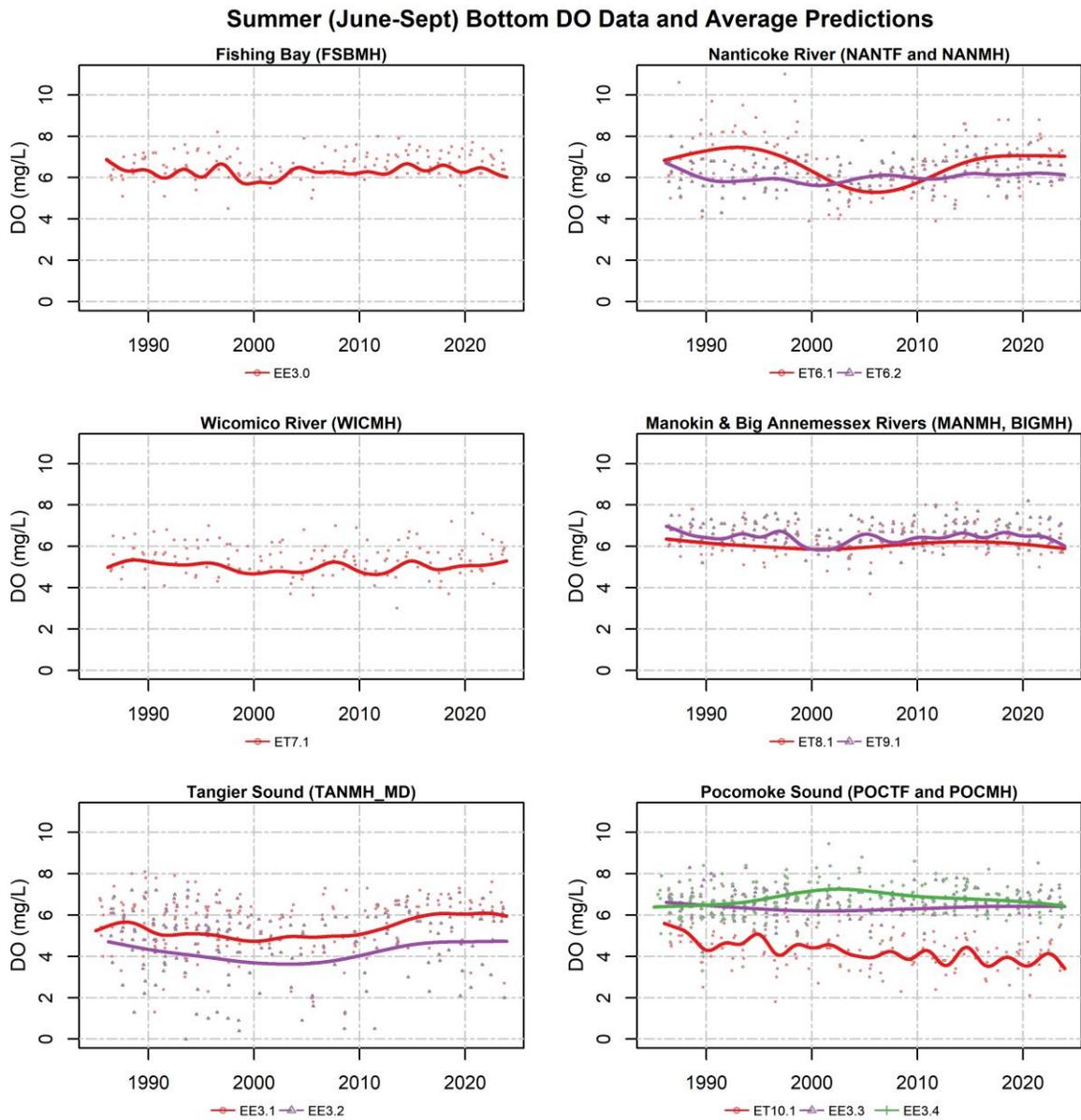


Figure 19. Summer (June-September) bottom DO data (dots) and summer mean long-term pattern generated from non-flow adjusted GAMs. Colored dots represent June-September data corresponding to the monitoring station indicated in the legend; colored lines represent mean summer GAM estimates for the noted monitoring stations.

4.7 Surface Water Temperature

Lower Eastern Shore tributary surface water temperatures are increasing at most stations over the long- and short-term (Figure 20). This is consistent with other studies in Chesapeake Bay that document long-term increases in tidal water temperatures (Hinson et al., 2022; Ding and Elmore, 2015). This is shown through possible or significant degradation at nearly every station across short- and long-term, and across flow-adjusted and non-flow-adjusted trends.

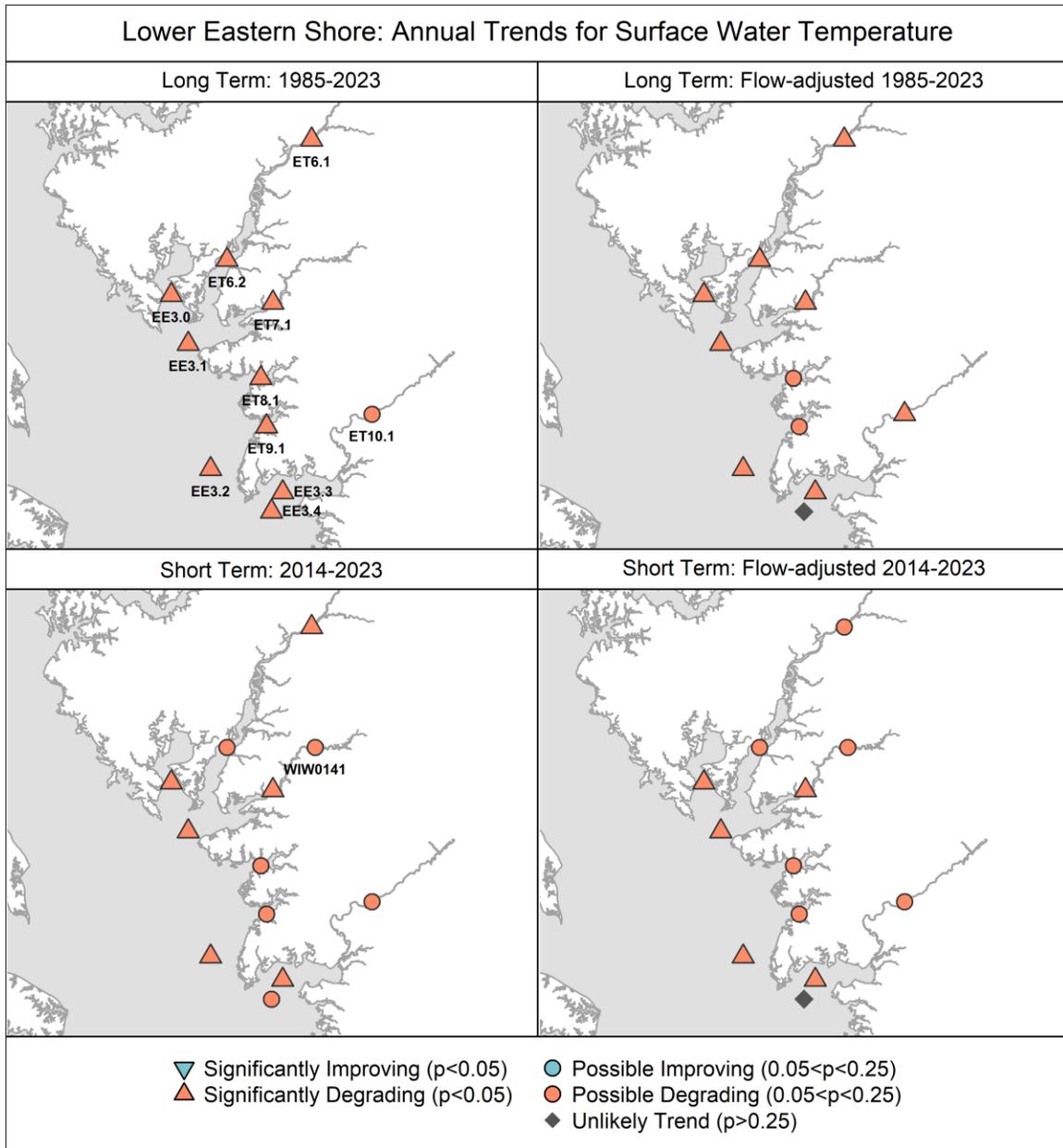


Figure 20. Surface water temperature trends as calculated by using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983. For more information on the tidal stations and Chesapeake Bay tidal water quality monitoring, refer to <https://www.chesapeakebay.net/what/programs/quality-assurance/tidal-water-quality-monitoring>.

Water temperatures in Chesapeake Bay range from below 0 to more than 30 degrees Celsius (Figure 21). The increasing long-term trends (Figure 20) are clear from the long-term averages of the data, even with the large seasonal variability. This is demonstrated in figure 21 and supported by the significant degradation shown in figure 20.

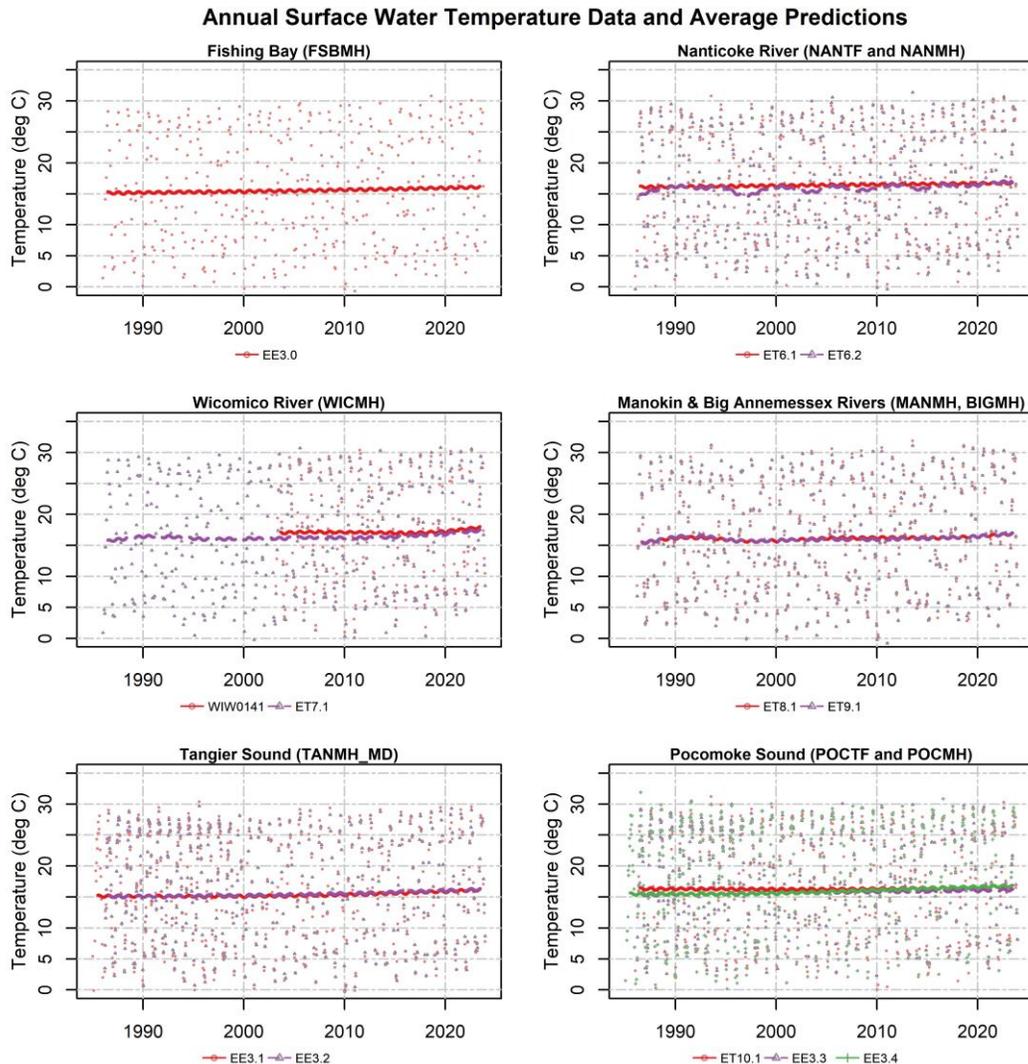


Figure 21. Annual surface water temperature data (dots) and average long-term pattern generated from non-flow adjusted Generalized Additive Models (GAMs). Colored dots represent data corresponding to the monitoring stations indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

5. Factors Affecting Trends

5.1 Watershed Factors

5.1.1. Effects of Physical Setting

Higher concentrations of nitrogen and phosphorus are found in Eastern Shore waterways due to unique combinations of hydrogeology, topography, and soils that promote the efficient transport of agricultural-associated nutrient applications to streams and tidal waters. The rate that nutrients move through the watershed partially depend on landscape position (Figure 22). Sediment loads are typically

low throughout the Eastern Shore because of the relatively flat topography of the Atlantic Coastal Plain. These higher concentrations coming from the Eastern Shore could be more impactful to Chesapeake Bay health due to the Eastern Shore's proximity to tidal waters (Ator and Denver, 2015). The Eastern Shore may have high yields with more nitrogen and phosphorous per unit area, but the actual load is low compared to other portions of the watershed.

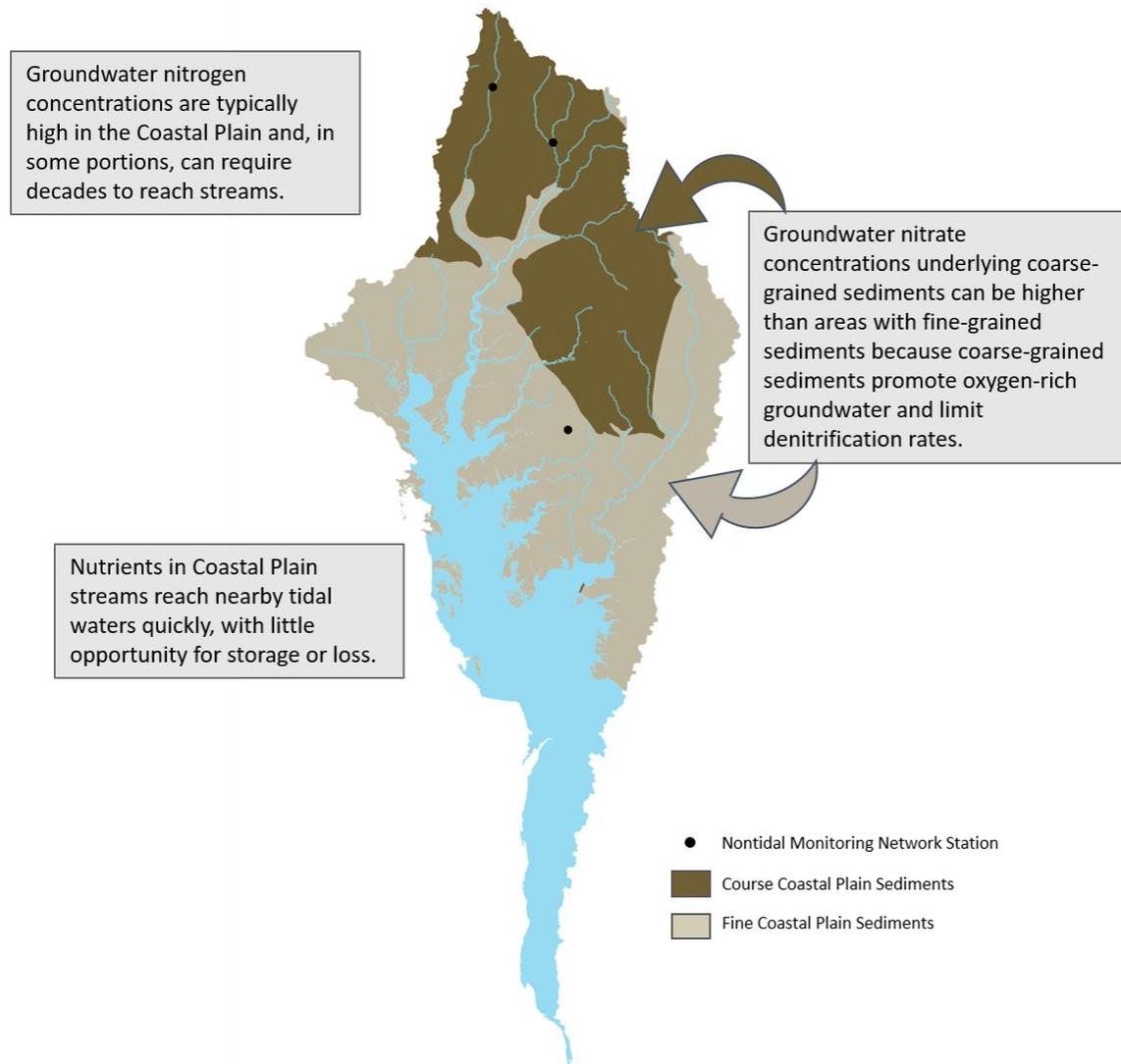


Figure 22. Effects of watershed hydrogeomorphology on nutrient transport to freshwater streams and tidal waters. Hydrogeomorphic region data credit to Brakebill and Kelley, 2023. Base map credit North American Datum 1983.

Nitrogen

Groundwater is the primary delivery pathway of nitrogen, as nitrate, to most streams in the Chesapeake Bay watershed (Ator and Denver, 2012; Lizarraga, 1997) and contributes about 70% of the nitrogen to Eastern Shore streams. Most of the nitrogen found in the Eastern Shore comes from agriculture, where nitrogen is applied to improve crop yields (Ator and Denver, 2015). The nitrogen fertilizers applied to

crops are rapidly mineralized into nitrate, a negatively charged ion that does not readily bind to soil and is transported with water. Some of the highest concentrations of groundwater nitrogen in the Bay watershed are present in portions of the Eastern Shore where oxygen-rich groundwater and relatively short groundwater flowpaths limit denitrification (Debrewer et al., 2008; Greene et al., 2005). Eastern Shore denitrification rates are low and nitrate concentrations are high in sandy soils and sediments (Böhlke and Denver, 1995; Denver et al., 2004), in soils that have been drained to support agricultural activities (Staver and Brinsfield, 2001), and in areas underlain by a thick surficial aquifer that prevents contact with deeper, anoxic groundwater (Böhlke and Denver, 1995). These features vary substantially from place to place throughout the Eastern Shore, but conditions limiting denitrification are common. In general, the lowest Eastern Shore nitrate concentrations discharge to streams along the perimeter of the Delmarva Peninsula, where groundwater is generally anoxic due to less permeable soils and a thinner surficial aquifer (Ator and Denver, 2015). The extremely low topographic relief of the Lower Eastern Shore has led to extensive ditching of agricultural fields and stream channelization to allow for water level control and better yields; however, the ditching network has also provided very short pathways for nitrogen movement into streams (Ator and Denver, 2015). Most Eastern Shore streamflow comes from groundwater discharging from the uppermost few meters of a shallow, surficial unconfined aquifer (Cushing et al., 1973, Sanford et al., 2012). More than half of the groundwater discharging to streams is older than 13 years (Sanford and Pope, 2013) so the high concentrations of nitrate that have increased in the unconfined aquifer (Debrewer et al., 2008) will likely contribute to streams for decades.

Phosphorus

Eastern Shore phosphorus concentrations are higher than most other regions of the Chesapeake Bay watershed (Ator et al., 2011) because phosphorus concentrations are high in soils underlying agricultural watersheds. Historically, manure was applied at rates to meet crop nitrogen demand, which led to applications of phosphorus that crops could not metabolize. The repeated high applications of phosphorus rich materials exceeded Eastern Shore cropping needs and have accumulated in field soils (Ator and Denver, 2015; Staver and Brinsfield, 2001). Such conditions can increase the amount of sediment-bound and dissolved phosphorus carried in runoff (Heckrath and others, 1995). Sandy soils common throughout the Eastern Shore can become fully phosphorus saturated relatively quickly because of their low phosphorus sorption capacity (Sharpley, 1980). As a result of such conditions, phosphorus can also be exported to streams from shallow soils and groundwater (Staver and Brinsfield, 2001). Reducing soil phosphorus concentrations can take a decade or more (Kleinman et al., 2011), and until this occurs, watershed phosphorus loads may be unresponsive to management practices (Jarvie et al., 2013; Sharpley et al., 2013).

Sediment

Despite increased sediment erosion associated with agricultural land uses, Eastern Shore sediment loads are typically as low as some undeveloped regions of the Bay watershed (Brakebill et al., 2010) because of the relatively flat topography of the Atlantic Coastal Plain. The sediment load of a given stream reach is a balance of sediment eroded from uplands and streambanks and sediment stored in floodplains and stream channels. Eastern Shore streambank erosion rates are reduced in areas with low topographic gradient, but are also affected by watershed drainage area (Gellis et al., 2015; Gellis and Noe, 2013; Gillespie et al., 2018; Hopkins et al., 2018), bank sediment density (Wynn and Mostaghimi, 2006), vegetation (Wynn and Mostaghimi, 2006), and other stream valley geomorphic properties (et al., 2018).

