# Rappahannock Tributary Summary:

# A summary of trends in tidal water quality and associated factors, 1985-2022.

October 22, 2024

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

This tributary summary updates information released in the Rappahannock Tributary Summary 1985-2018, which can be found here:

https://www.chesapeakebay.net/who/projects-archive/integrated-trends-analysis-team.

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*Authors:* Breck Sullivan (U.S. Geological Survey, USGS), Kaylyn Gootman (Environmental Protection Agency, EPA), Alex Gunnerson (Chesapeake Research Consortium), Sarah Betts (Franklin and Marshall College), Cindy Johnson (Department of Environmental Quality), Chris Mason (USGS), Elgin Perry (Perry LLC.), Gopal Bhatt (Penn State), Jeni Keisman (USGS), Jimmy Webber (USGS), Jon Harcum (Tetra Tech), Mike Lane (Old Dominion University), Olivia Devereux (Devereux Consulting), Qian Zhang (University of Maryland Center for Environmental Science, UMCES), Rebecca Murphy (UMCES), Renee Karrh (Maryland Department of Natural Resources), Tom Butler (EPA), Vanessa Van Note (EPA), Zhaoying (Angie) Wei (UMCES).

# Contents

# 1. Purpose and Scope

The Rappahannock Tributary Summary outlines change over time for a suite of monitored tidal water quality parameters and associated potential drivers of those trends for the period of 1985 to 2022, 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 ($PO_4$), surface dissolved inorganic nitrogen (DIN), surface total suspended solids (TSS), and summer surface DO concentrations are provided in 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 submerged 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 Rappahannock River. The intended audiences for this report include, but are not limited to, 1) technical managers within jurisdictions who are looking at tidal water quality data and trying to understand why patterns are occurring, 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. Our goal is for the Tributary Summary documents to be sources of readily available background for change over time in tidal water quality observed with monitoring data. The intended purpose of the Tributary Summary documents is to help answer questions related to water quality, show how landscape factors drive water quality change 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.

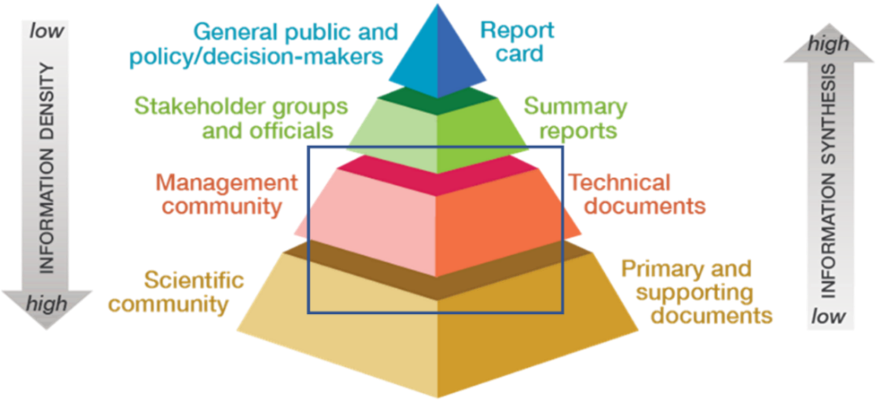


Figure 1: Conceptual model detailing different levels of information density and information synthesis. The intended audiences for the Tributary Summary documents are denoted by the blue box. Figure

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

# 2. Location

The Rappahannock River watershed covers approximately 4% of the Chesapeake Bay watershed. Its watershed is approximately 6,530 km$^2$ (Table 1) and is contained within the Commonwealth of Virginia (Figure 2). Major tributaries to the Rappahannock River include the Rapidan, Robinson, and Corrotoman Rivers.

| Tributary Name | Watershed Area km$^2$ |
|---|---:|
| VIRGINIA MAINSTEM | 164,197 |
| MARYLAND MAINSTEM | 71,967 |
| POTOMAC | 36,611 |
| JAMES | 25,831 |
| YORK | 6,537 |
| RAPPAHANNOCK | 6,530 |
| LOWER EASTERN SHORE | 4,532 |
| MARYLAND UPPER EASTERN SHORE | 2,441 |
| PATUXENT | 2,236 |
| CHOPTANK | 1,844 |
| PATAPSCO-BACK | 1,647 |
| MARYLAND UPPER WESTERN SHORE | 1,523 |
| MARYLAND LOWER WESTERN SHORE | 439 |

Table 1. Watershed areas 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, 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.

## 2.1 Watershed Physiography

The Rappahannock River watershed stretches across four major physiographic regions, namely, Blue Ridge, Mesozoic Lowland, Piedmont Crystalline, and Coastal Plain (Bachman et al., 1998) (Figure 2). The Piedmont physiography covers both carbonate and crystalline areas. The Coastal Plain physiography covers lowland, dissected upland, and upland areas. Implications of these physiographies for nutrient and sediment transport are summarized in Section 5.1.1.

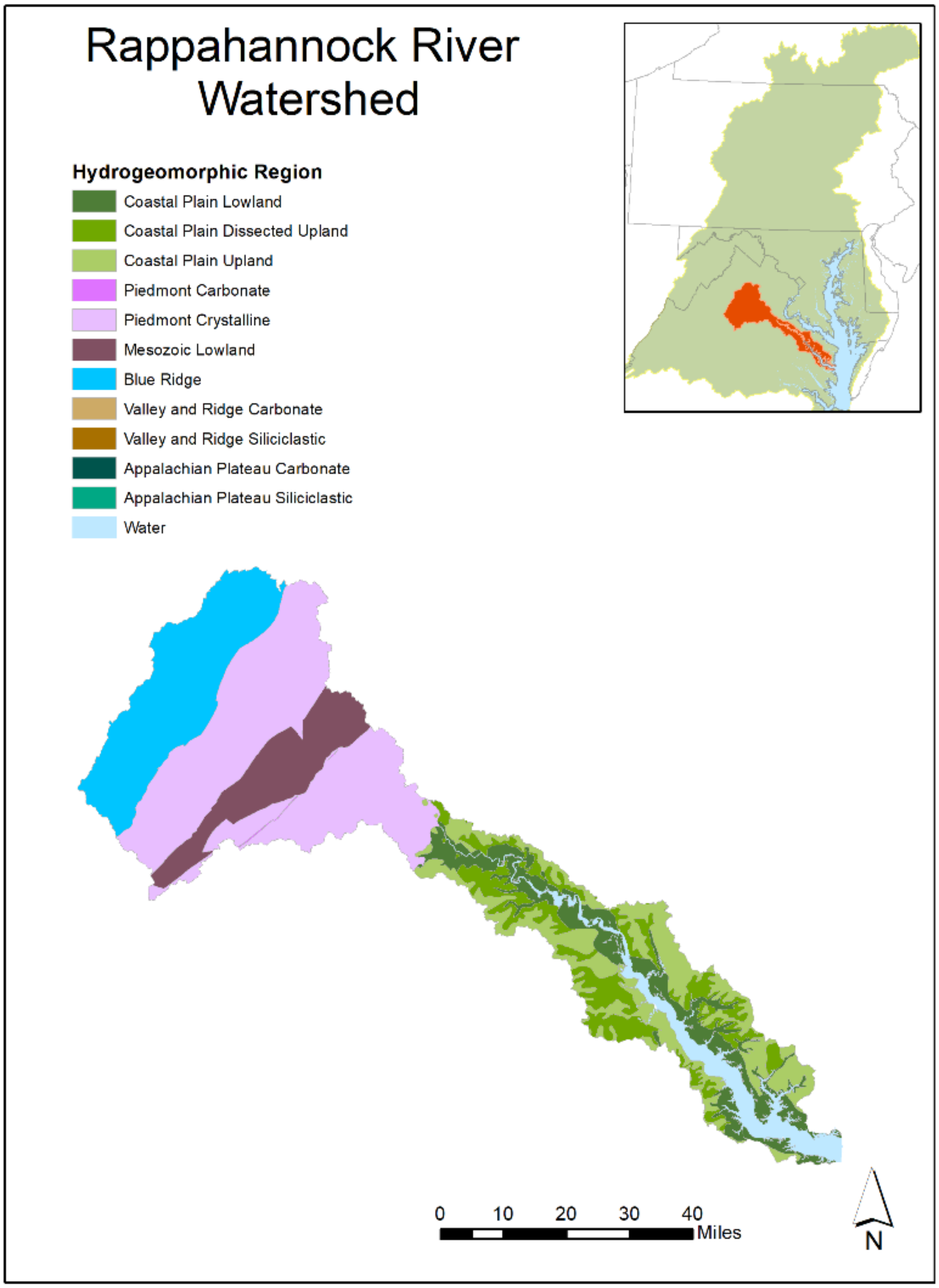


Figure 2. Distribution of physiography in the Rappahannock River watershed, shown in orange on the inset map. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983. Hydrogeomorphic region data credit Brakebill, J.W. (ed) and Kelley, S.K. (ed), 2000, Hydrogeomorphic Regions in the Chesapeake Bay Watershed: U.S. Geological Survey data release, https://doi.org/10.5066/P98WXDST

## 2.2 Land Use

Land use in the Rappahannock watershed is dominated (66%) by natural areas. Urban and suburban land areas have increased by 331 square kilometers since 1985, agricultural lands have decreased by 219 square kilometers, and natural lands have decreased by 111 square kilometers. Correspondingly, the proportion of urban land in this watershed has increased from 6% in 1985 to 11% in 2022 (Figure 3).