The lowest Eastern Shore sediment concentrations are present in portions of the Lower Eastern Shore (Brakebill et al., 2010), likely as a result of this area's extremely low topographic gradient. Recent development on the Lower Eastern Shore, and Delmarva peninsula, has increased concerns about the effect of impervious cover on sediment loads and bank erosion (Chris Brosch, Delaware Department of Agriculture, written commun., 2025).

Delivery to tidal waters

The delivery of nitrogen, phosphorus, and sediment in non-tidal Eastern Shore streams to tidal waters varies based on physical and chemical factors that affect in-stream retention, loss, or storage. In general, the proximity of much of the Eastern Shore to tidal waters limits opportunities for in-stream denitrification because of rapid transit (Staver and Brinsfield, 2001). There are no natural chemical processes that remove phosphorus from streams, but sediment and associated phosphorus can be trapped in floodplains before reaching tidal waters. High rates of sediment trapping by Coastal Plain nontidal floodplains and head-of-tide tidal freshwater wetlands creates a sediment shadow in many tidal rivers and limits sediment delivery to Chesapeake Bay (Ensign et al., 2014; Noe and Hupp, 2009). Shoreline erosion can be a larger source of sediment delivered to Eastern Shore estuaries than upland runoff or streambank erosion because of such trapping and because of the low relief of the Atlantic Coastal Plain (Yarbro et al., 1983).

5.1.2. Estimated Nutrient and Sediment Loads

Estimated nutrient and sediment loads of the Lower Eastern Shore Tributaries are a combination of simulated non-point source, atmospheric deposition, and reported point-source loads. These loads were obtained from the Chesapeake Bay Program Watershed Model's progress runs specific to each year from 1985 through 2022 (<https://cast.chesapeakebay.net/>). Nonpoint source loads were adjusted to represent actual hydrology using the method of the Chesapeake Bay Program's Loads to the Bay indicator (<https://www.chesapeakeprogress.com/clean-water/water-quality>). Over the period of 1985-2022, 0.33, 0.017, and 9.5 million tons of nitrogen, phosphorus, and suspended sediment loads were exported from this watershed, respectively (Figure 23). Mann-Kendall trends and Sen's slope estimates are summarized for each loading source in Table 2.

Estimated TN loads showed an overall increase of 83 ton/yr in the period between 1985 and 2022, which is not statistically significant ($p = 0.10$). This increase is entirely driven by nonpoint sources (97 ton/yr; $p < 0.05$). By contrast, long-term, statistically significant declines were observed with both point sources (-7.5 ton/yr; $p < 0.01$) and atmospheric deposition to the tidal waters (-8.9 ton/yr; $p < 0.01$). The significant point source reductions in TN are a result of substantial efforts to reduce nitrogen loads from major wastewater treatment facilities by implementing biological nutrient removal (Lyerly *et al.*, 2014). The significant decline in atmospheric deposition of TN to the tidal waters is consistent with findings that atmospheric deposition of nitrogen has decreased due to benefits from the Clean Air Act implementation (Eshleman *et al.*, 2013; Lyerly *et al.*, 2014).

Estimated TP loads showed an overall increase of 10 ton/yr in the period between 1985 and 2022, which is statistically significant ($p < 0.01$). This increase is entirely driven by nonpoint sources (12 ton/yr; $p < 0.01$). By contrast, point sources showed a statistically significant decline (-1.6 ton/yr; $p < 0.01$). The TP point source load reduction has also been attributed to significant efforts to reduce phosphorus in

wastewater discharge through the phosphorus detergent ban in the early part of this record, as well as technology upgrades at wastewater treatment facilities (Lyerly *et al.*, 2014).

Estimated suspended sediment (SS) loads showed an overall increase of 910 ton/yr in the period between 1985 and 2022, which is statistically significant ($p < 0.01$). This increase is entirely driven by nonpoint sources (910 ton/yr, $p < 0.01$). Like TP and TN, point source load of SS showed a statistically significant decline in this period (-6.4 ton/yr; $p < 0.01$).

Lower Eastern Shore

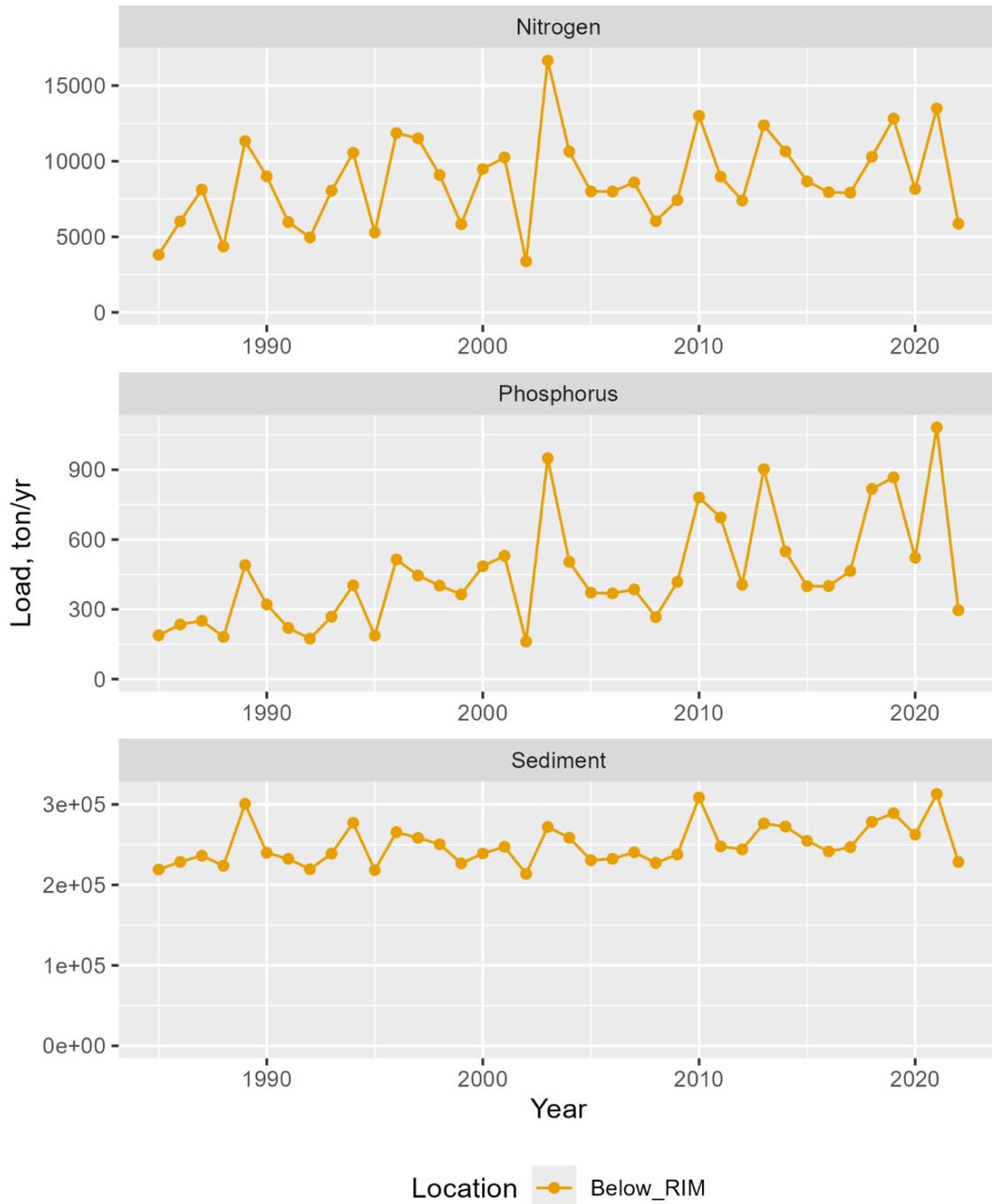


Figure 23. Estimated total loads (sum of River Input Monitoring, RIM, and below-RIM) of nitrogen (TN), phosphorus (TP), and suspended sediment (SS) to the Lower Eastern Shore Tributaries. Below-RIM estimates are a combination of simulated non-point and reported point-source loads. Loads from the different sources were obtained from the Chesapeake Bay Program Watershed Model progress runs specific to each year from 1985 through 2022 (<https://cast.chesapeakebay.net/>).

Table 2. Summary of Mann-Kendall trends for the period of 1985 - 2022 for total nitrogen (TN), total phosphorus (TP), and suspended sediment (SS) loads from the Lower Eastern Shore watershed.

Categories	TN		TP		SS	
	Trend, metric ton/yr	p-value	Trend, metric ton/yr	p-value	Trend, metric ton/yr	p-value
Below-RIM watershed ¹	83	0.10	10	< 0.01	910	< 0.01
<i>Below-RIM point source</i>	-7.5	< 0.01	-1.6	< 0.01	-6.4	< 0.01
<i>Below-RIM nonpoint source</i> ²	97	< 0.05	12	< 0.01	910	< 0.01
<i>Below-RIM tidal deposition</i>	-8.9	< 0.01	-	-	-	-

¹ Loads from the different sources were obtained from the Chesapeake Bay Program Watershed Model progress runs specific to each year from 1985 through 2022 (<https://cast.chesapeakebay.net/>).

² Nonpoint source loads were adjusted to represent actual hydrology using the method of the Chesapeake Bay Program's Loads to the Bay indicator (see <https://www.chesapeakeprogress.com/clean-water/water-quality>). The adjustment factor for each year is defined as the ratio between monitored load and watershed model simulated load for an applicable USGS River Input Monitoring (RIM) station. Because the Lower Eastern Shore Tributaries do not have RIM stations, adjustment factors need to be transferred from a different tributary that has a RIM station. In this regard, the Choptank River was selected for two reasons: (1) it is geographically proximate to the Lower Eastern Shore Tributaries, and (2) it is hydrologically similar to the Lower Eastern Shore Tributaries based on an analysis of annual riverflow anomalies.

5.1.3. Expected Effects of Changing Watershed Conditions

According to the Chesapeake Bay Program's Watershed Model known as the Chesapeake Assessment Scenario Tool (CAST; <https://cast.chesapeakebay.net/About/UpgradeHistory><https://cast.chesapeakebay.net/About/UpgradeHistory>, version Phase 6 - 7.14.0), changes in population size, land use, and pollution management controls between 1985 and 2023 would be expected to change long-term average nitrogen, phosphorus, and sediment loads to the tidal Lower Eastern Shore River by -19%, -54%, and -15%, respectively (Figure 24). In contrast to the annual loads analysis above, CAST loads are based on changes in management only and do not include annual fluctuations in weather. As management practices are implemented, there may be a delay between installation and impact on water quality, and this delay is known as lag time. CAST loads are calculated without lag times for delivery of pollutants or lags related to BMPs becoming fully effective after installation. In 1985, agriculture and developed were the two largest sources of nitrogen loads. By 2023, agriculture and developed remained the two largest sources of nitrogen loads. Overall, decreasing nitrogen loads from agriculture (-24%), natural (-2%), stream bed and bank (-19%), and wastewater (-80%) sources were partially counteracted by increases from developed (51%) and septic (36%) sources.

The two largest sources of phosphorus loads as of 2023 were the agriculture and shoreline sectors. Overall, expected declines from agriculture (-62%), developed (-12%), natural (-5%), stream bed and bank (-55%), and wastewater (-90%) sources were partially counteracted by increases from septic (10%) sources.

For sediment, the largest sources are shoreline and stream bed and bank areas: these two sources changed by 0% and -57%, respectively between 1985 and 2023. Sediment loads from the agriculture sector changed by -70%, whereas sediment load from developed areas changed by 47%.

Overall, changing watershed conditions are expected to result in the agriculture, natural, stream bed and bank, and wastewater sectors achieving reductions in nitrogen, phosphorus, and sediment loads between 1985 and 2023, whereas the non-tidal water atmospheric deposition and septic sectors are expected to increase in nitrogen, phosphorus, and sediment loads.

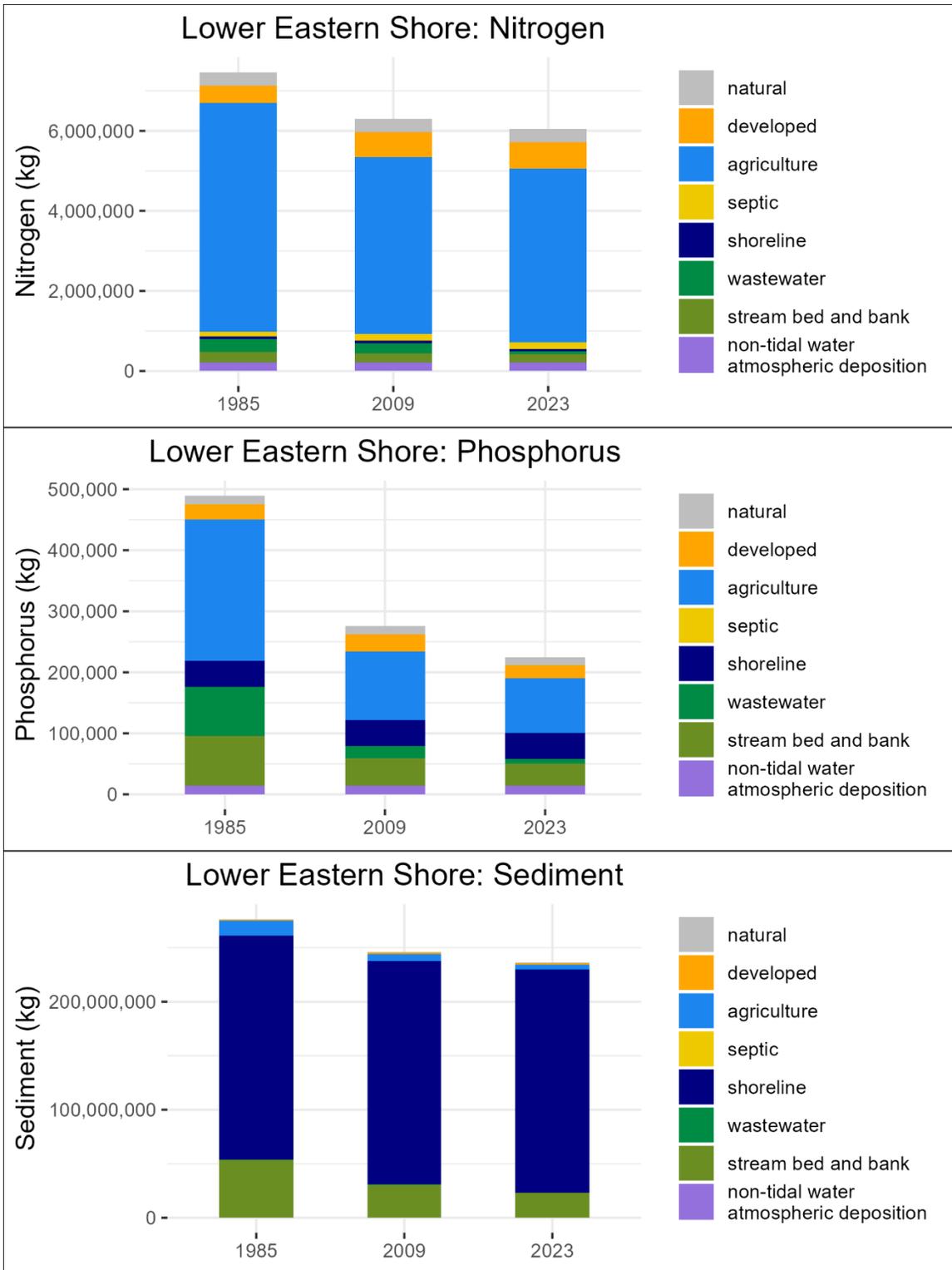


Figure 24. Expected long-term average loads of nitrogen, phosphorus, and sediment from different sources to the tidal Lower Eastern Shore, based on watershed conditions in 1985, 2009, and 2023 (CAST, 2023).

5.1.4. Best Management Practices (BMPs) Implementation

Data on reported BMP implementation are available for download from CAST (<https://cast.chesapeakebay.net/About/UpgradeHistory><https://cast.chesapeakebay.net/About/UpgradeHistory>, version Phase 6 - 7.14.0). Reported BMP implementations on the ground as of 1985, 2009, and 2023 are compared to planned 2025 implementation levels in Figure 25 for a subset of major BMP groups. As of 2023, tillage, cover crops, pasture management, forest buffer and tree planting, stormwater management, agricultural nutrient management, and urban nutrient management were credited for 1,285, 732, 8, 49, 12, 3,613, and 227 square kilometers, respectively. Implementation levels for some practices are already close to achieving their planned 2025 levels: for example, 116% of square kilometers for tillage had been achieved as of 2023. In contrast, about 84% of planned commodity & cover crops implementation had been achieved as of 2023.

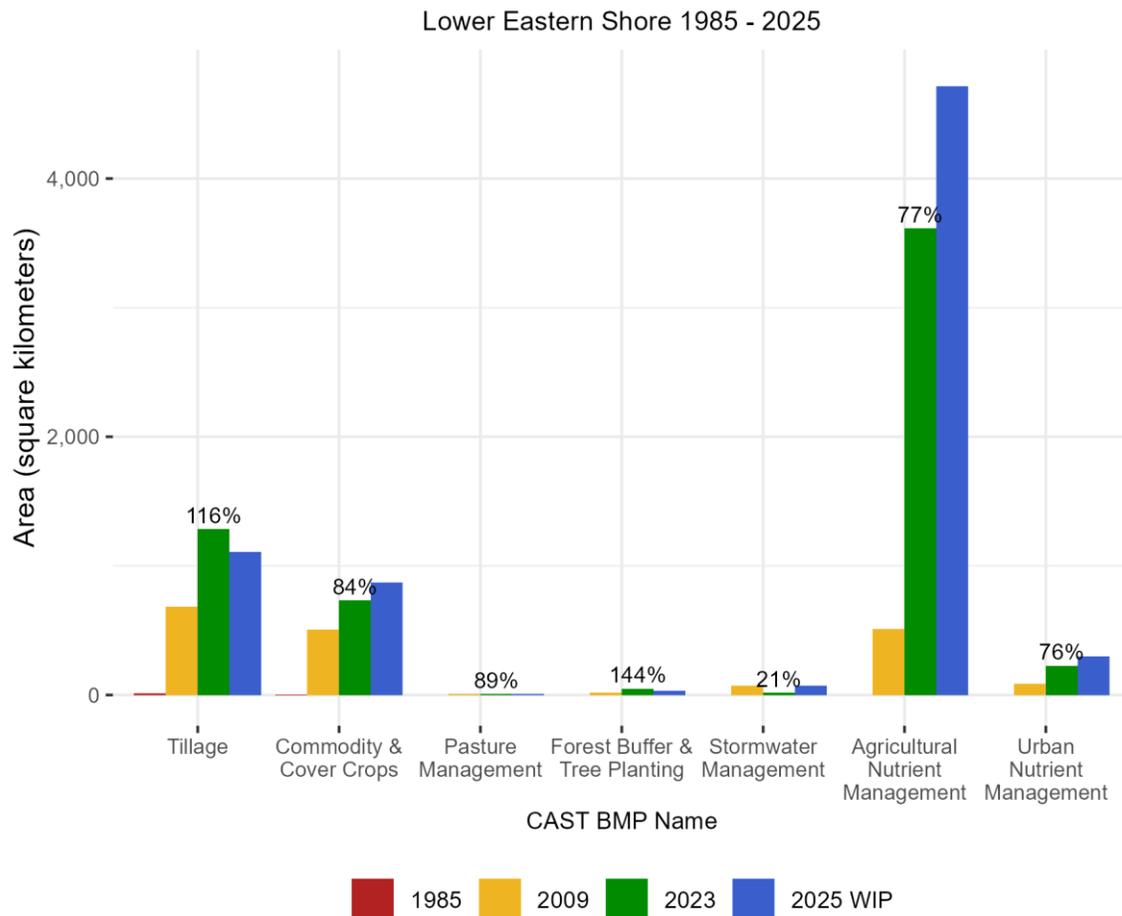


Figure 25. Best Management Practices (BMP) implementation in the Lower Eastern Shore watershed for the years 1985, 2009, 2023, and planned for 2025 through the Watershed Implementation Plans (WIP), (CAST, 2023).

Stream restoration and animal waste management systems are two important BMPs that cannot be compared directly with those above because they are measured in different units. However, progress towards implementation goals can still be documented. Stream restoration (agricultural and urban) increased from 0 meters in 1985 to 6,734 meters in 2023. Over the same period, animal waste management systems treated 9,872 animal units in 1985 and 1,945,709 animal units in 2023 (one animal unit represents 1,000 pounds of live animal). These implementation levels represent 35% and 100% of their planned 2025 implementation levels, respectively.

5.1.5. Flow-Normalized Watershed and Nutrient Sediment Loads

Flow normalization can better reveal temporal trends in river water quality by removing the effect of inter-annual variability in streamflow. Flow-normalized trends help scientists evaluate changes in load resulting from changing sources, delays associated with storage or transport of historical inputs, and/or implemented management actions (Hirsch et al., 2010). Flow-normalized nitrogen, phosphorus, and sediment trends have been reported for the short term (2014-2023) at non-tidal network stations throughout the watershed and can be found at the USGS Website Water Data For the Nation: U.S. Geological Survey National Water Information Systems (NWIS; Mason et al., 2023; USGS, 2022) (Table 3). These trends result from variability in nutrient applications, the delivery of nutrients and sediments from the landscape to streams, and from processes that affect in-stream loss or retention of nutrients and sediment. To learn more about monitored loads of TN, TP and SS at RIM stations and other nontidal stations in the watershed, please refer to the USGS Geonarrative: [Chesapeake Bay Nontidal Monitoring Network Loads and Trends](#).

Table 3. Short-term trends (2014-2023) of flow-normalized (FN) total nitrogen (TN), total phosphorus (TP), and suspended sediment (SS) loads for nontidal network monitoring locations in the Lower Eastern Shore watershed. Decreasing trends listed in blue, increasing trends listed in orange, results reported as "no trend" listed in black. TN = total nitrogen, TP = total phosphorus, SS = suspended sediment. TN= total nitrogen, TP= total phosphorus, SS= suspended sediment. A more detailed summary of flow-normalized loads and trends measured at all USGS Chesapeake Bay Nontidal Network stations (USGS, 2022) can be found at <https://waterdata.usgs.gov/>.

USGS Station ID	USGS Station Name	Trend start water year	Percent change in FN load, through water year 2023		
			TN	TP	SS
1486000	Manokin Branch near Princess Anne, MD	2014	-11	45	69.4
1487000	Nanticoke River near Bridgeville, DE	2014	2.81	35.1	21.5

5.2 Tidal Factors

Once pollutants reach tidal waters, a complex set of environmental factors interact with them to affect key habitat indicators like algal biomass, DO concentrations, water clarity, submerged aquatic vegetation (SAV) abundance, and fish populations (Figure 26) (Kemp *et al.*, 2005; Testa *et al.*, 2017). For example, phytoplankton growth depends not just on nitrogen and phosphorus (Fisher *et al.*, 1992; Kemp *et al.*, 2005; Zhang *et al.*, 2021), but also on light and water temperature (Buchanan *et al.*, 2005; Buchanan, 2020). In general, the saline waters of the lower Chesapeake Bay tend to be more transparent than tidal-fresh regions, and waters adjacent to nutrient input points are more affected by these inputs than more distant regions (Keisman *et al.*, 2019; Testa *et al.*, 2019). Dissolved oxygen concentrations are affected by salinity- and temperature-driven stratification of the water column, and conversely by wind-driven mixing, in addition to phytoplankton respiration and decomposition (Scully, 2010; Murphy *et al.*, 2011). When anoxia occurs at the water-sediment interface, nitrogen and phosphorus stored in the sediments can be released through anaerobic chemical reactions (Testa and Kemp, 2012). When low-oxygen water and sediment burial suffocate benthic plant and animal communities, their nutrient consumption and water filtration services are lost. Conversely, when conditions improve enough to support abundant SAV and benthic communities, their functions can sustain and even advance progress towards a healthier ecosystem (Cloern, 1982; Phelps, 1994; Ruhl and Rybicki, 2010; Gurbisz and Kemp, 2014).

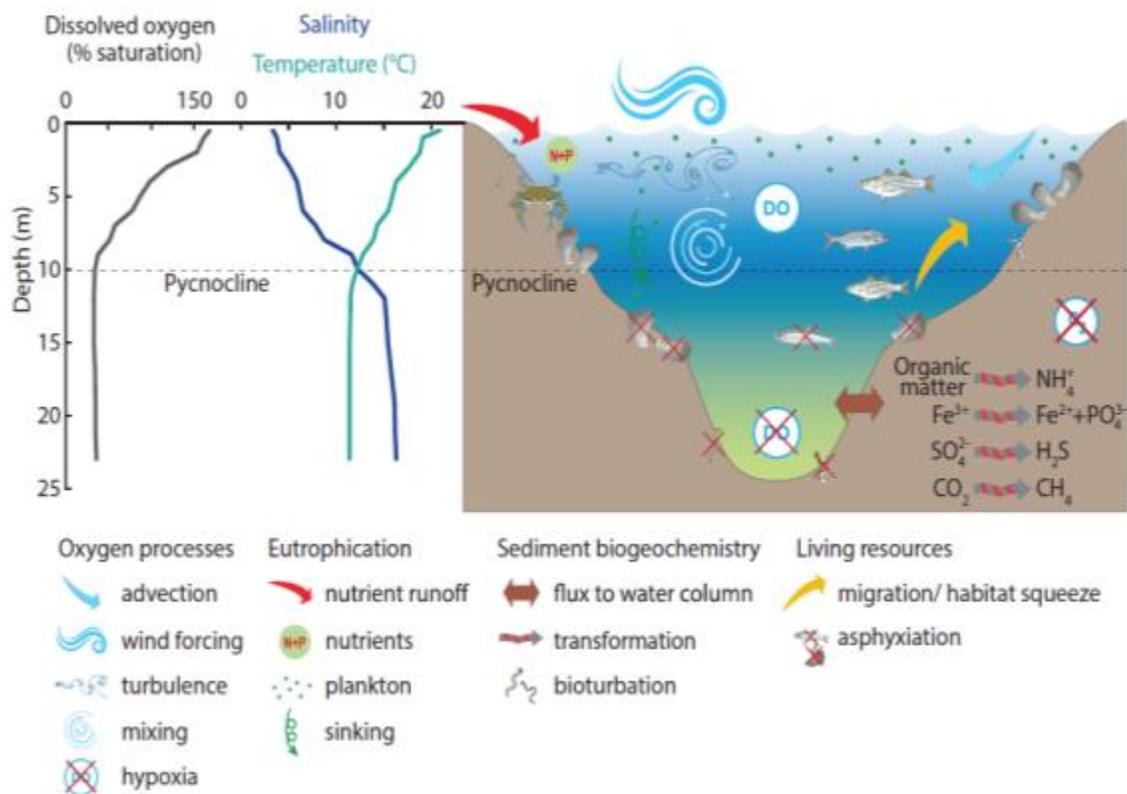


Figure 26. Conceptual diagram illustrating how hypoxia is driven by eutrophication and physical forcing, while affecting sediment biogeochemistry and living resources. From Testa *et al.* (2017).

5.2.1. Watershed and Estuarine Volume

High nutrient loads relative to tidal river size are indicative of areas that are more susceptible to eutrophication (Bricker et al., 2003; Ferreira et al., 2007). The relationship between watershed area and tidal river size may also be an important indicator of eutrophication potential; however, there are competing effects. A large watershed relative to the volume of receiving water would likely correlate with higher nutrient loads but would also correlate with a higher flow rate and decreased flushing time (Bricker et al., 2008). Figure 27 is a comparison of watershed areas versus estuarine volume for all estuaries and sub-estuaries identified in the CBP monitoring segment scheme. Larger estuaries will contain multiple monitoring segments and, in many cases, sub-estuaries. For example, the Nanticoke River includes monitoring segments in the oligohaline and mesohaline sections of the river. Table 4 shows the associated tributary name for the abbreviated name and group name represented in the watershed and estuarine volume figures. Figures 28 and 29 are comparisons of estimated annual average nitrogen and phosphorus loads, respectively, for the 2021 progress scenario in CAST versus the estuarine volume for the same set of estuaries and sub-estuaries.

The group of Lower Eastern Shore tributaries' estuary volume and watershed area contain approximately 7% of the total volume and 2% of the total watershed area of the Chesapeake Bay (Table 5). Individual tributaries in the Lower Eastern Shore rank across the spectrum of estuary volume and watershed area ratios. The subset of tributaries for the Lower Eastern shore are ranked 8th for the largest volume to watershed ratio. However, Big Annemessex River (Big) has a smaller estuarine volume and watershed area compared to many other tributaries. Nanticoke River (Nan) and Pocomoke River (Poc) have very similar watershed areas, but the Pocomoke River has a larger estuarine volume (Figure 27).

LowerE - Watershed Area vs Estuarine Volume

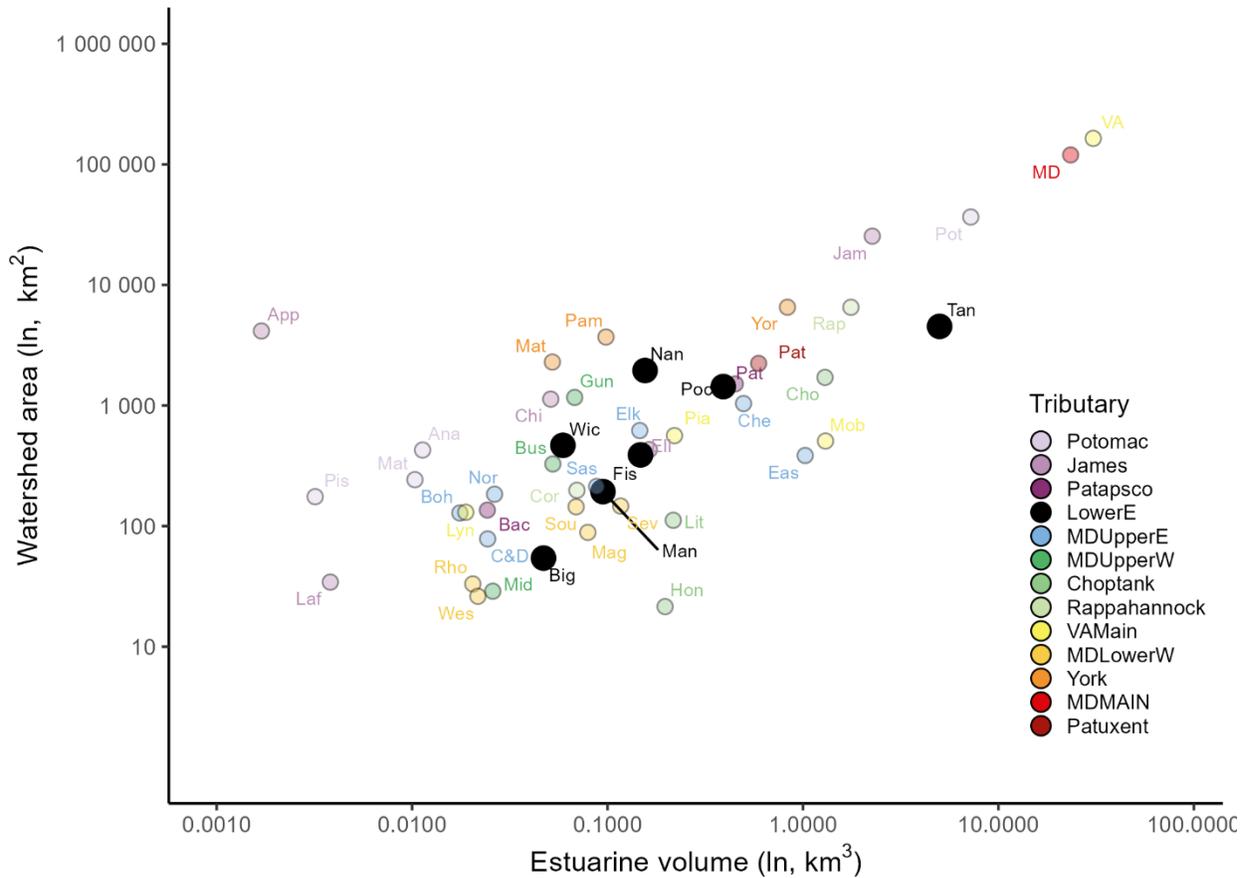


Figure 27. A comparison of watershed areas (km² vs estuarine volume (km³) for each tributary. The watershed area and volume data are represented on a natural logarithmic scale (ln). The table of tributary names and their abbreviations can be found below in Table 4.

Table 4. Lists the associated full tributary name for the abbreviated name and group name represented in the watershed and estuarine volume figures. The names are from the Chesapeake Assessment Scenario Tool (CAST; <https://cast.chesapeakebay.net/Home/TMDLTracking#tributaryRptsSectionhttps://cast.chesapeakebay.net/Home/TMDLTracking#tributaryRptsSection>).

<u>Abbreviated tributary name</u>	<u>Full tributary name</u>	<u>Group name</u>
Ana	Anacostia River	Potomac
App	Appomattox River	James
Bac	Back River	Patapsco
Big	Big Annemessex River	LowerE
Boh	Bohemia River	MDUpperE
Bus	Bush River	MDUpperW

C&D	Chesapeake & Delaware Canal	MDUpperE
Che	Chester River	MDUpperE
Chi	Chickahominy River	James
Cho	Choptank River	Choptank
Cor	Corrotoman River	Rappahannock
Eas	Eastern Bay	MDUpperE
Eli	Elizabeth River	James
Elk	Elk River	MDUpperE
Fis	Fishing Bay	LowerE
Gun	Gunpowder River	MDUpperW
Hon	Honga River	Choptank
Jam	James River	James
Laf	Lafayette River	James
Lit	Little Choptank River	Choptank
Lyn	Lynnhaven River	VAMain
Mag	Magothy River	MDLowerW
Man	Manokin River	LowerE
Mat	Mattawoman Creek	Potomac
Mat	Mattaponi River	York
MD	MD MAINSTEM	MD Main
Mid	Middle River	MDUpperW
Mob	Mobjack Bay	VAMain
Nan	Nanticoke River	LowerE
Nor	Northeast River	MDUpperE
Pam	Pamunkey River	York
Pat	Patapsco River	Patapsco
Pat	Patuxent River	Patuxent
Pia	Piankatank River	VAMain
Pis	Piscataway Creek	Potomac
Poc	Pocomoke River	LowerE
Pot	Potomac River	Potomac
Rap	Rappahannock River	Rappahannock
Rho	Rhode River	MDLowerW
Sas	Sassafras River	MDUpperE
Sev	Severn River	MDLowerW
Sou	South River	MDLowerW
Tan	Tangier Sound	LowerE
VA	VA MAINSTEM	VAMain
Wes	West River	MDLowerW
Wes	Western Branch (Patuxent River)	Patuxent

Wic	Wicomico River	LowerE
Yor	York River	York

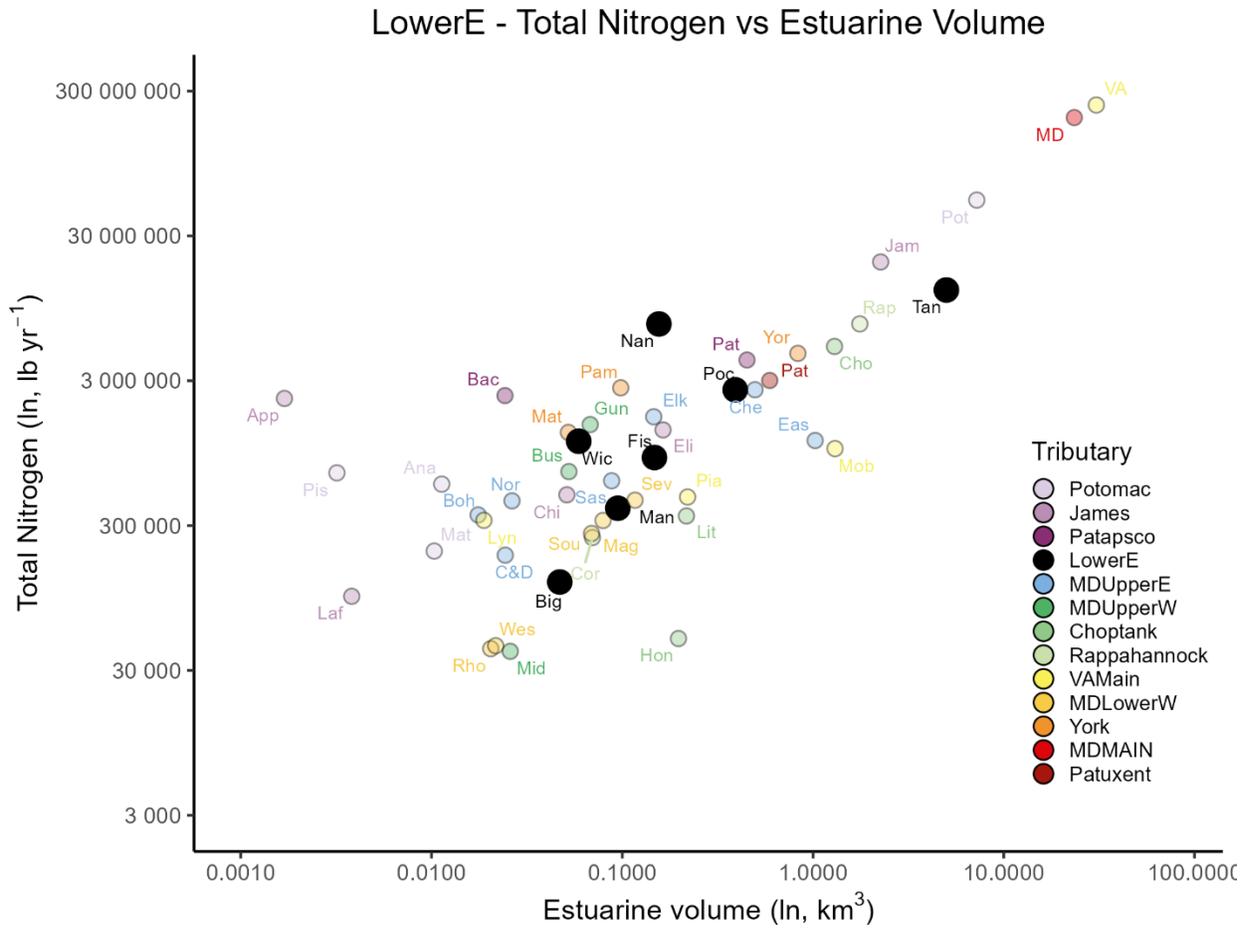


Figure 28. Average annual expected nitrogen loads versus estuarine volume. Nitrogen loads are from the 2021 progress scenarios in CAST (CAST, 2020), which is an estimate of nitrogen loads under long-term average hydrology given land use and reported management as of 2021.

LowerE - Total Phosphorus vs Estuarine Volume

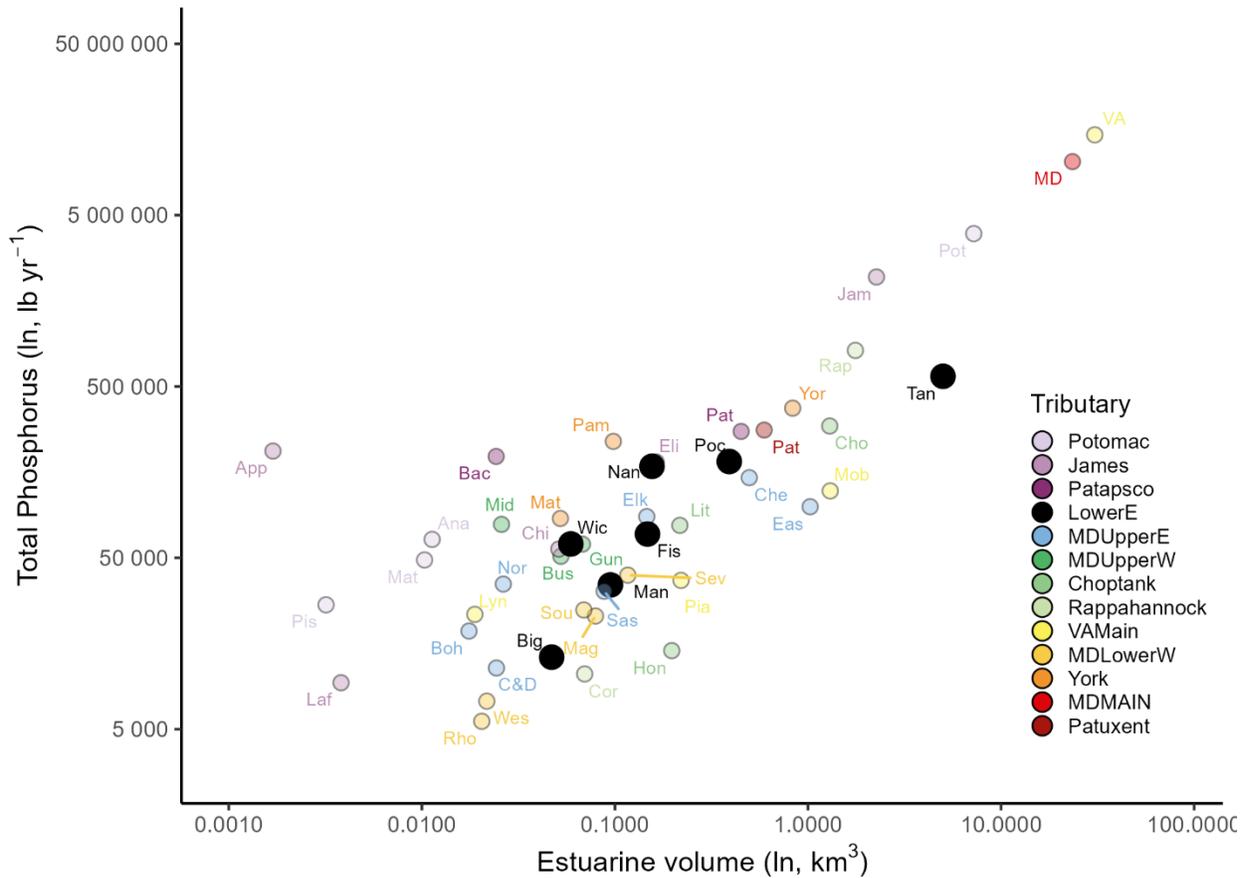


Figure 29: Average annual expected phosphorous loads versus estuarine volume. Nitrogen loads are from the 2021 progress scenarios in CAST (CAST, 2020), which is an estimate of nitrogen loads under long-term average hydrology given land use and reported management as of 2021.