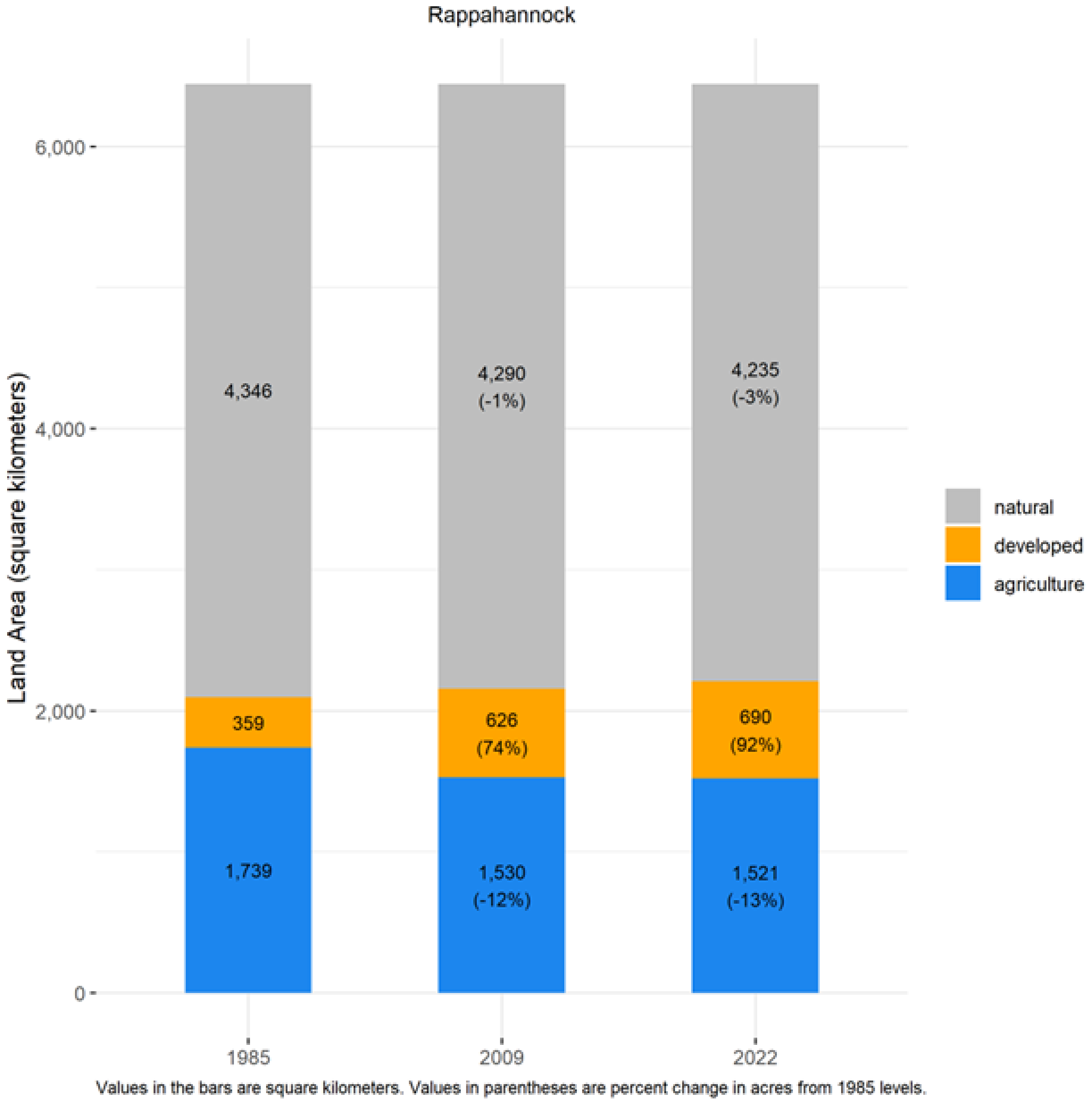


Figure 3. Distribution of land uses in the Rappahannock watershed. Percentages are the percent change from 1985 for each source sector. Data are from the Chesapeake Assessment Scenario Tool (CAST; https://cast.chesapeakebay.net/About/UpgradeHistory, version Phase 6 - 7.6.0).

In general, developed lands in 2001 were more concentrated within towns and major metropolitan areas. Since 2001, developed and semi-developed lands have expanded around these urban areas, as well as extending into previously undeveloped regions. This is demonstrated in Figure 4, which uses impervious surface coverage as a proxy for developed lands (Arnold and Gibbons, 1996). The impacts of land development differ depending on the use from which the land is converted (Keisman et al., 2019; Ator et al., 2019). Implications of changing land use for nutrient and sediment transport are summarized in Section 5.1.3.

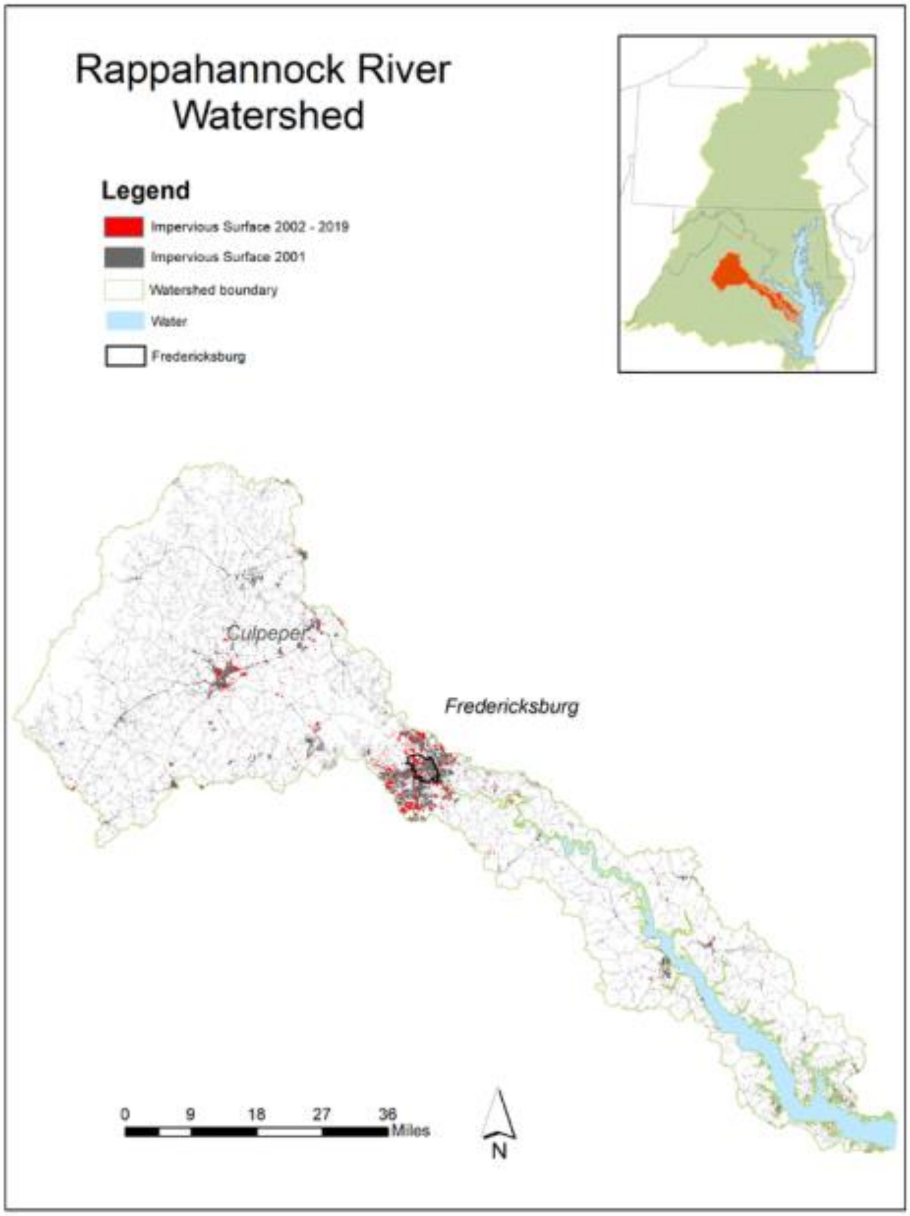


Figure 4. Distribution of impervious surface coverage in the Rappahannock River watershed, shown in orange on the insert map. Derived from the U.S. Geological Survey (USGS) National Land Cover Database

(2019). 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 portion of the Rappahannock River is split into the following segments (U.S. Environmental Protection Agency, 2004): Tidal Fresh (RPPTF), Oligohaline (RPPOH), and Mesohaline (RPPMH). One tributary of the Rappahannock River – the Corrotoman River (CRRMH) – is also represented (Figure 5).

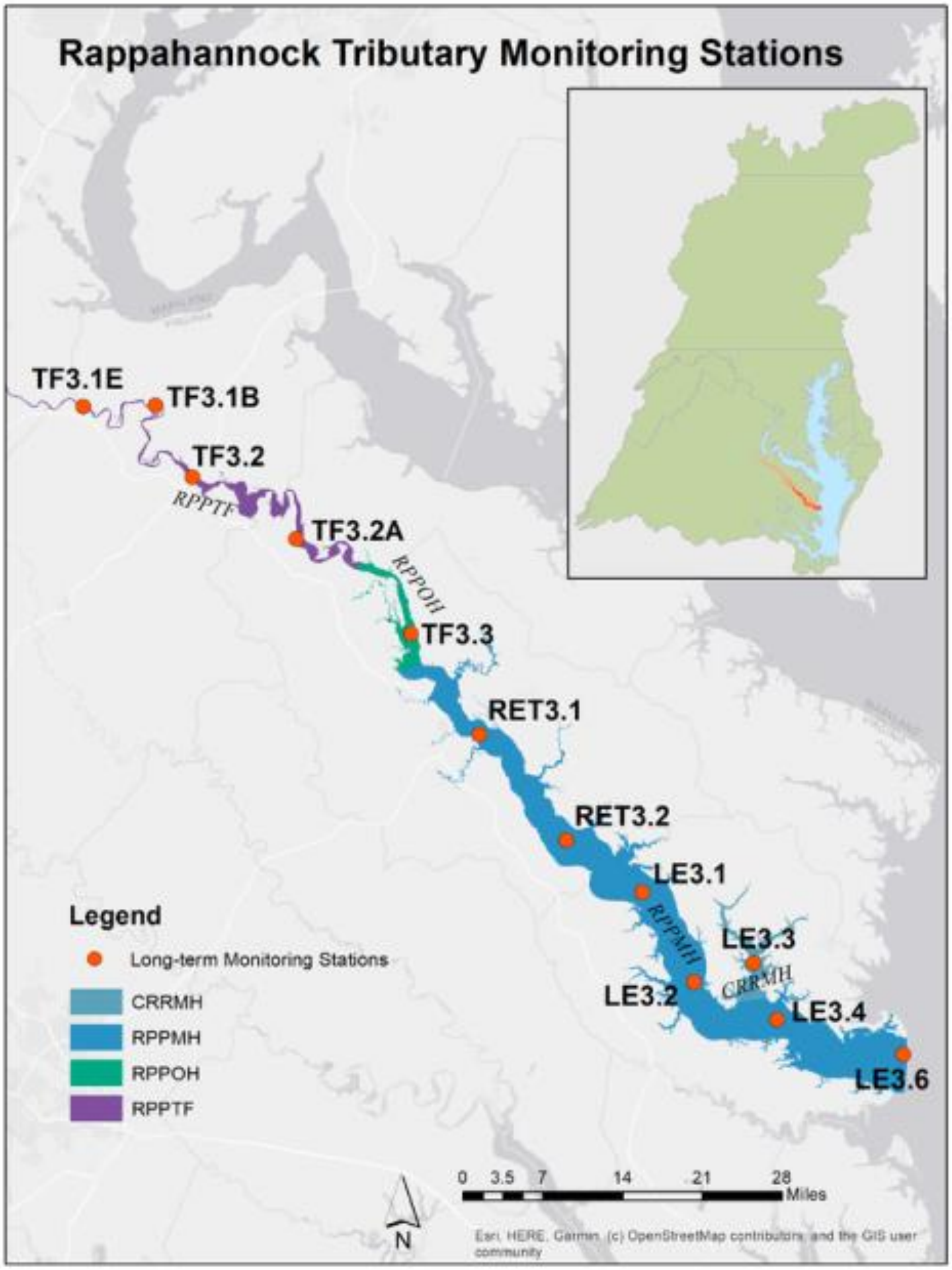


Figure 5. Map of tidal Rappahannock River segments and long-term monitoring stations. Base map credit Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community. World Geodetic System 1984. Any use of trade, firm, logos, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Long-term trends in water quality were analyzed by the Virginia Department of Environmental Quality (VA DEQ) and Old Dominion University (ODU) at 12 stations stretching from the tidal fresh region of the Rappahannock River, near Fredericksburg, VA, to the mouth of the Rappahannock River flowing into Chesapeake Bay (Figure 5). Water quality data at these stations are also used to assess if dissolved oxygen (DO) water quality criteria were attained. All tidal water quality data analyzed for this report are available from the Chesapeake Bay Program Data Hub (Chesapeake Bay Program, 2018). Other shallow-water monitoring has been conducted over the years and used for water quality criteria evaluation but is not shown in the long-term trend graphics in subsequent sections because of its shorter duration. For additional information please refer to the Virginia Institute of Marine Science (VIMS) Virginia Estuarine and Coastal Observatory System (VECOS), which serves up much of the extensive monitoring data that has been collected in the Rappahannock, (Virginia Institute of Marine Science (VIMS), 2023). Those observations are not included in subsequent trend graphics because the focus here is primarily on the long-term monitoring at fixed stations.

## 3. Tidal Water Quality Status

The Rappahannock River 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 (Table 1 in U.S. Environmental Protection Agency, 2003) include specific criteria for dissolved oxygen (DO), chlorophyll a, and water clarity/underwater bay grasses. For the purposes of this report, 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 interested 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 during a certain period, and if not, how far the segment is from meeting it. An attainment deficit of zero means 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 three segments, namely, RPPMH, RPPOH, and RPPTF. The other segment, CRRMH, was highly variable and never achieved full attainment status. The Deep Water (DW) and Deep Channel (DC) criteria were applicable to only one segment, i.e., RPPMH. For this segment, the DW attainment was generally worse than OW, and the DC attainment was generally the worst among the three criteria. Mann-Kendall trend results indicated only one significant trend in all segment-DU pairs, which is a long-term improvement in RPPMH DW-DO (Figure 6).