Table 5. Comparison of watershed area, which includes tidal wetland area, versus estuarine volume for all estuaries and sub-estuaries identified in the CBP monitoring segment scheme. Ratio of nitrogen and phosphorus loads to estuarine volumes. Data for watershed area and volume were obtained from CAST and nitrogen and phosphorous loads were obtained from 2021 progress scenarios in CAST.

Tributary	Area % Contribution ¹	Volume % Contribution ²	N Ratio ³	P Ratio ⁴
MDLowerW	0.11	0.39	3.67×10^6	3.26×10^5
MDUpperW	0.39	0.19	1.53×10^7	1.30×10^6
Patapsco	0.42	0.60	1.38×10^7	9.87×10^5
Choptank	0.47	2.16	3.26×10^6	2.26×10^5
Patuxent	0.63	0.75	5.34×10^6	5.20×10^5
MDUpperE	0.67	2.31	3.86×10^6	2.36×10^5
Rappahannock	1.71	2.31	4.19×10^6	4.50×10^5
LowerE	2.30	7.46	4.28×10^6	1.87×10^5
York	3.19	1.24	8.78×10^6	7.10×10^5
James	7.93	3.14	9.69×10^6	1.06×10^6
Potomac	9.54	9.17	7.53×10^6	5.58×10^5
MDMAIN	30.50	29.64	8.41×10^6	4.38×10^5
VAMain	42.13	40.63	7.55×10^6	4.64×10^5

¹ Percent area contribution to the total Chesapeake Bay watershed area (km²).

² Percent volume contribution to the total Chesapeake Bay estuarine volume (km³).

³ Ratio of Nitrogen loads to estuarine volume.

⁴ Ratio of Phosphorus loads to estuarine volume.

5.2.2. Long-Term Changes in Water Quality Longitudinal Profiles

This section presents a series of longitudinal profiles of five water quality parameters across all the Lower Eastern Shore stations. The water quality parameters include TN, TP, chlorophyll *a*, water clarity as measured by Secchi depth (Secchi), and bottom DO. The profiles are generated from the results of GAM models estimated for each station averaged over all years in the assessment period. Cluster analysis was used to group stations by seasonal patterns. The same color represents a group of stations with similar trends across the months. Stations within a group are identified in the associated tables (e.g., Table 5). Comparing these groups allows for assessment of both spatial and temporal patterns for a given parameter, and comparison among parameters allows for assessment of associations of parameters. Refer to Figure 5 to understand the difference between inland and more tidal stations.

For TN, the more inland stations (ET7.1, ET6.1, ET6.2) are distinguished from the more Bay-centered stations by having high TN in mid-winter and low TN in late summer (Figure 30).

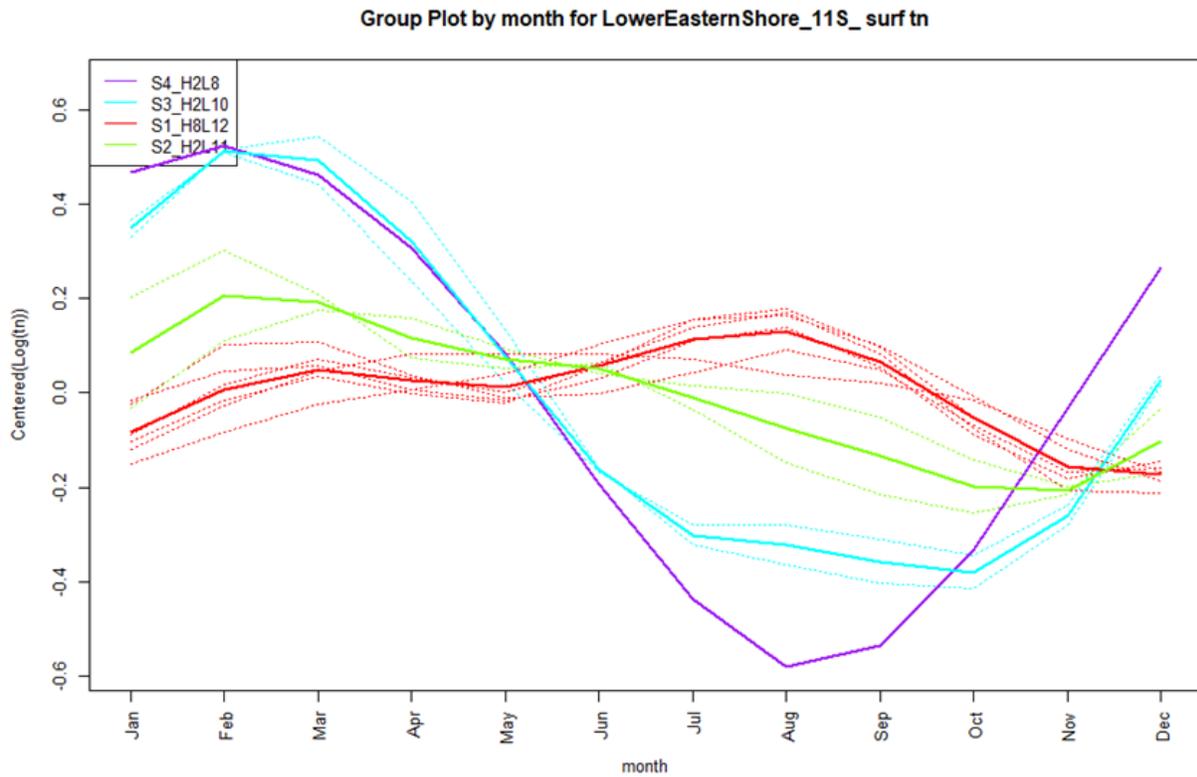


Figure 30: Monthly means of Total Nitrogen (TN) plotted with station groups segregated by color. Multiple dashed line traces within a group show variability among stations within that group.

Table 6. Cluster results for Total Nitrogen (TN) that refer to Figure 30.

Color	Label	Group	Station Name
red	S1_H8L12	3	EE3.0
red	S1_H8L12	3	EE3.2
red	S1_H8L12	3	EE3.3
red	S1_H8L12	3	EE3.4
red	S1_H8L12	3	ET8.1
red	S1_H8L12	3	ET9.1
chartreuse	S2_H2L11	4	EE3.1
chartreuse	S2_H2L11	4	ET10.1
cyan	S3_H2L10	2	ET6.2
cyan	S3_H2L10	2	ET7.1
purple	S4_H2L8	1	ET6.1

Majority of the stations have higher TP during the summer months and lower TP during the winter months. ET10.1 has much lower TP during the winter months than the other stations, and TP starts to increase earlier in the spring too (Figure 31).

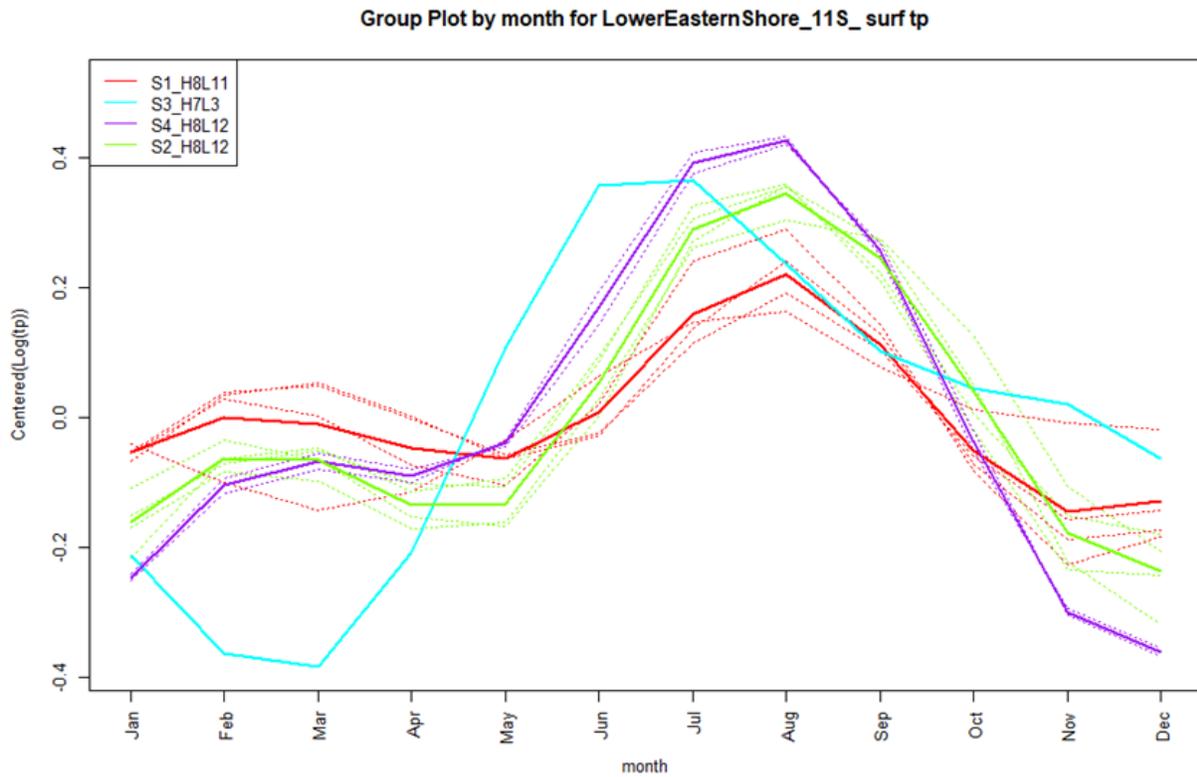


Figure 31: Monthly means of Total Phosphorous (TP) plotted with station groups segregated by color. Multiple dashed line traces within a group show variability among stations within that group.

Table 7. Cluster results for Total Phosphorous (TP) that refer to Figure 31.

Color	Label	Group	Station Name
red	S1_H8L11	1	EE3.0
red	S1_H8L11	1	ET6.1
red	S1_H8L11	1	ET6.2
red	S1_H8L11	1	ET7.1
chartreuse	S2_H8L12	4	EE3.1
chartreuse	S2_H8L12	4	EE3.2
chartreuse	S2_H8L12	4	EE3.3
chartreuse	S2_H8L12	4	ET9.1
cyan	S3_H7L3	2	ET10.1
purple	S4_H8L12	3	EE3.4
purple	S4_H8L12	3	ET8.1

The more Bay-centered stations show a steady increase and decrease throughout the year, while the more inland stations (ET10.1, ET6.2, ET 7.1, ET 6.1) show more dramatic changes. ET6.1, which is the

furthest inland station, has much lower chlorophyll *a* levels during the winter months compared to the other stations. ET6.1 also has the highest levels during the summer months too (Figure 32).

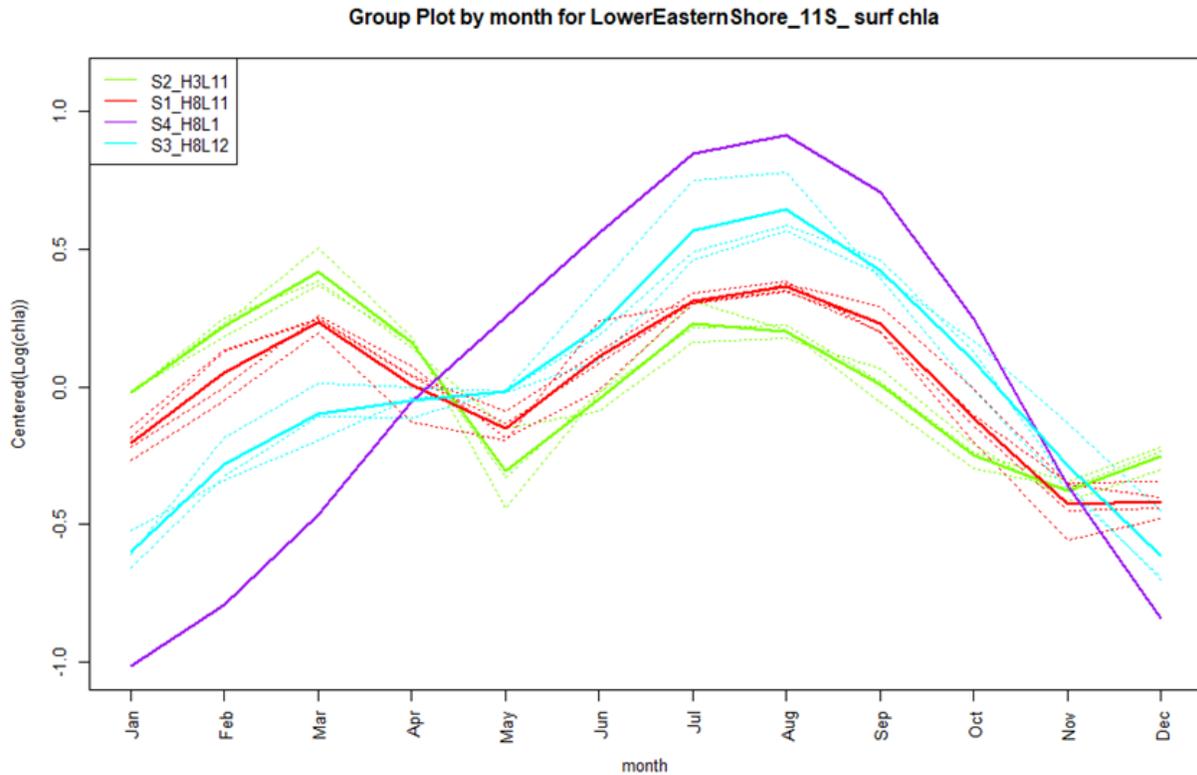


Figure 32: Monthly means of chlorophyll *a* plotted with station groups segregated by color. Multiple dashed line traces within a group show variability among stations within that group.

Table 8. Cluster results for chlorophyll *a* that refer to Figure 32.

Color	Label	Group	Station Name
red	S1_H8L11	2	EE3.3
red	S1_H8L11	2	EE3.4
red	S1_H8L11	2	ET8.1
red	S1_H8L11	2	ET9.1
chartreuse	S2_H3L11	1	EE3.0
chartreuse	S2_H3L11	1	EE3.1
chartreuse	S2_H3L11	1	EE3.2
cyan	S3_H8L12	4	ET10.1
cyan	S3_H8L12	4	ET6.2
cyan	S3_H8L12	4	ET7.1
purple	S4_H8L1	3	ET6.1

The more inland stations (ET10.1, ET 6.1, ET 6.2, ET 7.1) have a consistent secchi depth throughout the entire year. ET 8.1 and ET9.1 show the most fluctuation. ET 8.1 has the lowest water clarity during the summer months compared to the other stations, and clarity improves during the fall and early winter months (Figure 33).

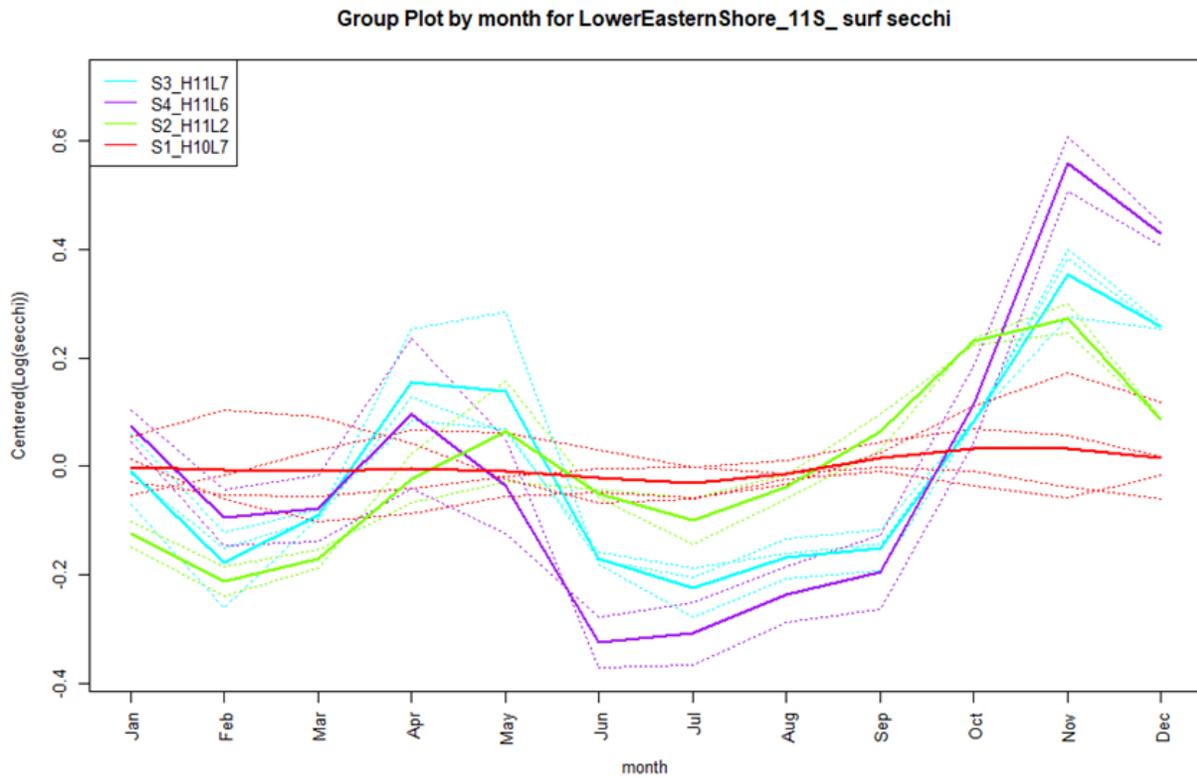


Figure 33: Monthly means of Secchi depth plotted with station groups segregated by color. Multiple dashed line traces within a group show variability among stations within that group. A larger log(secchi) represents improved water clarity.

Table 9. Cluster results for Secchi depth that refer to Figure 33.

Color	Label	Group	Station Name
red	S1_H10L7	4	ET10.1
red	S1_H10L7	4	ET6.1
red	S1_H10L7	4	ET6.2
red	S1_H10L7	4	ET7.1
chartreuse	S2_H11L2	3	EE3.0
chartreuse	S2_H11L2	3	EE3.1
cyan	S3_H11L7	1	EE3.2
cyan	S3_H11L7	1	EE3.3
cyan	S3_H11L7	1	EE3.4
purple	S4_H11L6	2	ET8.1

purple	S4_H11L6	2	ET9.1
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All of the stations show a similar pattern of higher DO concentrations in the fall and winter months and lower DO concentrations in the summer. Stations EE3.1, EE3.2, ET7.1 (purple) have some of the highest DO concentrations in the winter months but also have the lowest DO concentrations in the summer months (Figure 34).