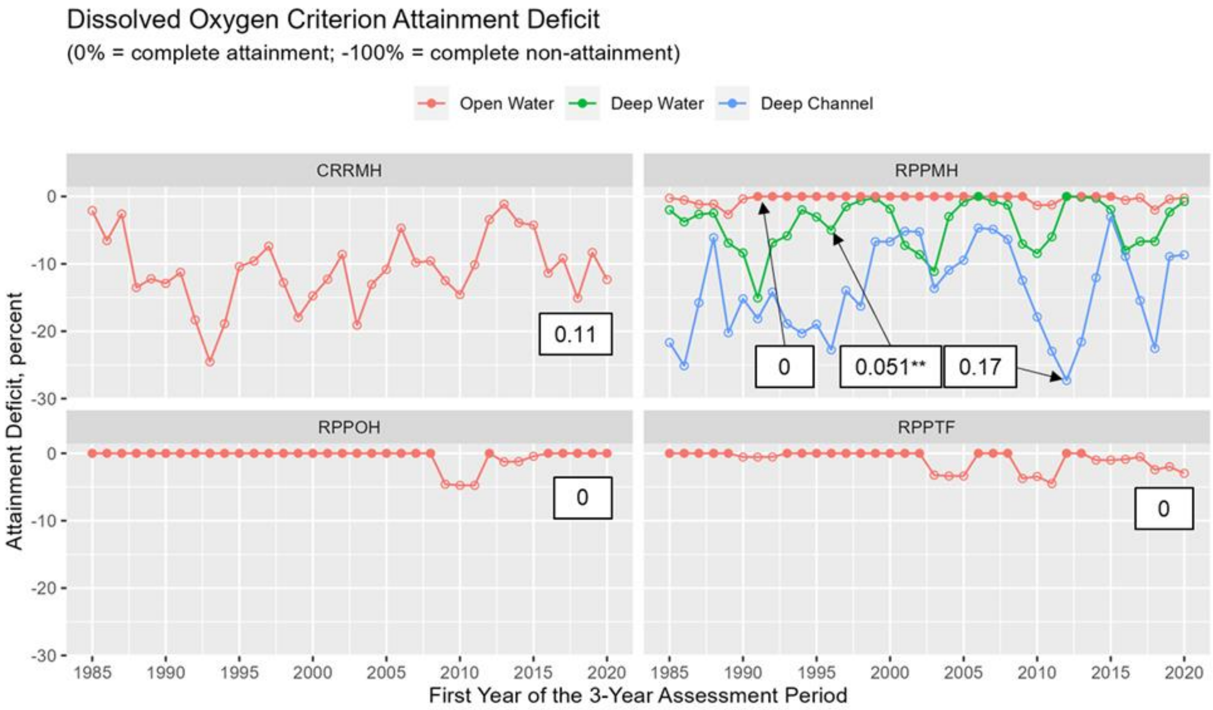


Figure 6. Attainment deficit for Open Water (30-day mean; June-September), Deep Water (30-day mean; June-September), and Deep Channel (Instantaneous; June-September) dissolved oxygen criteria for three-year assessment periods from the start of monitoring through the current (2020-2022) assessment period. 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 valuable information, such as whether progress is being made towards attainment in a segment that is not meeting the water quality criteria, or conversely whether conditions are degrading even if the criteria are currently being met. To illustrate this, the 2020-2022 attainment status for the OW and DC DO criteria shown in Figure 6 are overlain with the 1985-2022 trend in summer surface DO concentration and the 1985-2022 trend in bottom summer DO concentrations, respectively (Figure 7). The 30-day mean OW summer DO criterion was met in one of the four segments for the 2020-2022 period. Surface oxygen has increased in the segment that met the OW criterion and in the mesohaline segments and has decreased in the tidal fresh segment where the OW criterion was not met. Only the portion of the RPPMH segment colored orange contains the Deep Channel designated use. Bottom oxygen has also decreased in the Rappahannock River mesohaline segment where the DC water quality criterion was not met. This example shows the utility of establishing criteria and monitoring of water quality conditions relative to established goals for those criteria. It also demonstrates the relevance of trend results in relation to criteria assessments.

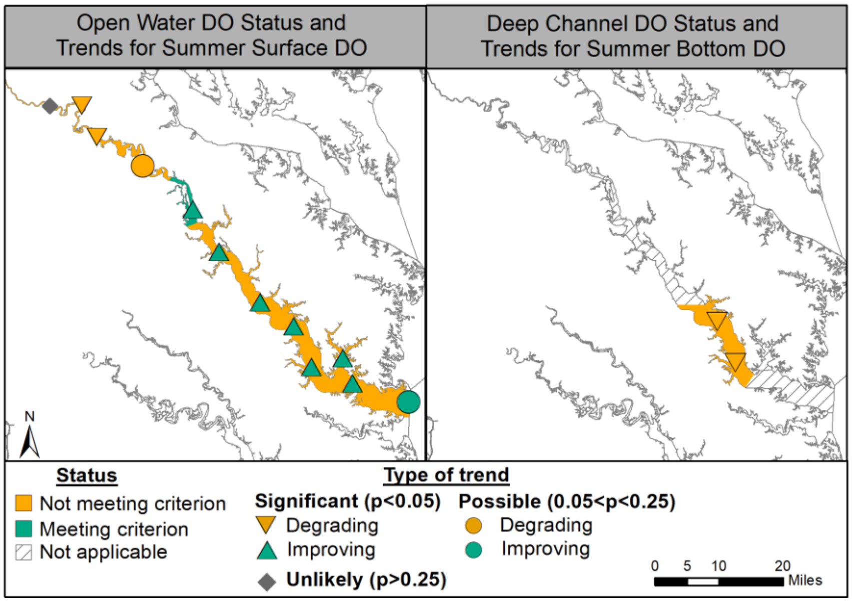


Figure 7. Pass-fail dissolved oxygen (DO) criterion status for 30-day Open Water (OW) summer DO and DC instantaneous DO designated uses in Rappahannock River segments along with long-term trends in DO concentrations. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 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 12 tidal stations labeled in Figure 5. Refer to Murphy *et al.* (2019) for more details on the GAM implementation that is applied each year by VA Department of Environmental Quality and Old Dominion University for these stations in collaboration with the Chesapeake Bay Program and Maryland analysts.

Results shown below in each set of maps (e.g., 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 at a given station, 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 the location in the Rappahannock River, sometimes gaged river flow is used for this adjustment and sometimes salinity is used, but we refer to the following 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 from the GAM fit. For each percent change computation, the level of statistical confidence was computed. Change was considered 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 hypothesis tests but allows us to provide a more complete picture of the results, identifying locations where change might be starting to occur and should be 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. The flow-adjusted GAM line graphs are not shown so that the figures better represent what living resources (e.g., fish species, SAV, blue crabs) experience.

## 4.1 Surface Total Nitrogen

Annual total nitrogen (TN) concentration trends vary across the Rappahannock tidal stations (Figure 8). There are more improving and possibly improving trends than degrading trends at the most upstream tidal fresh stations over both the short- and long-term with observed and flow-adjusted approaches. The middle and lower estuary stations show a mixture of trends. The short-term flow-adjusted trends are mostly degrading at the mesohaline stations compared to the long-term trends. Note that while the tidal monitoring program started in 1985, some of the long-term trend results shown for TN utilize data beginning in 1994 due to laboratory limitations prior to 1994. Long-term trends for the other parameters include data from 1985 to present.

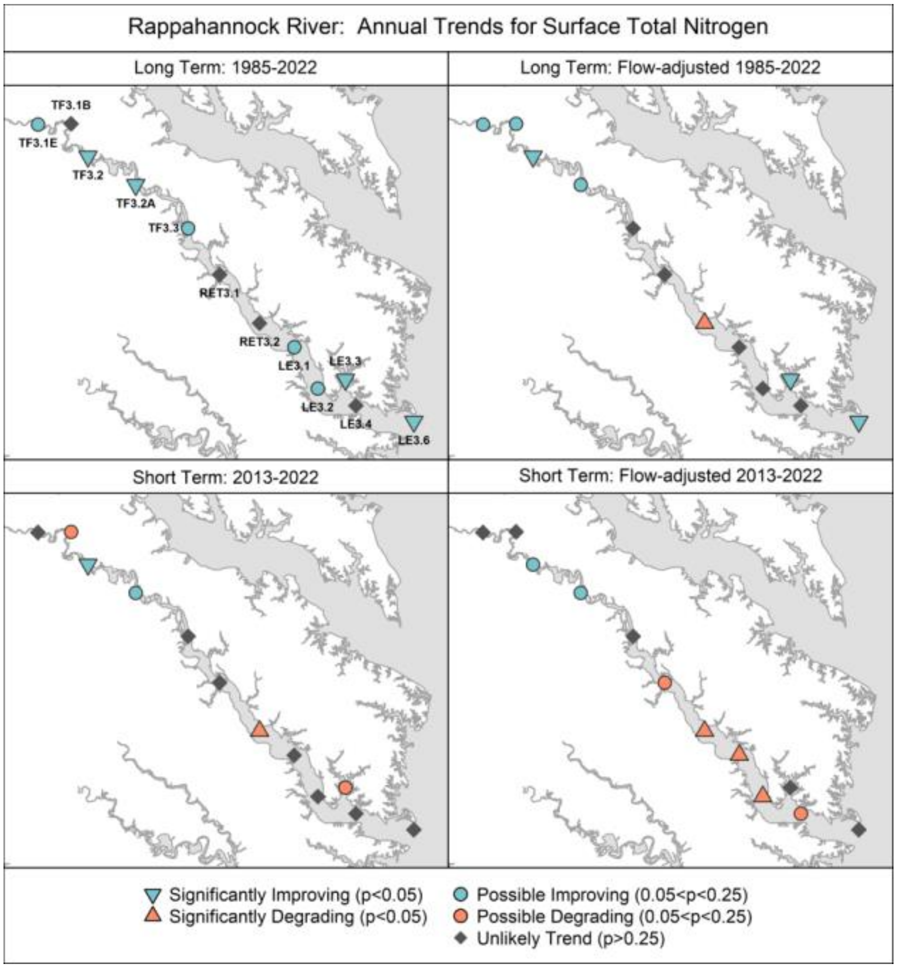


Figure 8. Flow-adjusted surface TN trends as calculated using Generalized Additive Models (Murphy *et al.* 2019). Note that for the Rappahannock River, most of these trends begin in 1994 due to data availability. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Both the data and the non-flow-adjusted mean annual GAM estimates show slight decreases at the tidal-fresh stations presented in the top left panel of Figure 9. An upswing in TN in 2018 - 2019 is clear in many of these graphs as well, which can be attributed to higher river flows in those years, but most stations steady off or show decline in TN starting in 2020 (Figure 9). For TN at most of the VA tributary stations, the records before 1994 contain too many values below the detection limits to accurately model the patterns; therefore, many of the time series start in 1994.

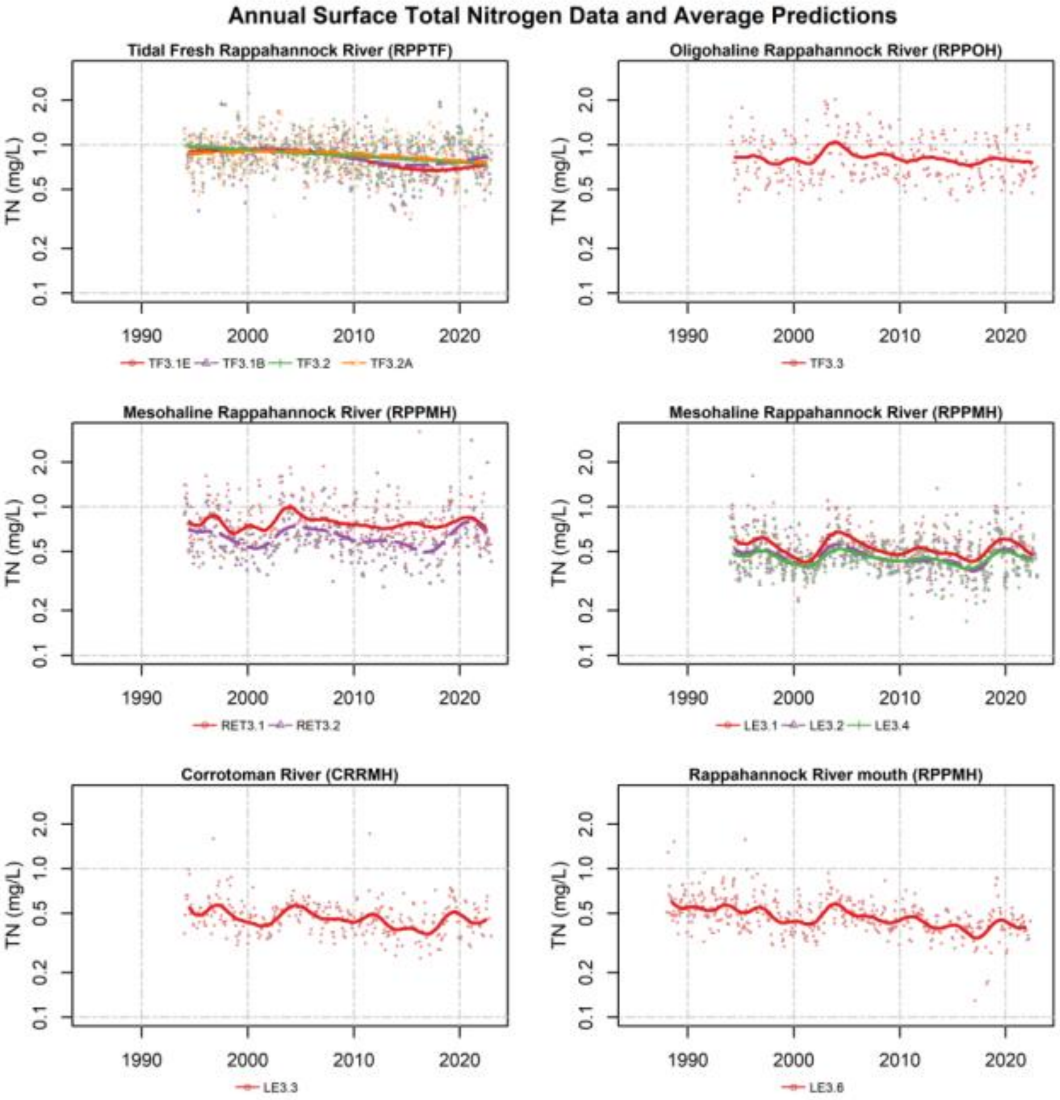


Figure 9. Surface TN data (dots) and average long-term patterns generated from non-flow adjusted Generalized Additive Models (GAMs). Colored dots represent data corresponding to the monitoring

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

## 4.2 Surface Total Phosphorus

Surface total phosphorus (TP) trends show degrading conditions in the long- and short-term for downstream stations (Figure 10). More stations show stable or degrading conditions over the short-term compared to the long-term, especially in the upstream stations.

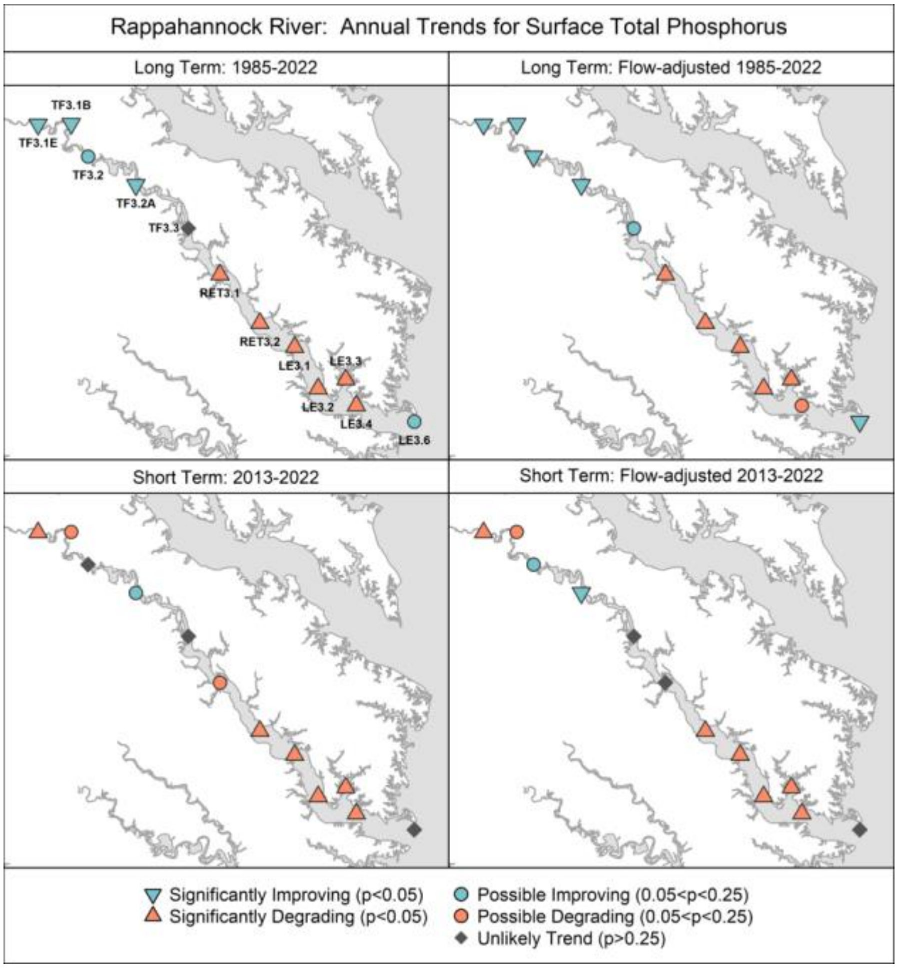


Figure 10. Flow-adjusted surface TP trends as calculated using Generalized Additive Models (Murphy et al. 2019) trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

The most noticeable decrease in TP concentrations occurred at the tidal fresh stations (top left panel, Figure 11). Data and GAM estimates are fairly consistent at other stations, with an increase in the last few years that has resulted in the degrading trends as show in Figure 10.