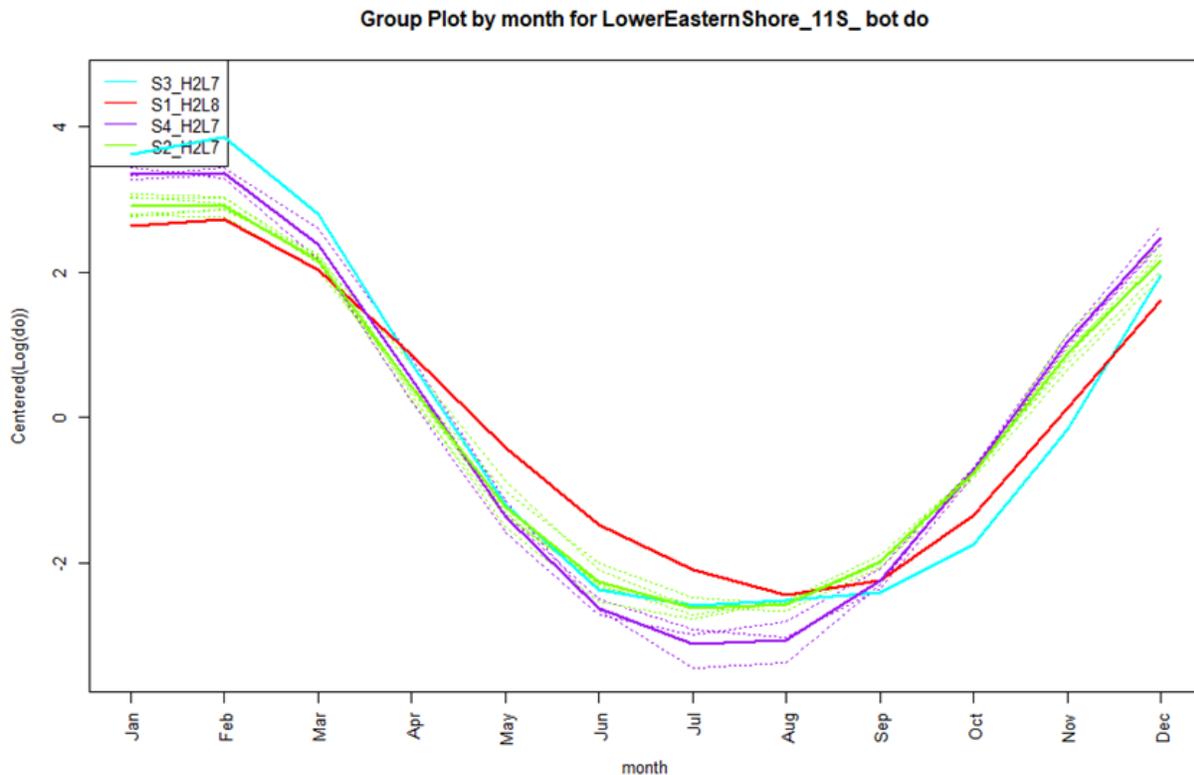


Figure 34: Monthly means of Dissolved Oxygen (DO) concentration plotted with station groups segregated by color. Multiple dashed line traces within a group show variability among stations within that group.

Table 10. Cluster results for Dissolved Oxygen (DO) concentration that refer to Figure 34.

Color	Label	Group	Station Name
red	S1_H2L8	2	ET6.1
chartreuse	S2_H2L7	4	EE3.0
chartreuse	S2_H2L7	4	EE3.3
chartreuse	S2_H2L7	4	EE3.4
chartreuse	S2_H2L7	4	ET6.2
chartreuse	S2_H2L7	4	ET8.1
chartreuse	S2_H2L7	4	ET9.1
cyan	S3_H2L7	1	ET10.1

purple	S4_H2L7	3	EE3.1
purple	S4_H2L7	3	EE3.2
purple	S4_H2L7	3	ET7.1

5.3 Changing Environmental Conditions

As one of the most vulnerable areas in the nation, all aspects of the Chesapeake Bay watershed and tributaries are experiencing changing environmental conditions, and the impacts are already being observed. Overall, the watershed is experiencing increases in precipitation and temperatures which shape Chesapeake Bay tributary water quality trends (Najjar et al., 2010). These trends differ spatially and temporally throughout the watershed, and impacts are exacerbated by local stressors (e.g., land subsidence, land-use change, growth and development). Therefore, this section of the Tributary Summary is not an exhaustive discussion of how changing environmental conditions are influencing water quality in Chesapeake Bay tributaries but instead is an acknowledgement of the influence of some stressors on the trends discussed in this report. Efforts aimed to increase understanding of these changing environmental conditions on water quality patterns can help explain the progress gaps and transform monitoring findings into actionable information.

5.3.1. Extreme Weather and Increased Precipitation

Under typical weather conditions, fresh water flowing from rivers and streams makes up about half of Chesapeake Bay’s entire water volume. However, extremes in rainfall—whether too much or too little—can have varying effects on the Bay ecosystem. During large rain events, river flow increases, delivering more fresh water into the Bay and decreasing the Bay’s salinity (Murphy et al., 2019). During extreme rain events, sediment and nutrients may be scoured from behind river dams resulting in extraordinarily high nutrient and sediment loads to the Bay (Langland, 2015). Stormwater runoff delivers nitrogen, phosphorus, and sediment into rivers and the Bay causing an increase in nutrient concentrations, which create dead zones and feed algal blooms. During periods with little rainfall or extended drought, the decrease in freshwater flows results in saltier conditions, affecting habitats and aquatic species.

The correlation of water quality with extreme weather events is observed through the Chesapeake Bay Water Quality Standards Attainment Indicator (Figure 35) (CBP, 2023). The attainment indicator uses a subset of the criteria otherwise necessary for a complete regulatory accounting of water quality standards attainment assessments of tidal water Chesapeake Bay dissolved oxygen, water clarity and chlorophyll *a*. The indicator, therefore, is recognized as an estimate of true attainment of these water quality standards. Dips in the attainment of long-term water quality standards show the responsiveness of Chesapeake Bay to extreme events such as Hurricane Ivan in 2004 and Hurricane Irene in 2011. When viewed in isolation, these extreme events would lead to non-attainment. However, the indicator shown in Figure 35 also shows that estimated attainment recovers relatively quickly in the aftermath of extreme events, thus highlighting the resiliency of the Bay.

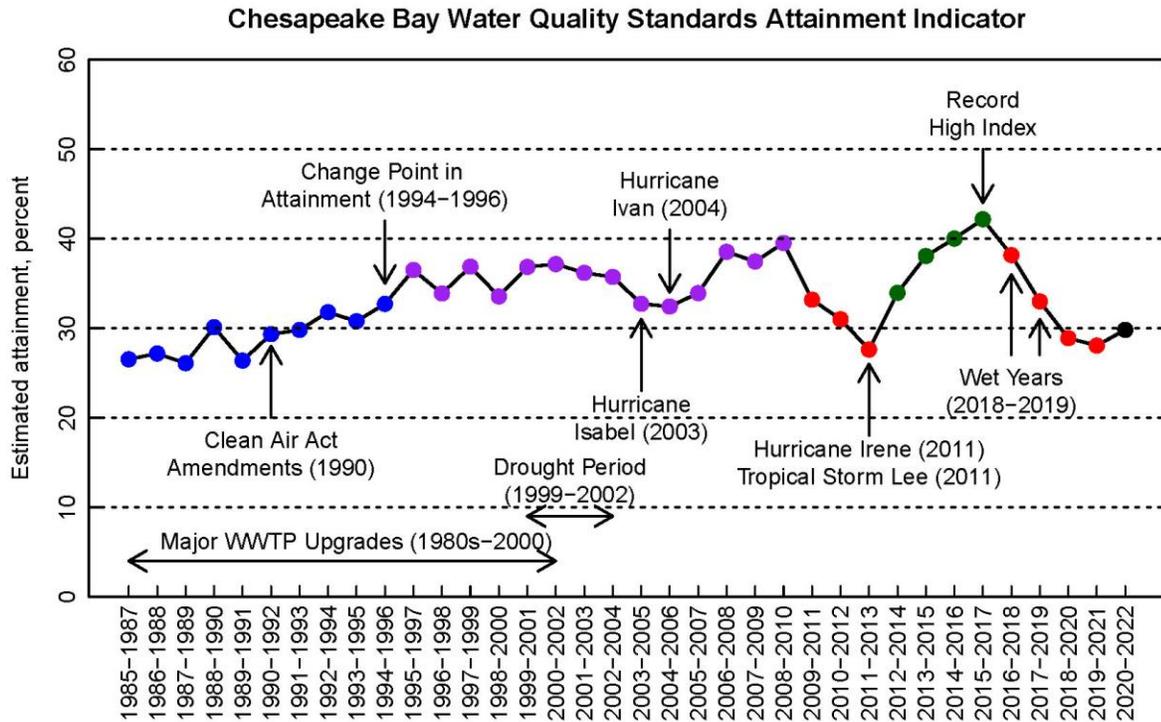


Figure 35. Chesapeake Bay Water Quality Standards Attainment Indicator valuated using three parameters from 1985 – 2021: dissolved oxygen, water clarity or submerged aquatic vegetation abundance, and chlorophyll a. Colors represent a different period: blue represents the period before the change point, purple represents the period of steady attainment results, red represents the period of decreasing attainment after high flow years, and green represents the period of increasing attainment.

One-off events such as hurricanes are not the only measure influencing progress towards water quality attainment. Unusually prolonged wet weather in 2018 and 2019 caused higher than average river flows entering Chesapeake Bay, delivering high pollutant loads during that period (Figures 35, 36, 37, 38). Experts attribute the reduction in pollutant loads in 2020 to a combination of reduced river flow from less rainfall and to management actions controlling pollution in the Bay and watershed (CBP, 2023).

Pollution Loads and River Flow to the Chesapeake Bay (1990-2022)

River and Watershed Input of Pollution Loads. Years denote the water year measured between October 1 and September 30.

[VIEW CHART](#) [VIEW TABLE](#)

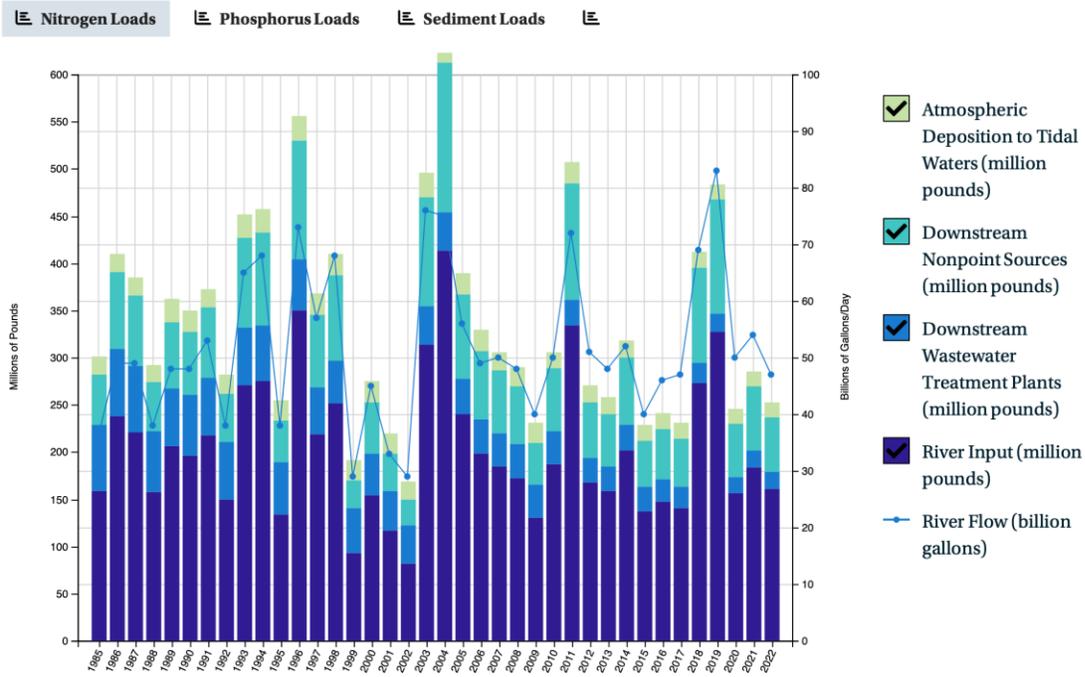


Figure 36: Nitrogen loads and River Flow to Chesapeake Bay (1990-2022); River and Watershed Input of Nitrogen Loads. Years denote the water year measured between October 1 and September 30. Figure from Chesapeake Bay Program, 2023 (<https://www.chesapeakeprogress.com/clean-water/water-quality>).

Pollution Loads and River Flow to the Chesapeake Bay (1990-2022)

River and Watershed Input of Pollution Loads. Years denote the water year measured between October 1 and September 30.

[VIEW CHART](#) [VIEW TABLE](#)

[Nitrogen Loads](#) **[Phosphorus Loads](#)** [Sediment Loads](#)

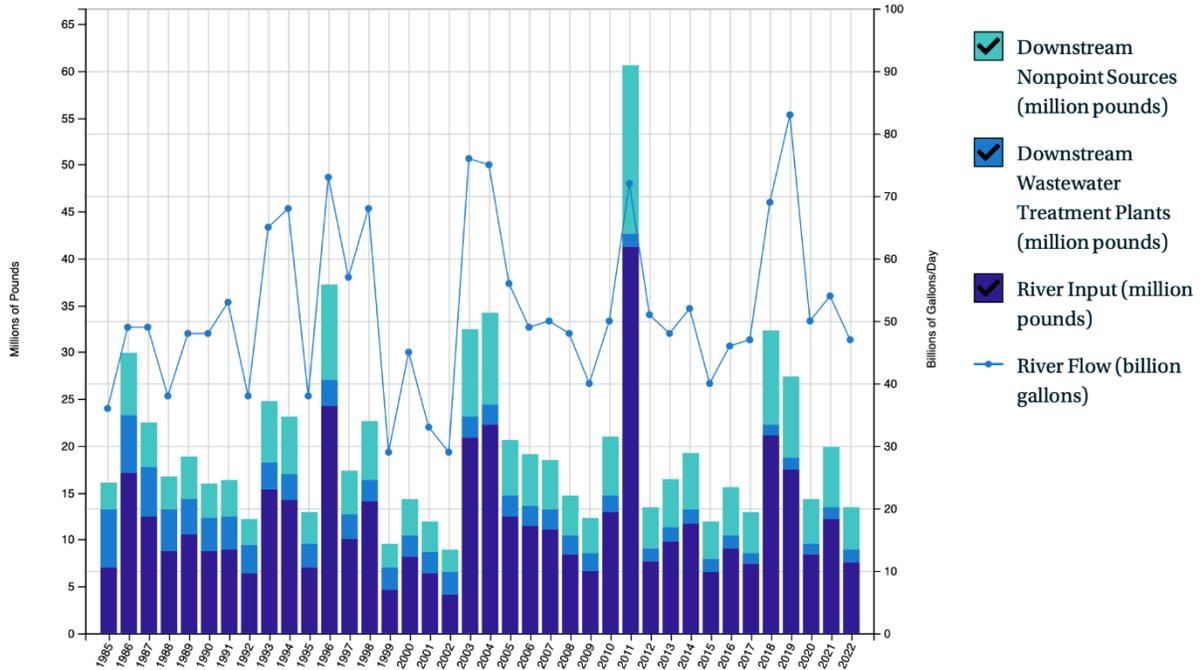


Figure 37: Phosphorus loads and River Flow to Chesapeake Bay (1990-2022); River and Watershed Input of Phosphorus Loads. Years denote the water year measured between October 1 and September 30. Figure from Chesapeake Bay Program, 2023 (<https://www.chesapeakeprogress.com/clean-water/water-quality>).

Pollution Loads and River Flow to the Chesapeake Bay (1990-2022)

River and Watershed Input of Pollution Loads. Years denote the water year measured between October 1 and September 30.

[VIEW CHART](#) [VIEW TABLE](#)

[Nitrogen Loads](#) [Phosphorus Loads](#) **[Sediment Loads](#)** [Sulfate Loads](#)

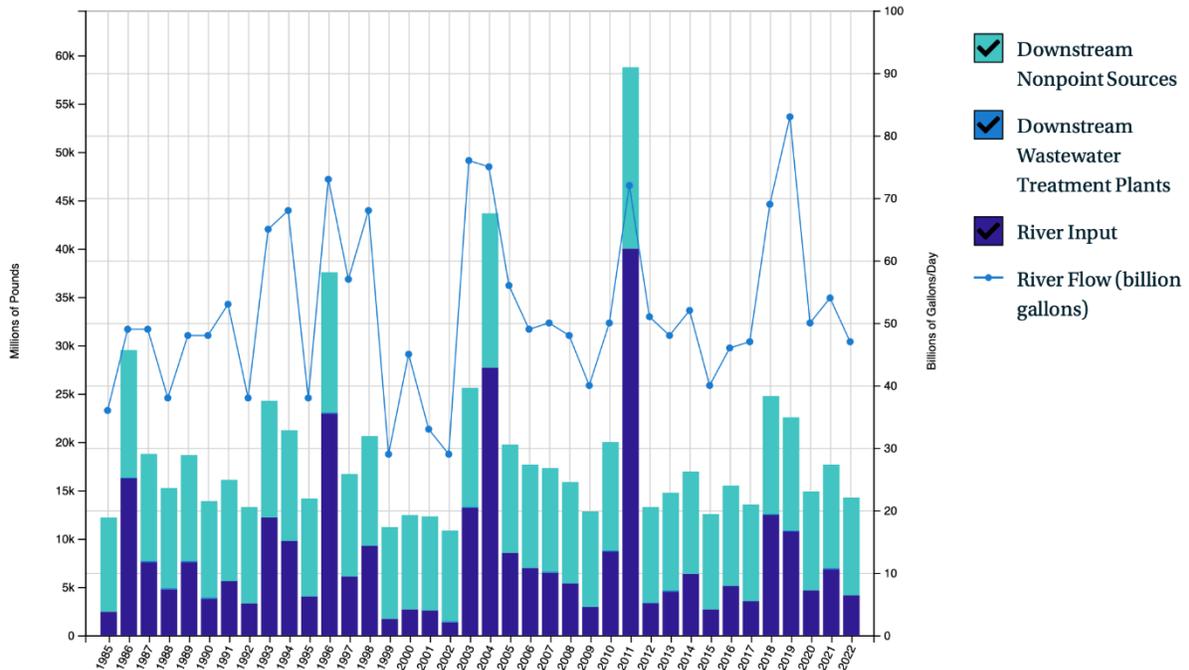


Figure 38: Sediment loads and River Flow to Chesapeake Bay (1990-2022); River and Watershed Input of Sediment loads. Years denote the water year measured between October 1 and September 30. Figure from Chesapeake Bay Program, 2023 (<https://www.chesapeakeprogress.com/clean-water/water-quality>).

Many models predict increases in average annual precipitation for the Chesapeake Bay region, but studies have found greater seasonality in the projected precipitation change (Kunkel et al. 2013). Winter and spring projections show increased precipitation, followed by periods of drought (Pyke et al. 2008; Najjar et al. 2010). These studies are supportive for understanding stream flow, but local assessments of changing environmental conditions and variability are still needed for determining vulnerability for the Bay (St. Laurent et al., 2021). Figure 39 shows Parameter-elevation relationship on independent slope model (PRISM Group, 2014) data at the land-river scale spatially aggregated to the Lower Eastern Shore tributary basin. Mean annual precipitation for the Lower Eastern Shore Tributary from 1981 to 2023 shows a gradual increase over the period of record.

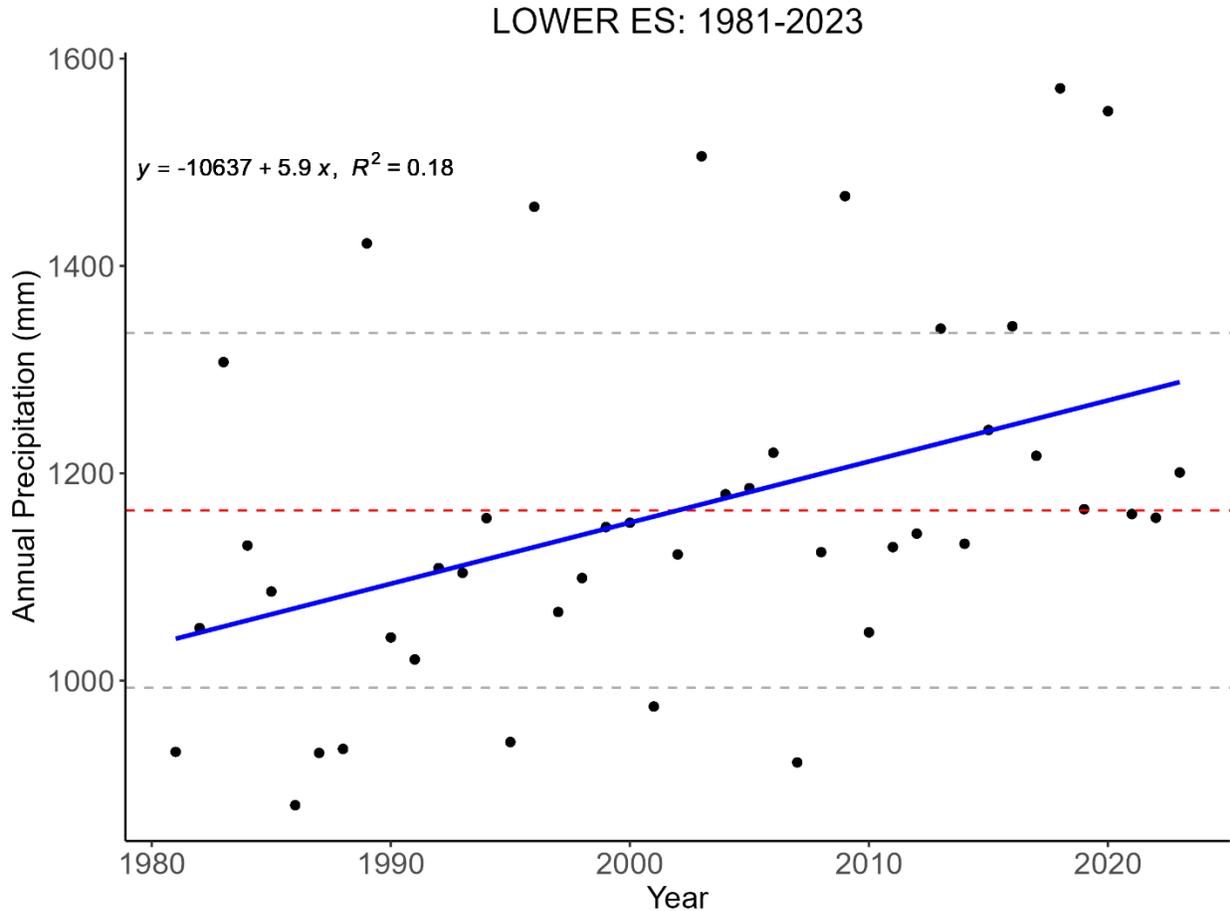


Figure 39. Lower Eastern Shore annual precipitation from 1981 – 2023 from the Parameter-elevation Regressions on Independent Slopes Model (PRISM). The red dashed line indicates the mean precipitation for this period, and the dashed gray lines represent the upper and lower standard deviations from the mean value for this period. The blue line represents a positive linear regression where the accompanying equation and R^2 can be found in the top left corner of the figure.

5.3.2. Warming Water Temperatures

The Chesapeake Bay is shallow, with a mean depth of 6.5 m, which means that atmospheric variability has a large influence on water column temperatures (St. Laurent, 2021). As described in Section 4.7, both long-term and short-term surface water temperature trends across the tidal areas of the Lower Eastern Shore are experiencing statistically significant warming (Figure 40). Increased atmospheric temperatures are forcing factors that contribute to warmer water temperatures. Trends from resulting marine heat waves, or prolonged anomalously warm events, indicate increases in marine heat wave frequency, duration, and cumulative yearly intensity (Mazzini and Pianca, 2022).

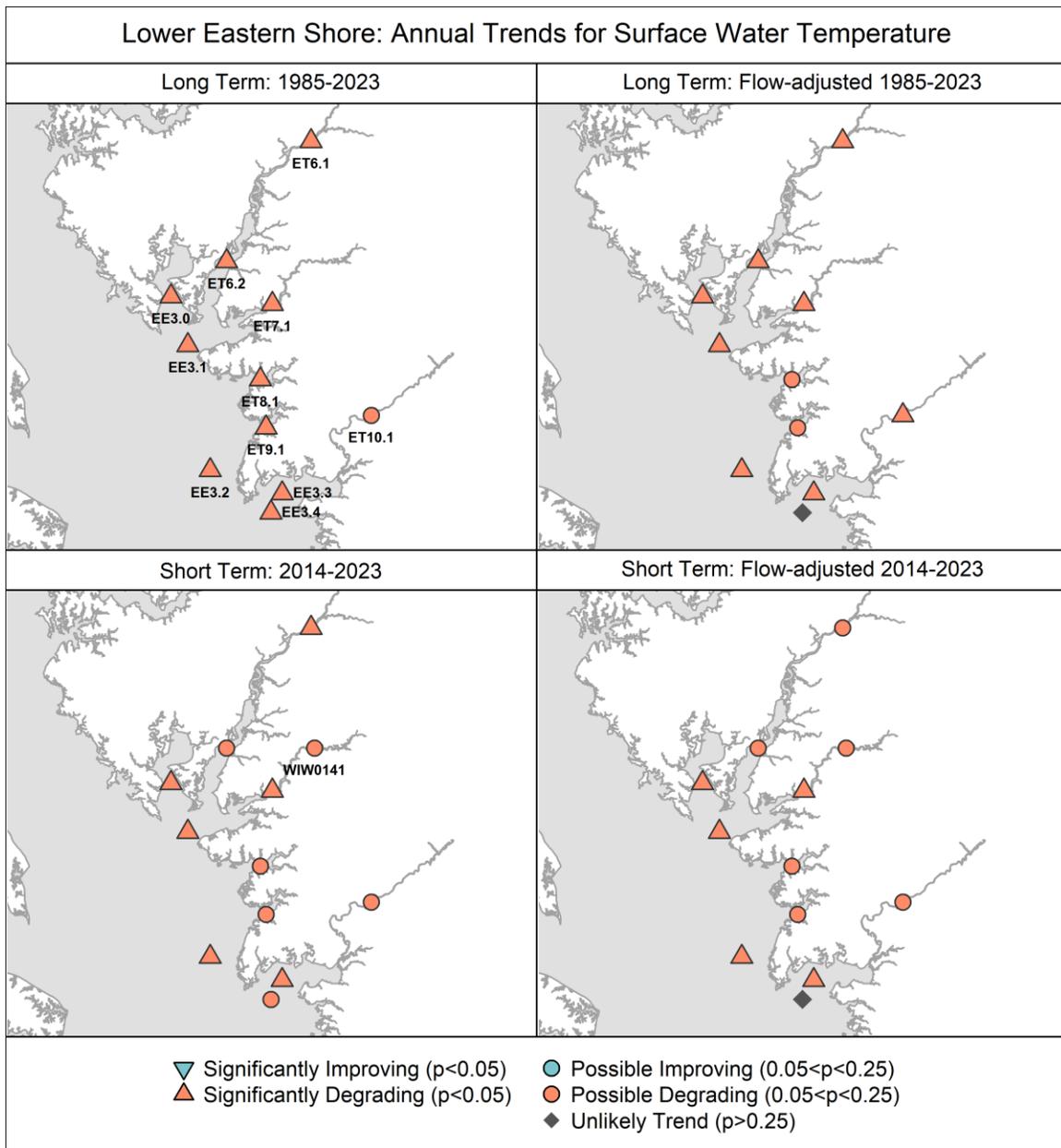


Figure 40. Annual flow-adjusted surface water temperature trends as calculated using Generalized Additive Models (Murphy et al., 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983. For more information on the tidal stations and Chesapeake Bay tidal water quality monitoring, refer to <https://www.chesapeakebay.net/what/programs/quality-assurance/tidal-water-quality-monitoring>.

5.3.3. Sea-Level Rise

Sea level has risen due to the thermal expansion of ocean water and melting of glaciers and ice sheets (USGS, 2018). Over the past century, Chesapeake Bay waters have risen by about 1 foot, and according to a USGS study, Chesapeake Bay waters are predicted to rise another 1.3 to 5.2 feet over the next 100

years (Eggleston and Pope, 2013). This rate is higher than the global sea level rise average because the Chesapeake Bay region is also impacted by land subsidence, or sinking of land due to removal or displacement, half of which is estimated to be from groundwater removal (Eggleston and Pope, 2013).

NOAA Tides and Currents provides sea-level trends across the U.S. Within the Lower Eastern Shore, a station located on the South side of the Choptank River in Cambridge, Maryland shows an increasing sea-level trend of 4.06 mm/year (Figure 41) (NOAA, 2025).

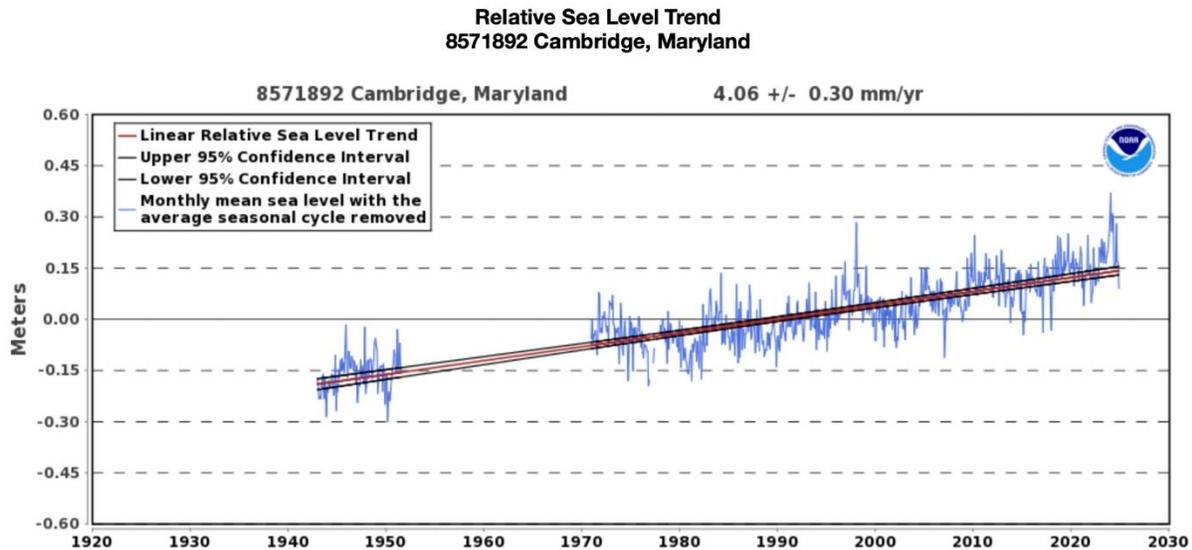


Figure 41. Cambridge, Maryland monthly mean sea levels without the regular season fluctuations from coastal ocean temperatures, salinity, wind, atmospheric pressure, and ocean currents. The relative sea level trend also shows the 95% confidence interval (NOAA, 2025).

Higher water levels in Chesapeake Bay can result in loss of marshes and wetlands due to saltwater inundation. This is occurring due to erosion rates that are outpacing marsh accretion and/ or marsh migration being blocked by development (Eggleston and Pope, 2013). Wetland habitat loss eliminates natural structures that trap pollution entering the Bay, which is why it is critical to consider changing environmental conditions, such as sea-level rise, when pursuing, designing, implementing, and maintaining restoration efforts (NOAA, 2023a).

5.3.4. Connecting to Living Resources

Although measuring and discussing changing environmental conditions and their impacts on water quality is critical, it is also important to understand these influences in the context of the living resources that water quality standards were designed to protect. Warming water temperatures reduce the solubility of oxygen in water (Tian et al., 2021). With both higher average and extreme water temperatures, habitats are limited by both low oxygen and high temperatures. Key aquatic species with economic and cultural value to the Chesapeake Bay, such as striped bass (*Morone saxatilis*), encounter a habitat squeeze as bottom hypoxia and warm surface temperatures compress suitable habitat space in the highest and lowest portions of the water column (Parhman et al., 2023). Another consideration is that warming waters in Chesapeake Bay favor pathogenic bacteria like *Vibrio vulnificus*, which threaten

human health directly through key living resources that are valued for human consumption, such as oysters (Archer et al., 2023; Wright et al., 1996) and indirectly through relationships with the key fisheries they support (Batiuk et al., 2023). Increased precipitation also presents challenges for living resources by reducing suitable habitat. Heavier precipitation can yield increased hypoxia as the rate of phosphorus flushing from the landscape increases, and for oysters, heavy freshwater flows may lower salinity to a harmful level (Kimmel et al., 2014).

The NOAA Seasonal Summaries offer more information on how changing environmental conditions impact living resources at finer spatial and temporal scales. These data describe salinity, DO, freshwater flow, and water temperature across Chesapeake Bay and provide critical insight into ecosystem conditions. Applications of the NOAA seasonal summaries include informing ecosystem-based management for fisheries at the state and regional level and comparing the recent seasonal data with long-term averages. The NOAA Seasonal Summaries can be accessed at NOAA Chesapeake Bay Interpretive Buoy System (NOAA, 2023b).

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Appendix A: Glossary of Terms

Anoxic - condition in which the water column is characterized by a complete absence of oxygen. Anoxic conditions typically result from excessive decomposition of organic material by bacteria, high respiration by phytoplankton, stratification of the water column due to salinity or temperature effects or a

combination of these factors. Anoxic conditions can result in fish kills or localized extinction of benthic communities.

Anthropogenic - resulting from or generated by human activities.

Benthos - refers to organisms that dwell on or within the bottom of a waterway or waterbody. Includes both hard substratum habitats (e.g., oyster reefs) and sedimentary habitats (sand and mud bottoms).

B-IBI - the benthic index of biotic integrity of Weisberg et al. (1997). The B-IBI is a multi-metric index that compares the condition of a benthic community to reference conditions.

Biological Nutrient Removal (BNR) - A temperature dependent process in which the ammonia nitrogen present in wastewater is converted by bacteria first to nitrate nitrogen and then to nitrogen gas. This technique is used to reduce the concentration of nitrogen in sewage treatment plant effluents.

Chlorophyll *a* - a green pigment found in plant cells that functions as the receptor for energy in the form of sunlight. This energy is used in the production of cellular materials for growth and reproduction in plants. Chlorophyll *a* concentrations are measured in micrograms per liter ($\mu\text{g/L}$) and are used as an estimate of the total biomass of phytoplankton cells in the water column. In general, high levels of chlorophyll *a* are believed to be indicative of excessive growth of phytoplankton resulting from excess nutrients such as nitrogen and phosphorus in the water column.

Chlorophytes - algae belonging to the division Chlorophyta often referred to as true "green algae." Chlorophytes occur in unicellular, colonial, and filamentous forms and are generally more common in tidal freshwater and oligohaline portions of estuaries.

Cryptomonads - algae belonging to the division Cryptophyta that have accessory pigments in addition to chlorophyll *a* which give these small, flagellated cells a red, brown, or yellow color.

Cyanophytes (or Cyanobacteria) - algae-like bacteria belonging to the division Cyanophyceae that are prokaryotic and that occur in single-celled, filamentous, and colonial forms. In general, high concentrations of cyanophytes are considered indicative of poor water quality.

Diatoms - algae belonging to the division Bacillariophyta that have a cell wall that is composed primarily of silica and that consists of two separate halves. Most diatoms are single celled, but some are colonial and filamentous forms. Diatoms are generally considered to be indicative of good water quality and are appropriate food for many zooplankton.

Dinoflagellates - biflagellated, predominately unicellular protists that are capable of photosynthesizing. Many dinoflagellates are covered with cellulose plates or with a series of membranes. Some dinoflagellates periodically reproduce in large numbers causing blooms that are often referred to as "red tides." Certain species produce toxins and blooms of these forms have been implicated in fish kills. High concentrations of dinoflagellates are generally considered indicative of poor water quality.

Dissolved oxygen (DO) - the concentration of oxygen in solution in the water column, measured in milligrams per liter (mg/L). Most aquatic organisms rely on oxygen for cellular metabolism, and as a result, low levels of dissolved oxygen adversely affect important living resources such as fish and the benthos. In general, dissolved oxygen levels decrease with increasing pollution.

Dissolved inorganic nitrogen (DIN) - the concentration of inorganic nitrogen compounds including ammonia (NH_4), nitrates (NO_3) and nitrites (NO_2) in the water column measured in milligrams per liter (mg/L). These dissolved inorganic forms of nitrogen are directly available for uptake by phytoplankton by diffusion without first undergoing the process of decomposition. High concentrations of dissolved inorganic nitrogen can result in excessive growth of phytoplankton which in turn can adversely affect other living resources.

Dissolved inorganic phosphorus (PO_4) - the concentration of inorganic phosphorus compounds consisting primarily of orthophosphates (PO_4). The dissolved inorganic forms of phosphorus are directly available for uptake by phytoplankton by diffusion without first undergoing the process of decomposition. High concentrations of dissolved inorganic phosphorus can result in excessive growth of phytoplankton which in turn can adversely affect other living resources.

Estuary - A semi-enclosed body of water that has a free connection with the open sea and within which seawater is diluted measurably with freshwater derived from land drainage.

Eukaryote - organisms made of cells containing discrete organelles and a nucleus separated from the cytoplasm by a membrane.

Fall line - location of the maximum upstream extent of tidal influence in an estuary typically characterized by a waterfall.

Fixed Point Stations - stations for long-term trend analysis whose location is unchanged over time.

Flow adjusted concentration (FAC) - concentration which has been recalculated to remove the variation caused by freshwater flow into a stream. By removing variation caused by flow, the effects of other factors such as nutrient management strategies can be assessed.

Habitat - a local environment that has a community distinct from other such habitat types. For the B-IBI of Chesapeake Bay, seven habitat types were defined as combinations of salinity and sedimentary types - tidal freshwater, oligohaline, low mesohaline, high mesohaline sand, high mesohaline mud, polyhaline sand and polyhaline mud.

Hypoxic - condition in which the water column is characterized by dissolved oxygen concentrations less than 2 milligrams per liter (mg/L) but greater than 0 mg/L. Hypoxic conditions typically result from excessive decomposition of organic material by bacteria, high respiration by phytoplankton, stratification of the water column due to salinity or temperature effects or a combination of these factors. Hypoxic conditions can result in fish kills or localized extinction of benthic communities.

Light attenuation (KD) - Absorption, scattering, or reflection of light by dissolved or suspended material in the water column expressed as the change in light extinction per meter of depth. Light attenuation reduces the amount of light available to submerged aquatic vegetation.

Loading - the total mass of contaminant or nutrient added to a stream or river generally expressed in kilograms per year (kg/yr) or pounds per year (lbs/yr).

Macrobenthos - a size category of benthic organisms that are retained on a mesh of 0.5 millimeters (mm).

Mesohaline - refers to waters with salinity values ranging between 0.5 and 18.0 parts per thousand (ppt).

Metric - a parameter or measurement of ecological community structure (e.g., abundance, biomass, species diversity).

Non-point source - a source of pollution that is distributed widely across the landscape surrounding a water body (e.g., run-off from residential and agricultural land) instead of being at a fixed location (e.g., wastewater treatment plant outlet).

Oligohaline - refers to waters with salinity values ranging between 0.5 and 5.0 parts per thousand (ppt).

Percent of light at the leaf surface (PLL) - the percentage of light at the surface of the water column that reaches the surface of the leaves of submerged aquatic vegetation generally estimated for depths of 0.5 and 1.0 meter (m). Without sufficient light at the leaf surface, submerged aquatic plants cannot perform photosynthesis and hence cannot grow or reproduce.

Phytoplankton - that portion of the plankton capable of producing its own food by photosynthesis. Typical members of the phytoplankton include diatoms, dinoflagellates, and chlorophytes.

P-IBI - the phytoplankton index of biotic integrity (Buchanan et al., 2005; Lacouture et al., 2006). The P-IBI is a multi-metric index that compares the condition of a phytoplankton community to reference conditions.

Plankton - aquatic organisms that drift within and that are incapable of movement against water currents. Some plankton have limited locomotor ability that allows them to change their vertical position in the water column.

Point source - a source of pollution that is concentrated at a specific location such as the outfall from a sewage treatment plant or factory.

Polyhaline - refers to waters with salinity values ranging between 18.0 and 30 parts per thousand (ppt).

Primary productivity - the rate of production of living material through the process of photosynthesis that for phytoplankton is typically expressed in grams of carbon per liter of water per hour. High rates of primary productivity are generally considered to be related to excessive concentrations of nutrients such as nitrogen and phosphorus in the water column.

Probability based sampling - all locations within a stratum have an equal chance of being sampled. Allows estimation of the percent of the stratum meeting or failing the benthic restoration goals.

Prokaryote - organisms the cells of which do not have discrete organelles or a nucleus (e.g., Cyanobacteria).

Pycnocline - a rapid change in salinity in the water column indicating stratification of water with depth, resulting from changes in either salinity or water temperature.

Random Station - a station selected randomly within a stratum. In every successive sampling event, new random locations are selected.

Recruitment - The successful dispersal, settlement, and development of larval forms of plants or animal to a reproducing adult.

Reference condition - the structure of benthic communities at reference sites.

Reference sites - sites determined to be minimally impacted by anthropogenic stress. Conditions at these sites are considered to represent goals for restoration of impacted benthic communities. Reference sites were selected by Weisberg et al. (1997) as those outside highly developed watersheds, distant from any point-source discharge, with no sediment contaminant effect, with no low dissolved oxygen effect, and with a low level of organic matter in the sediment.

Restoration Goal - refers to obtaining an average B-IBI value of 3.0 for a benthic community indicating that values for metrics approximate the reference condition.

Riparian Buffer - An area of trees and shrubs with a minimum width of 100 feet located up gradient, adjacent, and parallel to the edge of a water feature which 1) reduces excess amounts of sediment, organic matter, nutrients, and other pollutants in surface runoff, 2) reduces soluble pollutants in shallow ground water flow, 3) creates shade along water bodies to lower aquatic temperatures, 4) provides a source of detritus and large woody debris for aquatic organisms, 5) provides riparian habitat and corridors for wildlife, and 6) reduces erosion of streambanks and shorelines.

Salinity - the concentration of dissolved salts in the water column measured in milligrams per liter (mg/L), parts per thousand (ppt) or practical salinity units (psu). The composition and distribution of plant and animal communities is directly affected by salinity in estuarine systems. The effects of salinity on living resources must be taken into consideration when interpreting the potential effects of human activities on living resources.