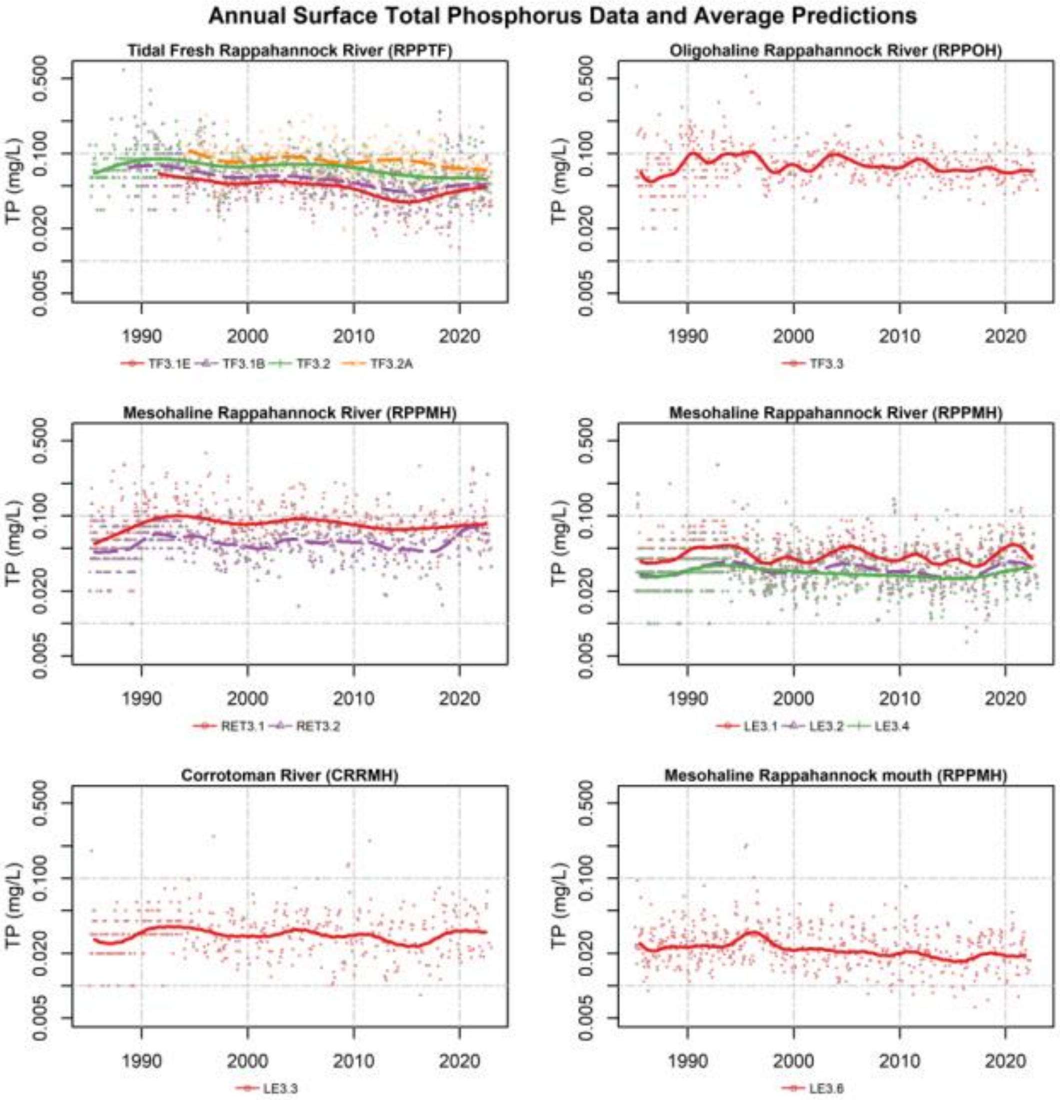


Figure 11. Surface TP data (dots) and average long-term pattern generated from non-flow adjusted Generalized Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring 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 trends (Figure 12) are consistently degrading at a stretch of stations in the middle part of the Rappahannock River. The most upstream tidal fresh stations and the mesohaline stations predominantly have no trends, except for a couple improvements in short-term flow-adjusted chlorophyll *a*.

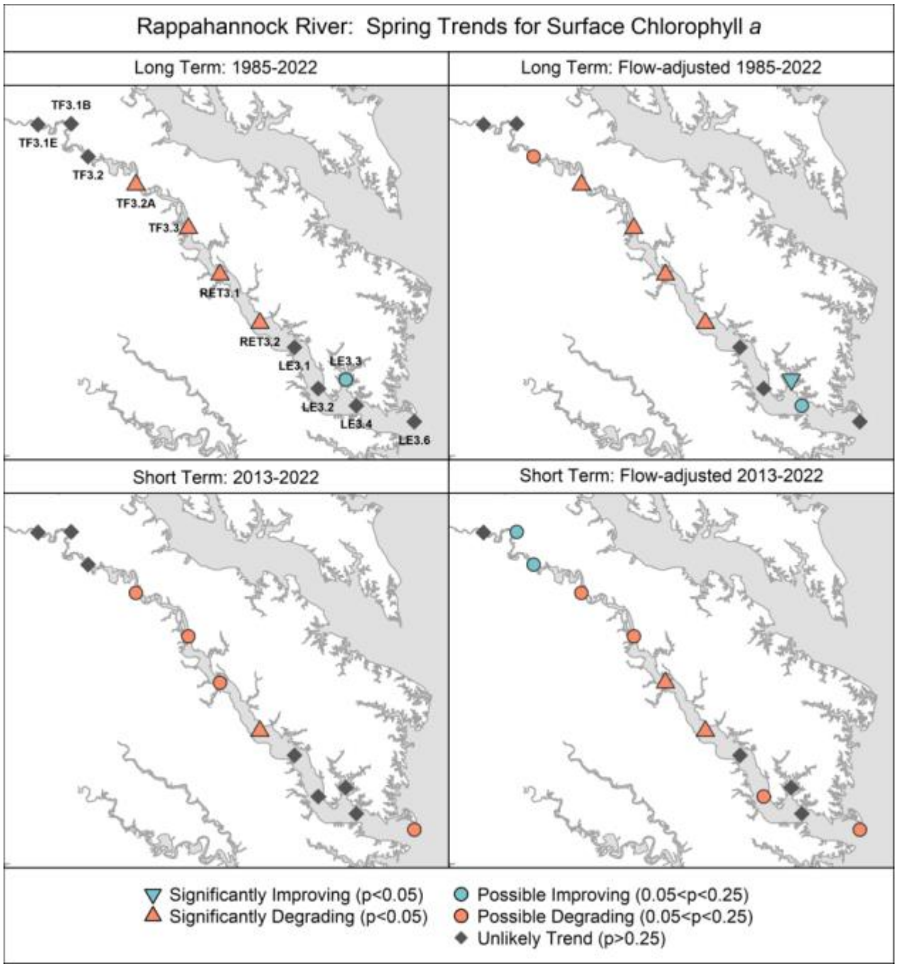


Figure 12. Flow-adjusted surface spring (March-May) chlorophyll *a* trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

A high amount of variability exists in the long-term patterns of some of the chlorophyll *a* data sets and average spring GAM estimates (Figure 13). The increases in TF3.1E to RET3.1 are clear from the GAM graphics.