Secchi depth - the depth of light penetration expressed in meters as measured using a Secchi disk. Light penetration depth directly affects the growth and recruitment of submerge aquatic vegetation.

Stratum - a geographic region of unique ecological condition or managerial interest.

Submerged aquatic vegetation (SAV) - rooted vascular plants (e.g., *Zostera marina* (eelgrass), *Ruppia maritima* (widgeongrass), *Stuckenia pectinata* (sago pondweed)) that grow in shallow water areas. SAV is important in marine environments because it is a major food source, provides refuge for juvenile crabs and fish, stabilizes sediments preventing shoreline erosion and excessive suspended materials in the water column, and produces oxygen in the water column.

Threshold - a value of a metric that determines the B-IBI scoring. For all metrics except abundance and biomass, two thresholds are used - the lower 5th percentile and the 50th percentile (median) of the distribution of values at reference sites. Samples with metric values less than the lower 5th percentile are scored as a 1. Samples with values between the 5th and 50th metrics are scored as 3, and values greater than the 50th percentile are scored as 5. For abundance and biomass, values below the 5th and above the 95th percentile are scored as 1, values between the 5th and 25th and the 75th and 95th percentiles are scored as 3 and values between the 25th and 75th percentiles are scored as 5.

Tidal freshwater - refers to waters with salinity values ranging between 0 and 0.5 parts per thousand (ppt) which are located in the upper reaches of the estuary at or just below the maximum upstream extent of tidal influence.

Total nitrogen (TN) - the concentration of both inorganic and organic compounds in the water column which contain nitrogen measured in milligrams per liter (mg/L). Nitrogen is a required nutrient for protein synthesis. Inorganic forms of nitrogen are directly available for uptake by phytoplankton while organic compounds must first be decomposed by bacteria prior to being available for use for other organisms. High levels of total nitrogen can be detrimental to living resources either as a source of nutrients for excessive phytoplankton growth or as a source of excessive bacterial decomposition that can increase the incidence and extent of anoxic or hypoxic events.

Total phosphorus (TP) - the concentration of both inorganic and organic compounds in the water column which contain phosphorus measured in milligrams per liter (mg/L). Phosphorus is a required nutrient for cellular metabolism and the production of cell membranes. Inorganic forms of phosphorus are directly available for uptake by phytoplankton while organic compounds must first be decomposed by bacteria prior to being available for use for other organisms. High levels of total phosphorus can be detrimental to living resources either as a source of nutrients for excessive phytoplankton growth or as a source of excessive bacterial decomposition that can increase the incidence and extent of anoxic or hypoxic events.

Total suspended solids (TSS) - the concentration of suspended particles in the water column, measured in milligrams per liter (mg/L). The composition of total suspended solids includes both inorganic (fixed) and organic (volatile) compounds. The fixed suspended solids component is composed of sediment particles, while the volatile suspended solids component is composed of detrital particles and planktonic organisms. The concentration of total suspended solids directly affects water clarity, which in turn affects the development and growth of submerged aquatic vegetation.

Appendix B: Additional Plots

Additional tidal trend maps and plots are available below:

- Bottom Total Nitrogen:

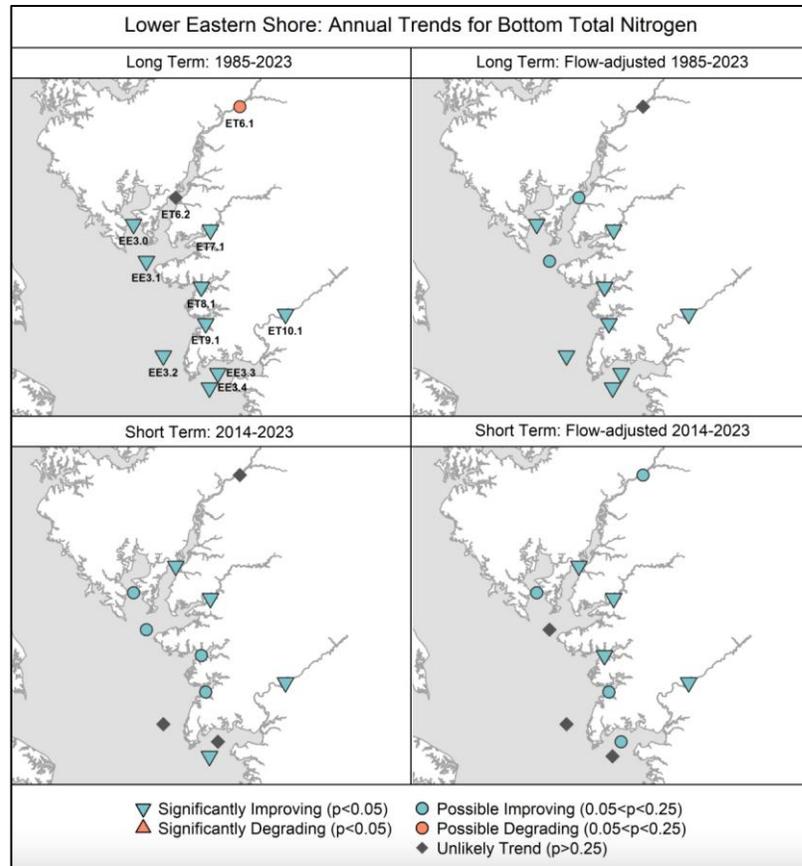


Figure B1. Annual flow-adjusted surface total nitrogen trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983. For more information on the tidal stations and Chesapeake Bay tidal water quality monitoring, refer to <https://www.chesapeakebay.net/what/programs/quality-assurance/tidal-water-quality-monitoring>.

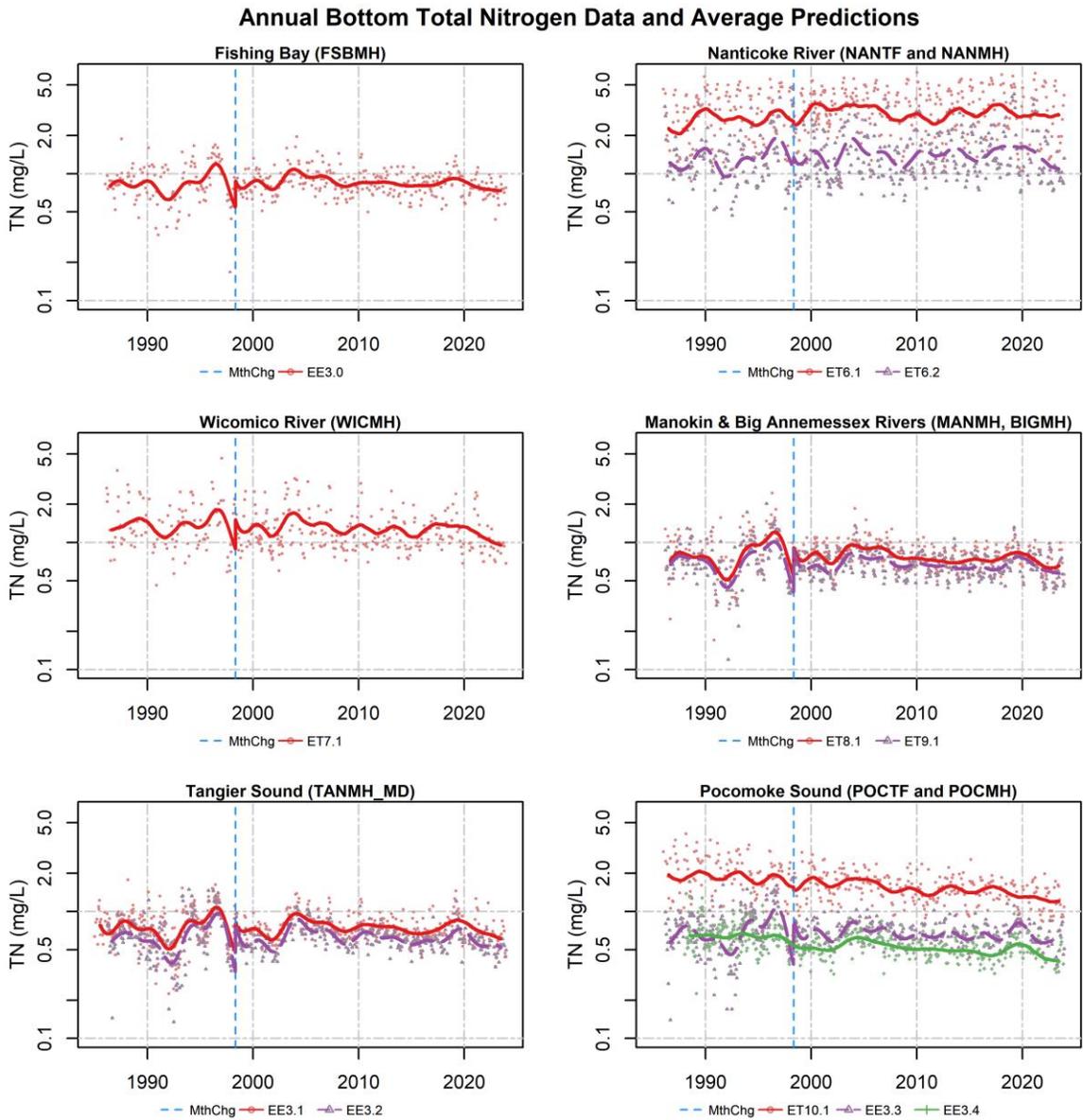


Figure B2. Annual bottom total nitrogen data (dots) and average long-term pattern generated from non-flow adjusted Generative Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

- Bottom Total Phosphorus

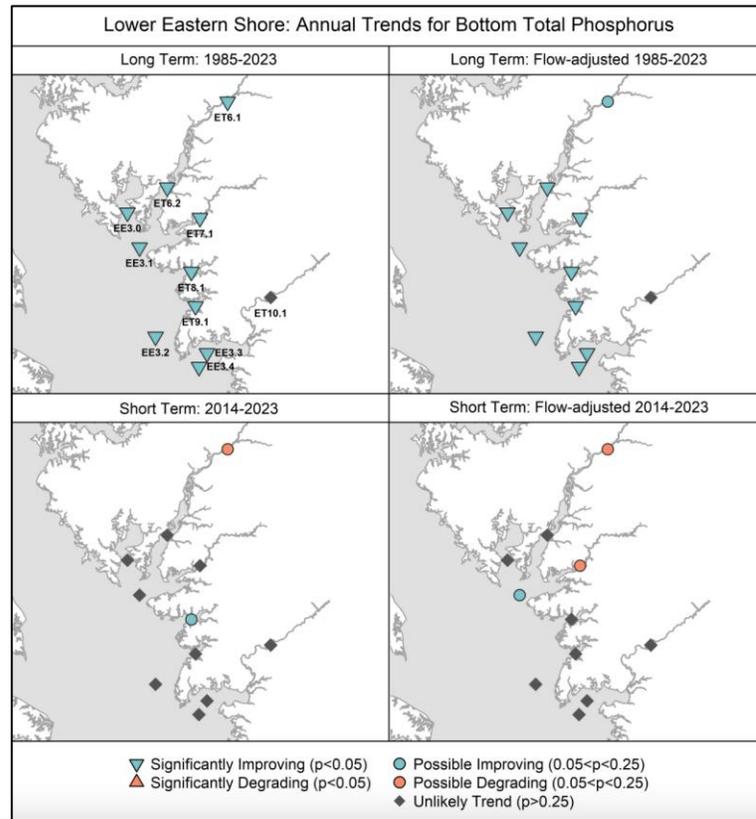


Figure B3. Annual flow-adjusted surface total phosphorus trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983. For more information on the tidal stations and Chesapeake Bay tidal water quality monitoring, refer to <https://www.chesapeakebay.net/what/programs/quality-assurance/tidal-water-quality-monitoring>.

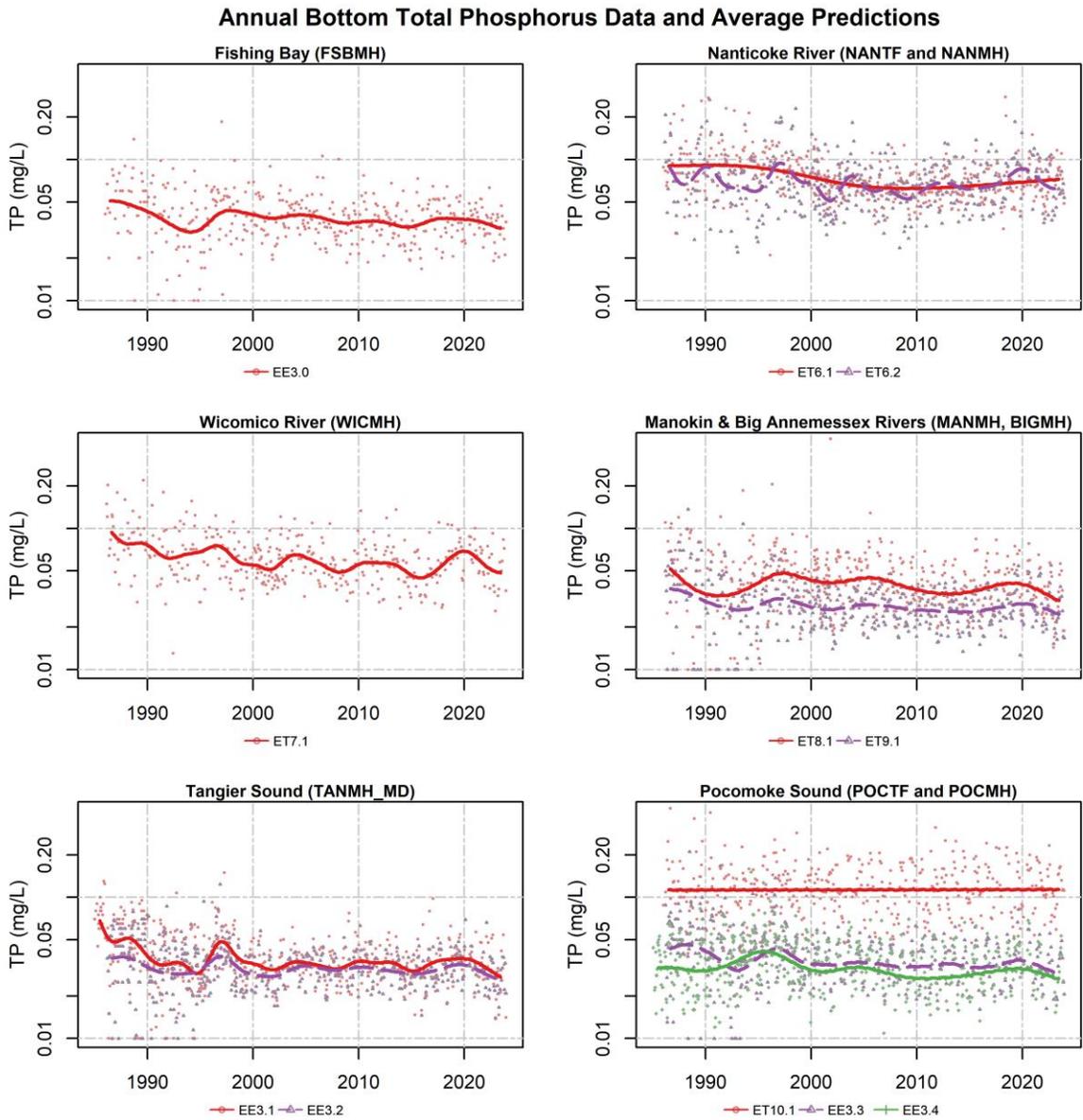


Figure B4. Annual bottom total phosphorus data (dots) and average long-term pattern generated from non-flow adjusted Generative Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

- Surface Dissolved Inorganic Nitrogen

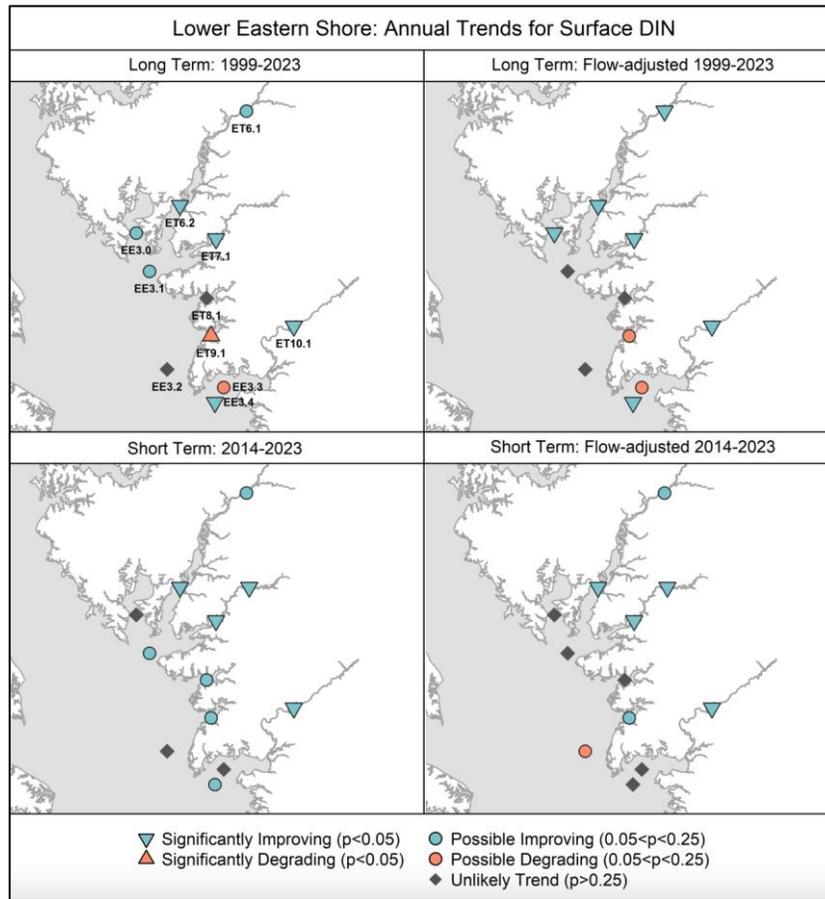


Figure B5. Annual flow-adjusted surface dissolved inorganic nitrogen trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983. For more information on the tidal stations and Chesapeake Bay tidal water quality monitoring, refer to <https://www.chesapeakebay.net/what/programs/quality-assurance/tidal-water-quality-monitoring>.