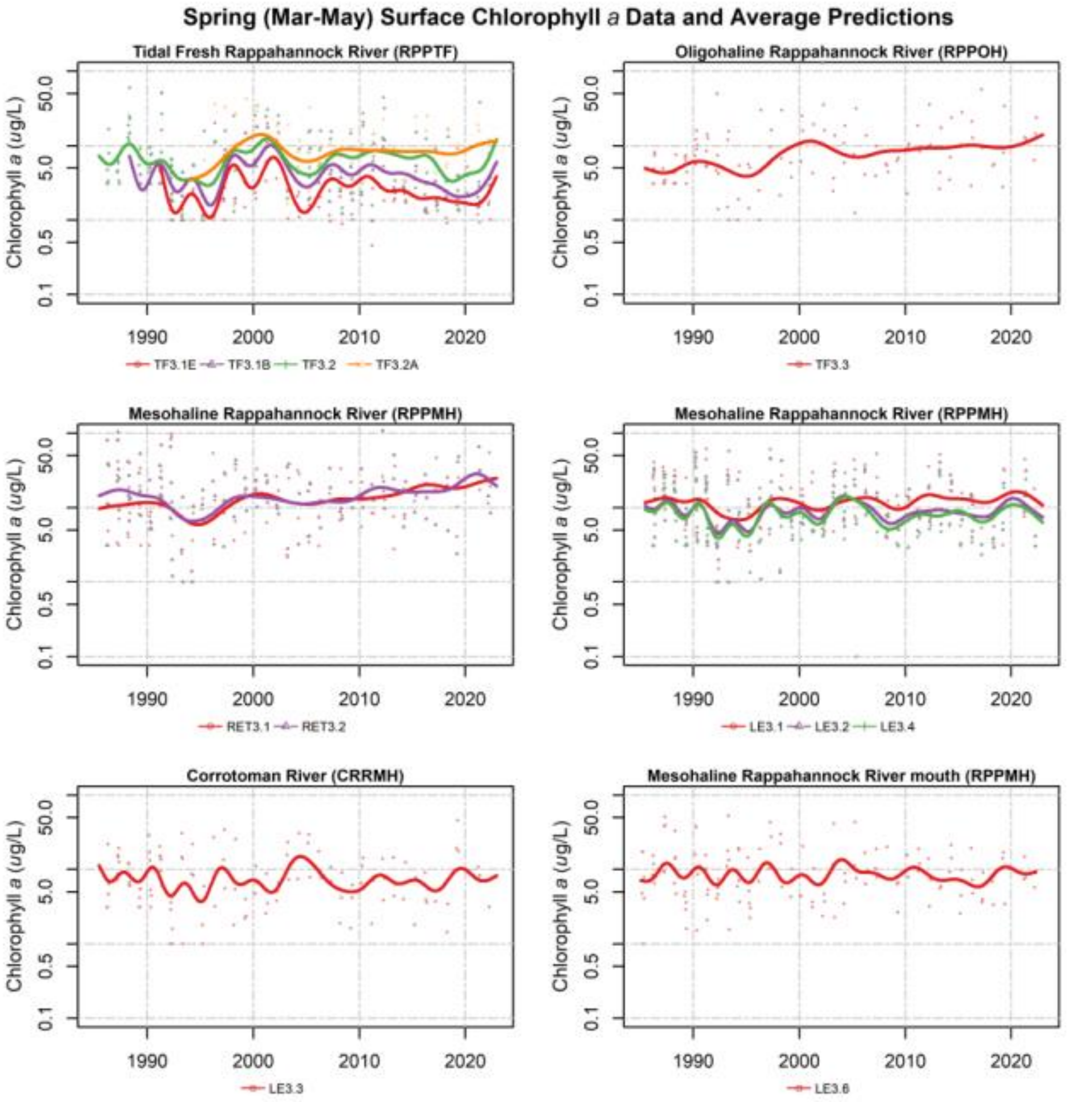


Figure 13. Surface spring Chlorophyll *a* data (dots) and average long-term pattern generated from non-flow adjusted Generalized Additive Models (GAMs). Colored dots represent March-May data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean spring GAM estimates for the noted monitoring stations.

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

Summer long-term chlorophyll *a* trends are degrading in the same middle region as spring trends, but also include more degrading trends at the LE stations as well. In general, these degrading trends are more likely over the long- than the short-term. The three most upstream tidal fresh stations are improving or showing no trend for both the short- and long-term, with and without flow-adjustment.

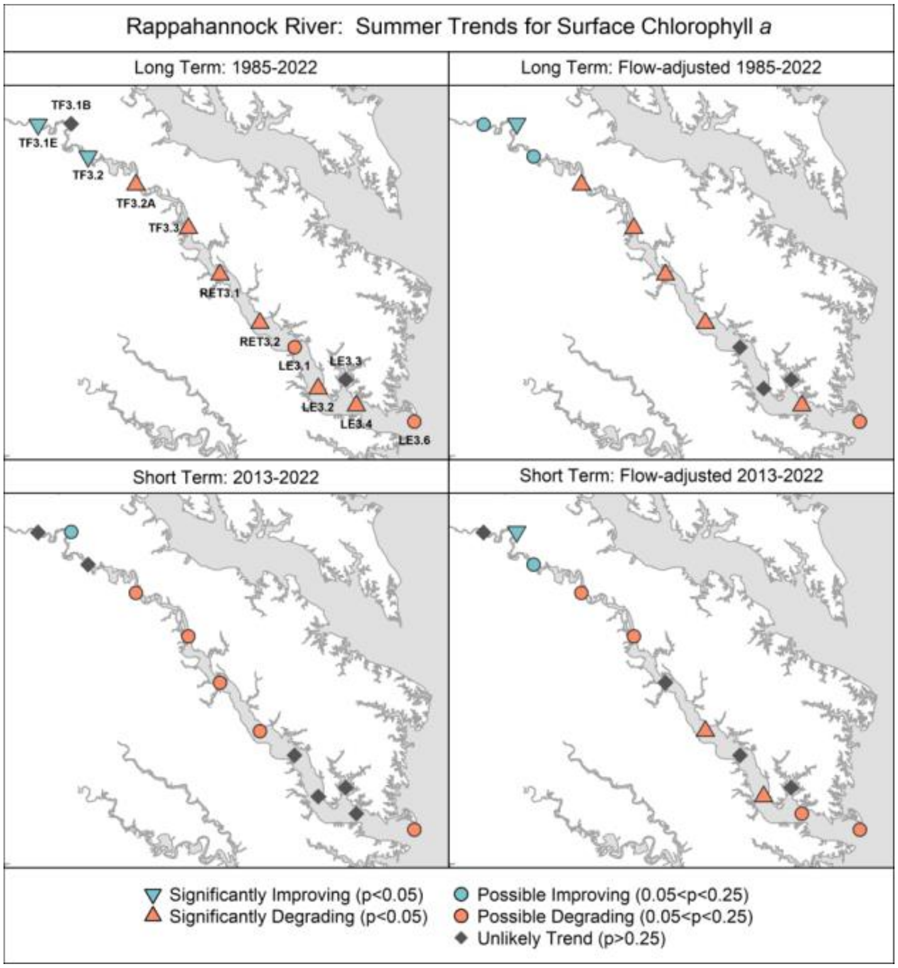


Figure 14. Flow-adjusted surface summer (July-September) chlorophyll *a* trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

A high amount of variability continues to exist in the summer long-term patterns of some of the chlorophyll *a* data sets and average spring GAM estimates. However, the magnitude of the summer tidal fresh chlorophyll *a* concentrations (Figure 15, top left panel) is much higher than it is in spring (Figure 13).

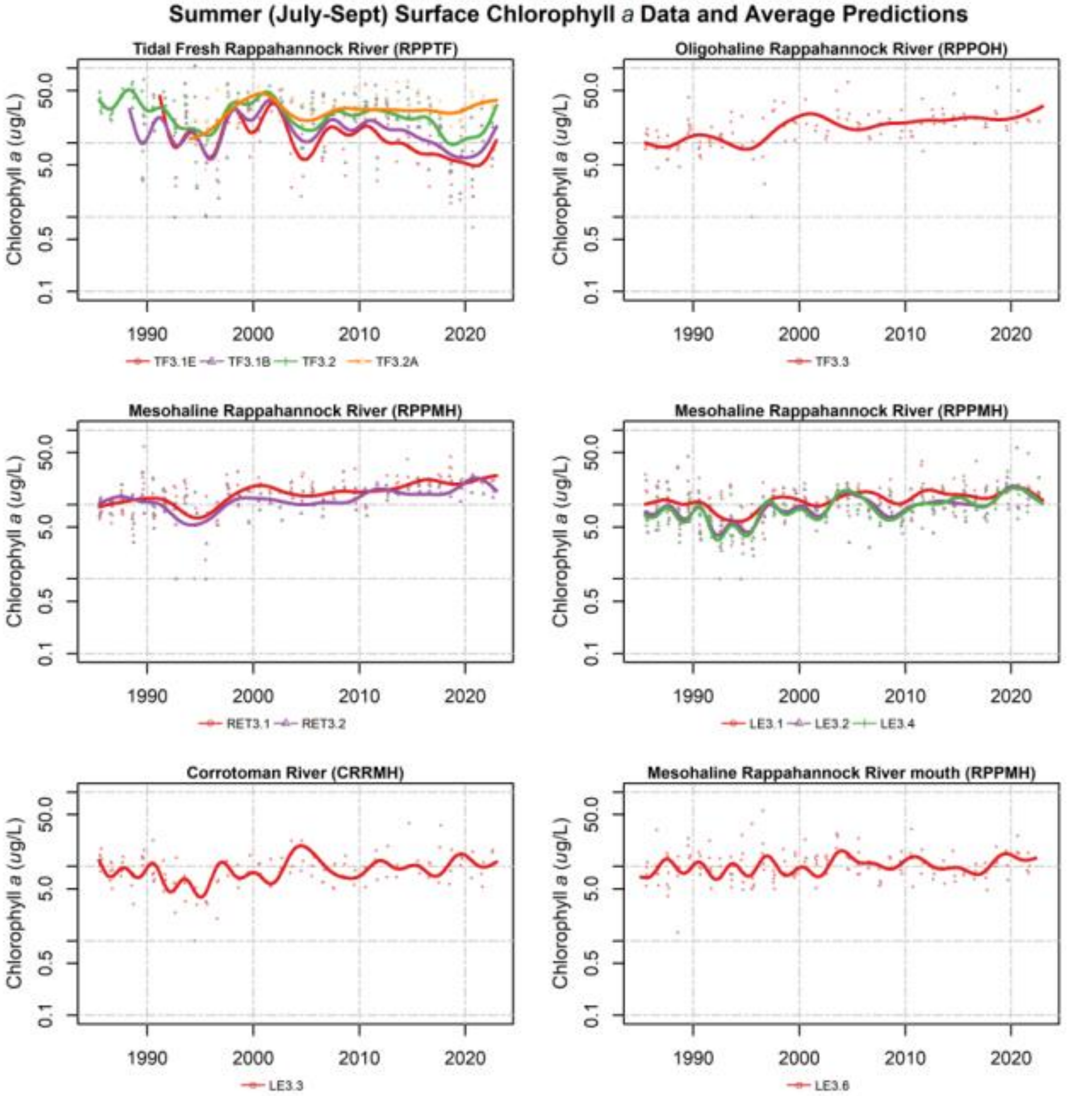


Figure 15. Surface summer chlorophyll *a* data (dots) and average long-term pattern generated from non-flow adjusted Generalized Additive Models (GAMs). Colored dots represent July-September data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean summer 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 varied along the tributary (Figure 16). The long-term spatial pattern is somewhat similar to trends in summer chlorophyll *a* (Figure 14) with improvements in the tidal fresh and degradations but no trends elsewhere. Long-term degradation in Secchi depth was observed at most stations. Fewer degrading trends persist over the short-term period with no trends observed at most stations.  There are also several new improving or possibly improving short-term trends.