Annual Surface Dissolved Inorganic Nitrogen Data and Average Predictions

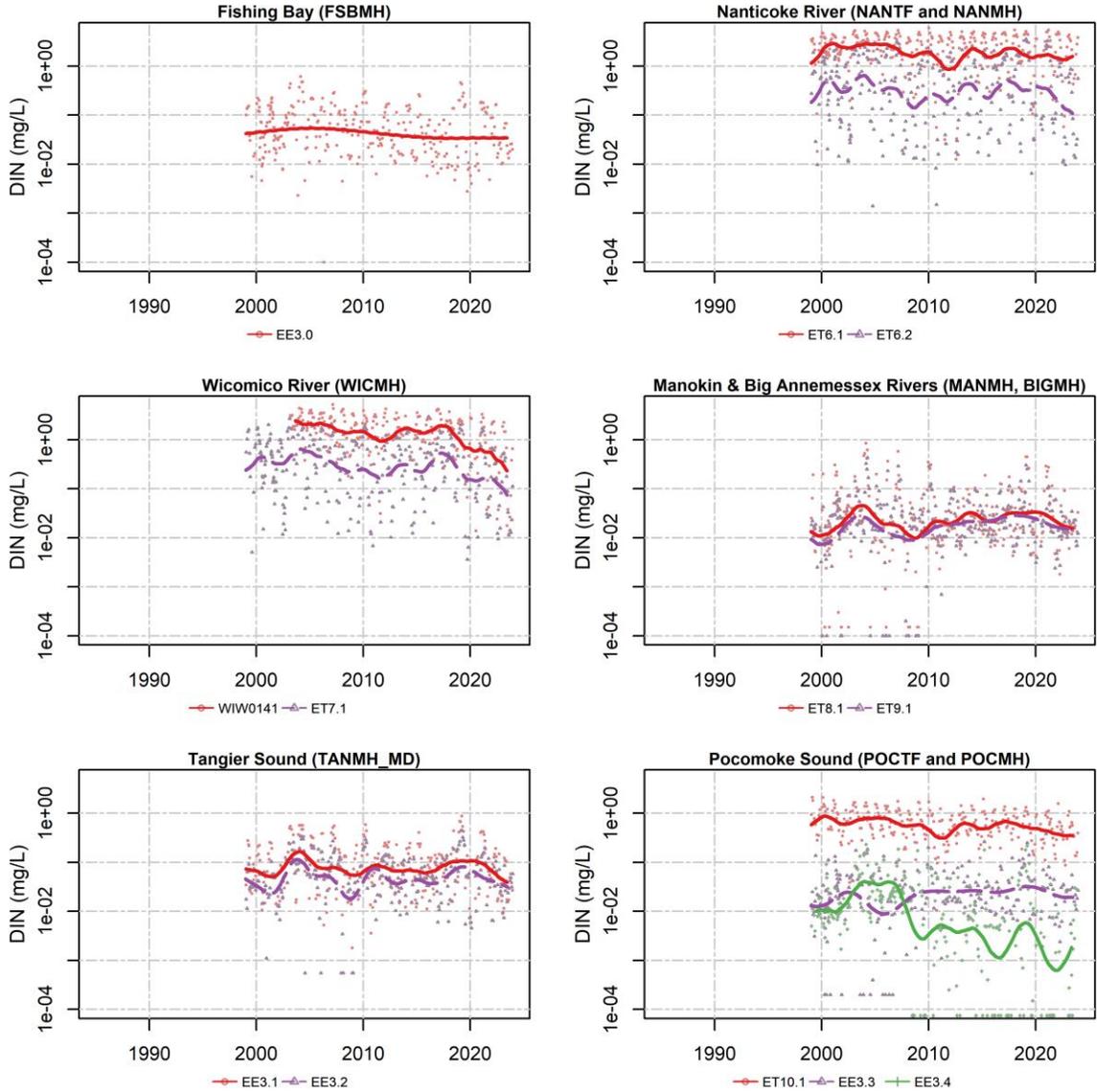


Figure B6. Annual surface dissolved inorganic nitrogen data (dots) and average long-term pattern generated from non-flow adjusted Generative Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

- Surface Orthophosphate

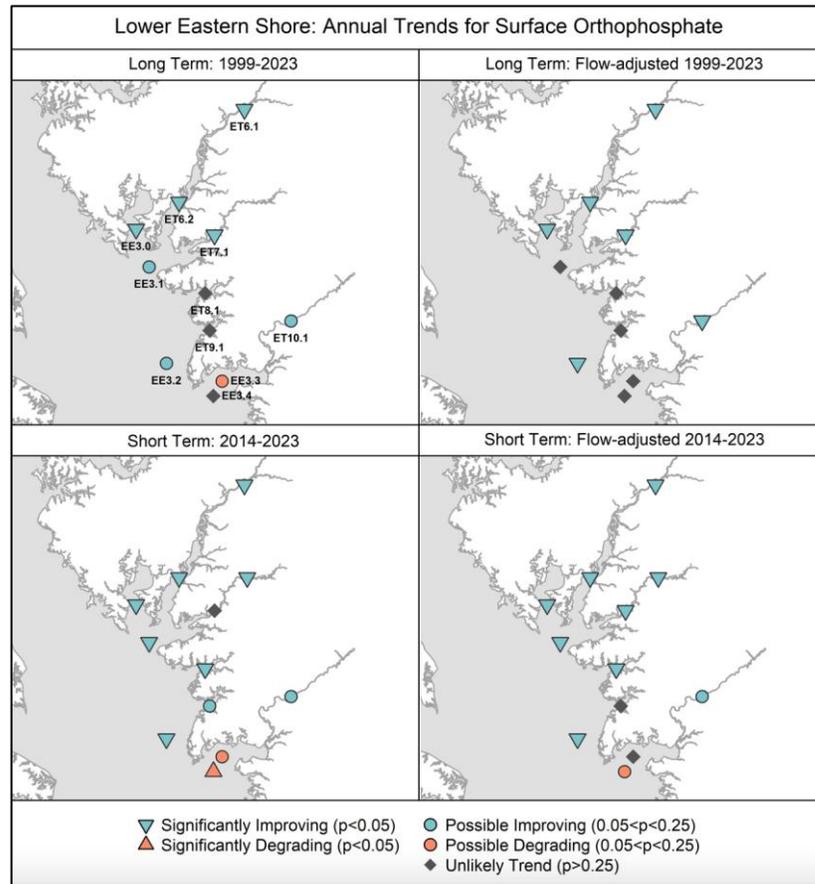


Figure B7. Annual flow-adjusted surface orthophosphate trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983. For more information on the tidal stations and Chesapeake Bay tidal water quality monitoring, refer to <https://www.chesapeakebay.net/what/programs/quality-assurance/tidal-water-quality-monitoring>.

Annual Surface Orthophosphate Data and Average Predictions

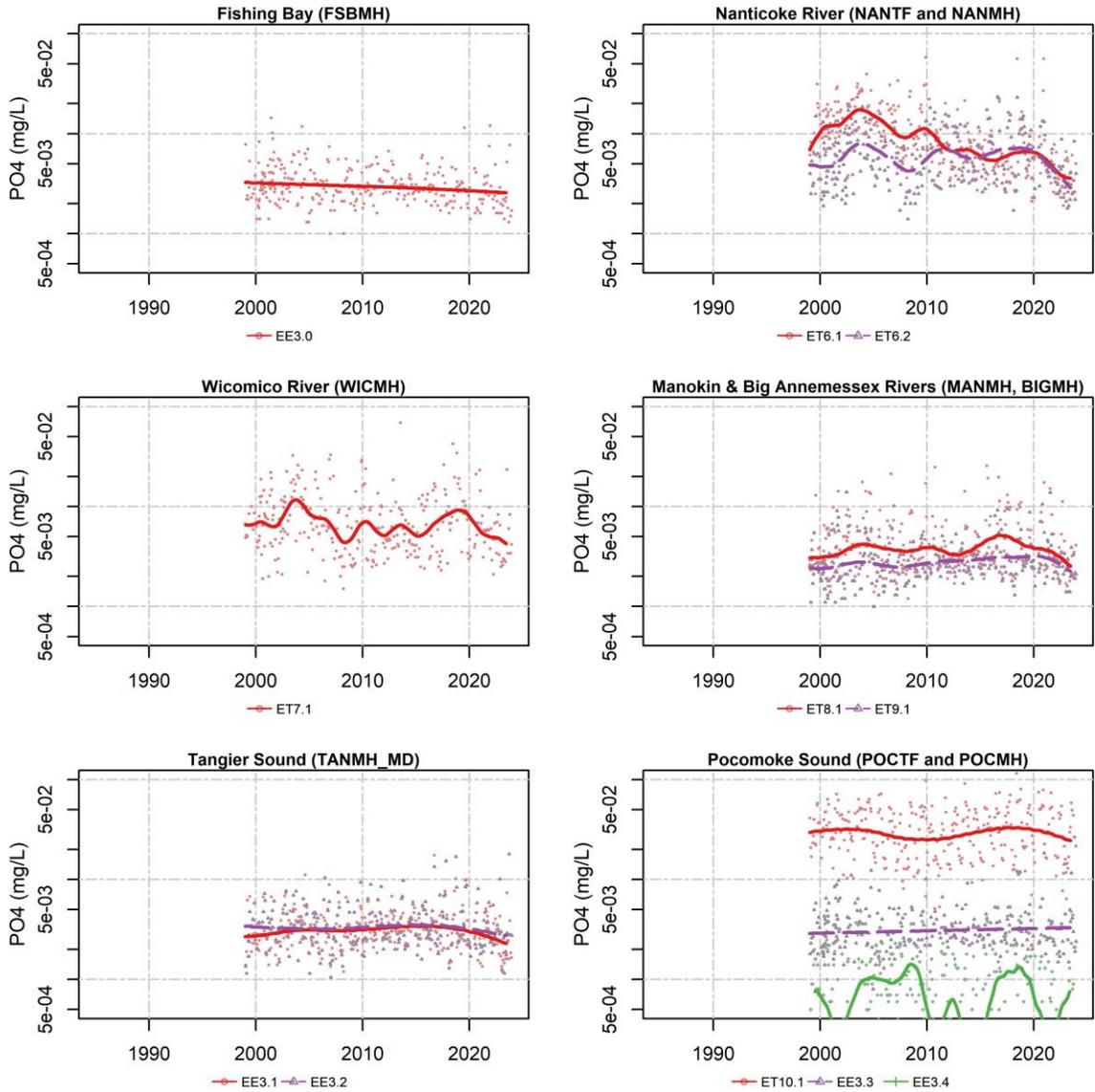


Figure B8. Annual surface orthophosphate data (dots) and average long-term pattern generated from non-flow adjusted Generative Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

- Surface Total Suspended Solids

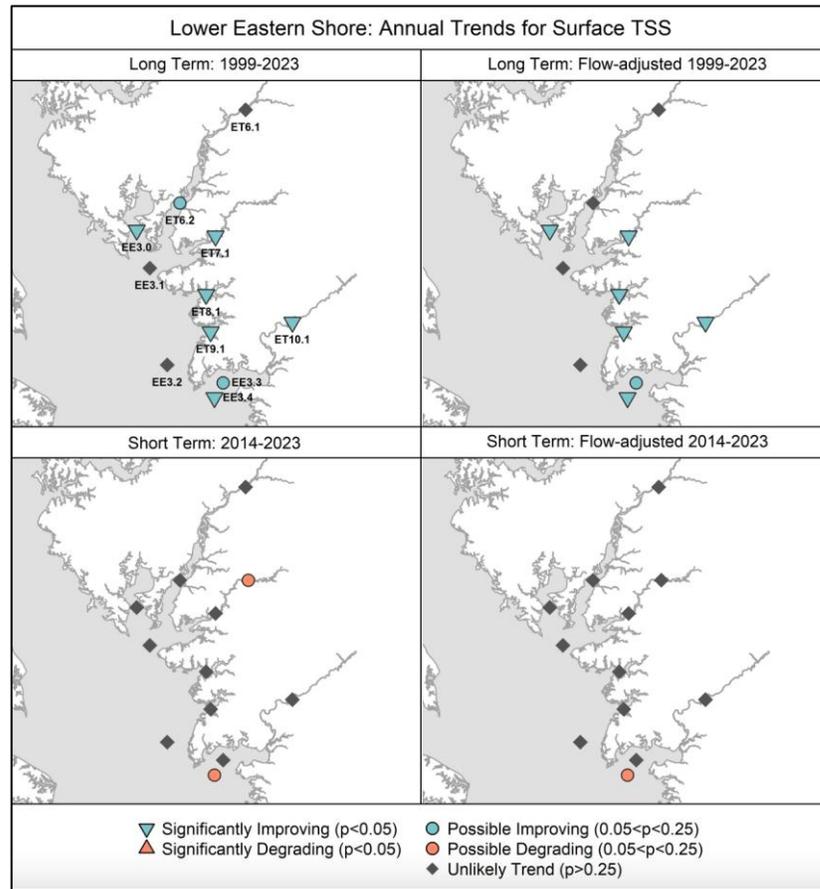


Figure B9. Annual flow-adjusted surface total suspended solids trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983. For more information on the tidal stations and Chesapeake Bay tidal water quality monitoring, refer to <https://www.chesapeakebay.net/what/programs/quality-assurance/tidal-water-quality-monitoring>.

Annual Surface Total Suspended Solids Data and Average Predictions

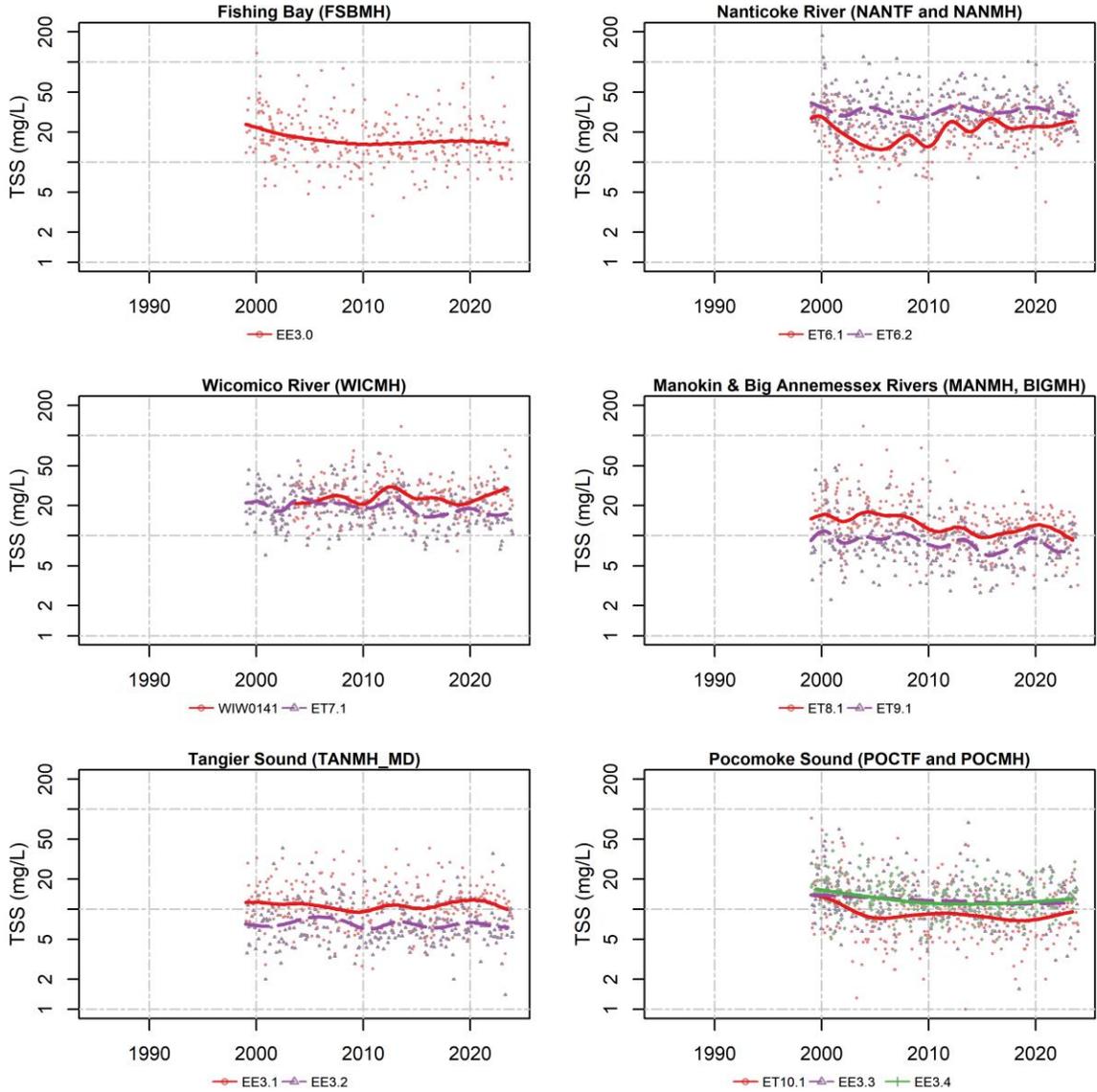


Figure B10. Annual surface total suspended solids (dots) and average long-term pattern generated from non-flow adjusted Generative Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

- Summer Surface Dissolved Oxygen

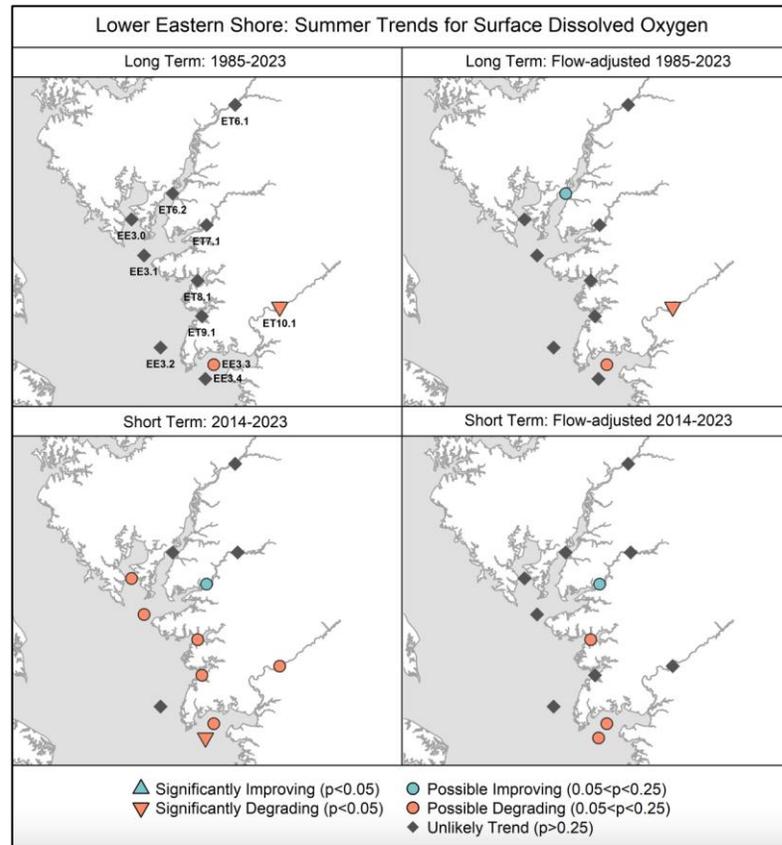


Figure B11. Annual flow-adjusted surface summer dissolved oxygen trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983. For more information on the tidal stations and Chesapeake Bay tidal water quality monitoring, refer to <https://www.chesapeakebay.net/what/programs/quality-assurance/tidal-water-quality-monitoring>.

Summer (June-Sept) Surface DO Data and Average Predictions

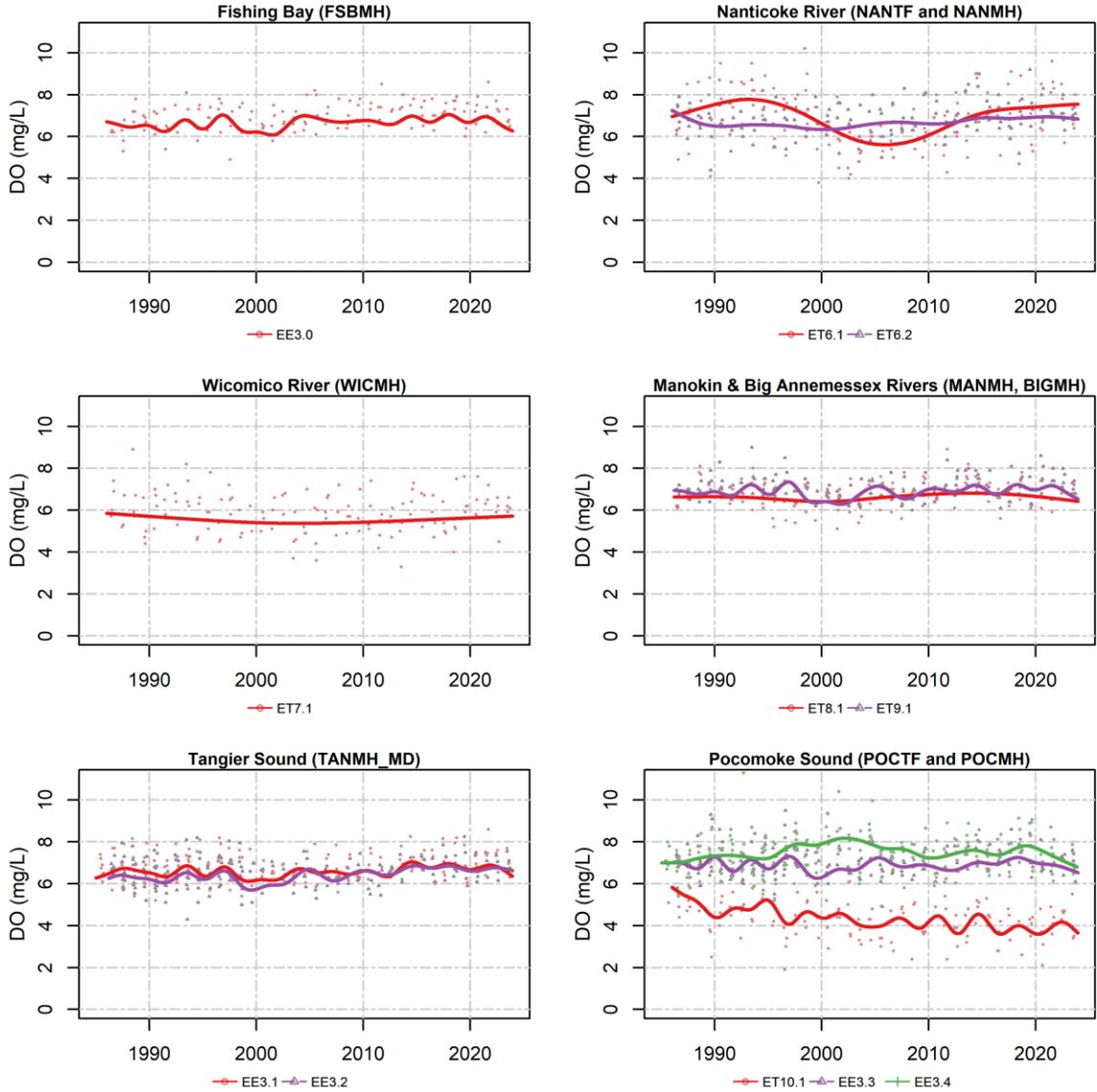


Figure B12. Annual surface dissolved oxygen data (dots) and average long-term pattern generated from non-flow adjusted Generative Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.