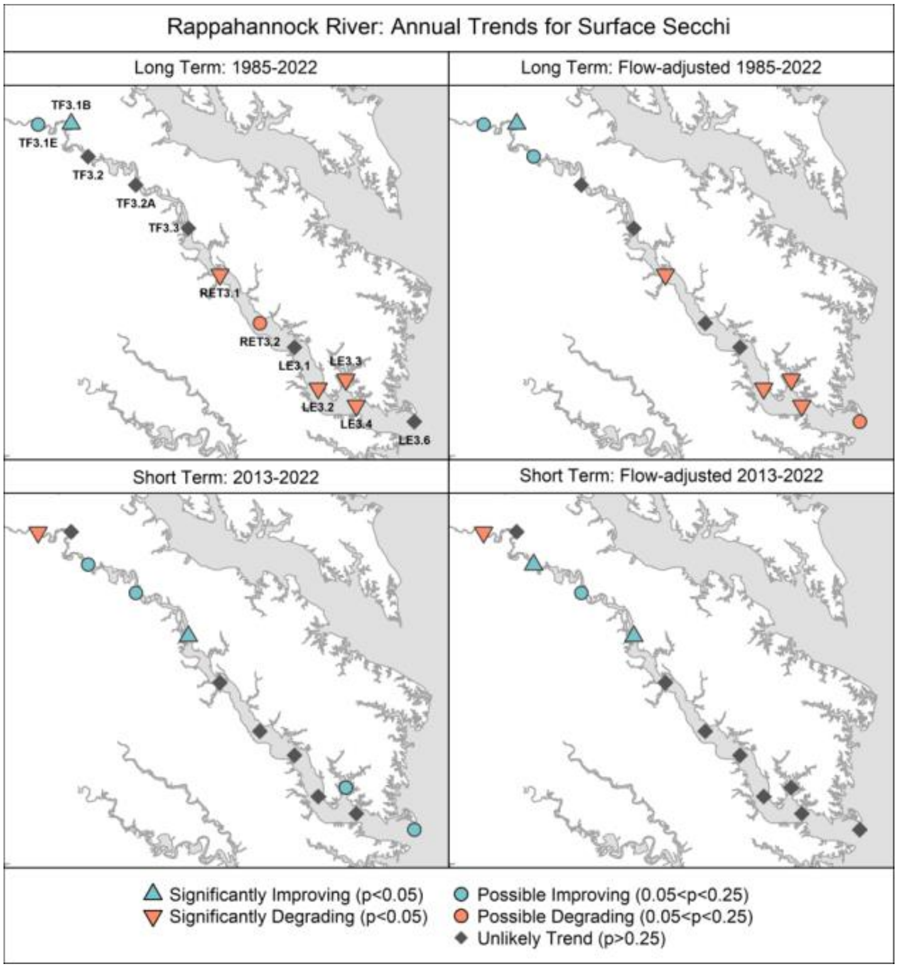


Figure 16. Annual flow-adjusted Secchi depth trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Secchi depth is clearly deeper at the mesohaline stations than at the tidal fresh or oligohaline stations in the Rappahannock River (Figure 17). The different trends in Secchi depth along the tributary are apparent here with improvements (i.e., increases in depth) at the mesohaline stations in recent years and degradations elsewhere.

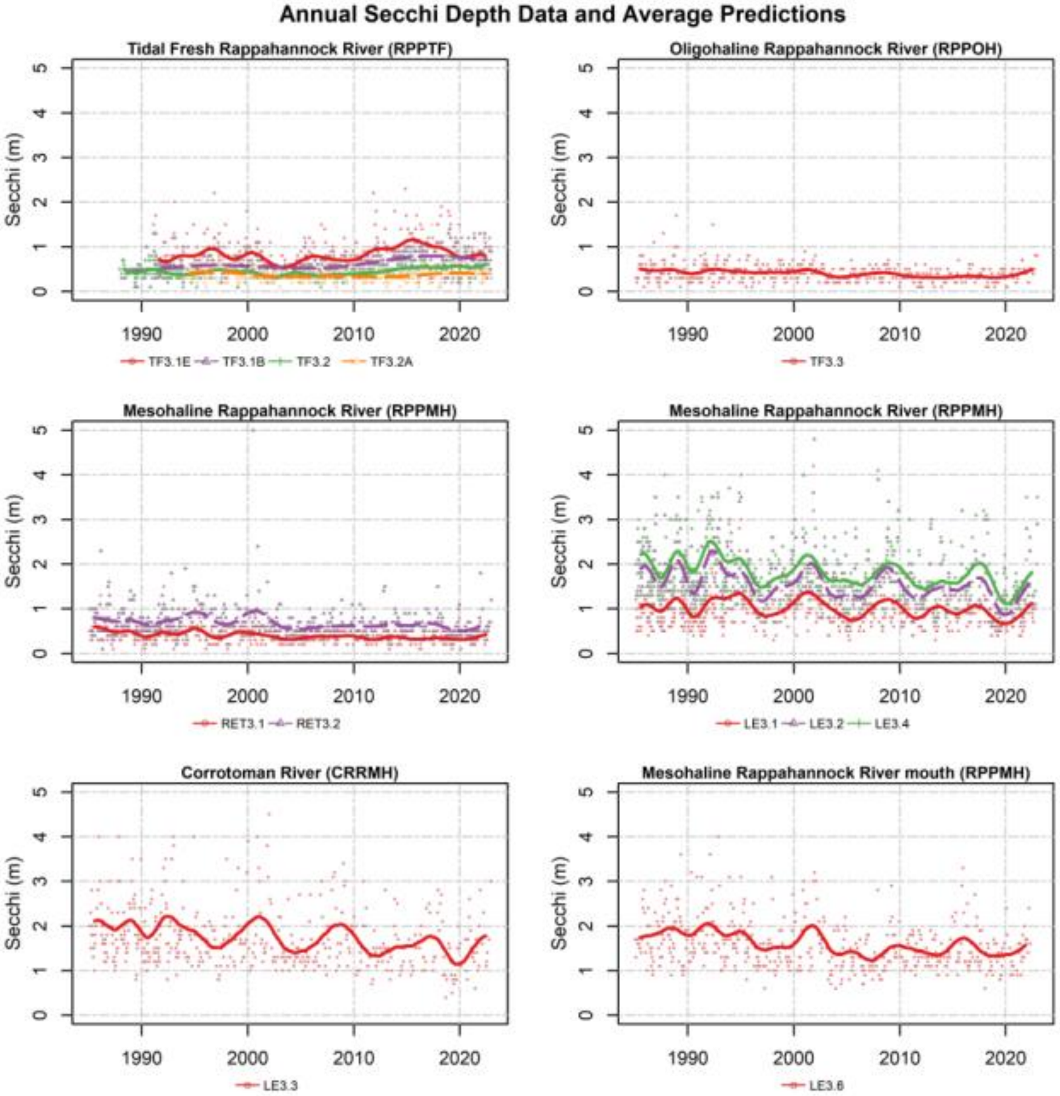


Figure 17. Annual Secchi depth data (dots) and average long-term patterns generated from non-flow adjusted Generalized Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted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

## 4.6 Summer Bottom Dissolved Oxygen (June-September)

Long-term observed bottom oxygen concentrations in the Rappahannock River have degraded at almost all stations, with a few exceptions including improvements at TF3.3 and LE3.6 (top left, Figure 18). Long-term flow-adjusted trends are also degrading from stations RET3.1 to LE3.4. Over the short-term, the more upstream stations' either show mixed trends or no-trends, while the downstream stations mostly show degrading trends. Station LE3.6, which is within the mainstem of Chesapeake Bay, shows conflicting trends in the observed long-term vs. short-term but has no-trend in both long- and short-term flow-adjusted bottom oxygen concentrations.

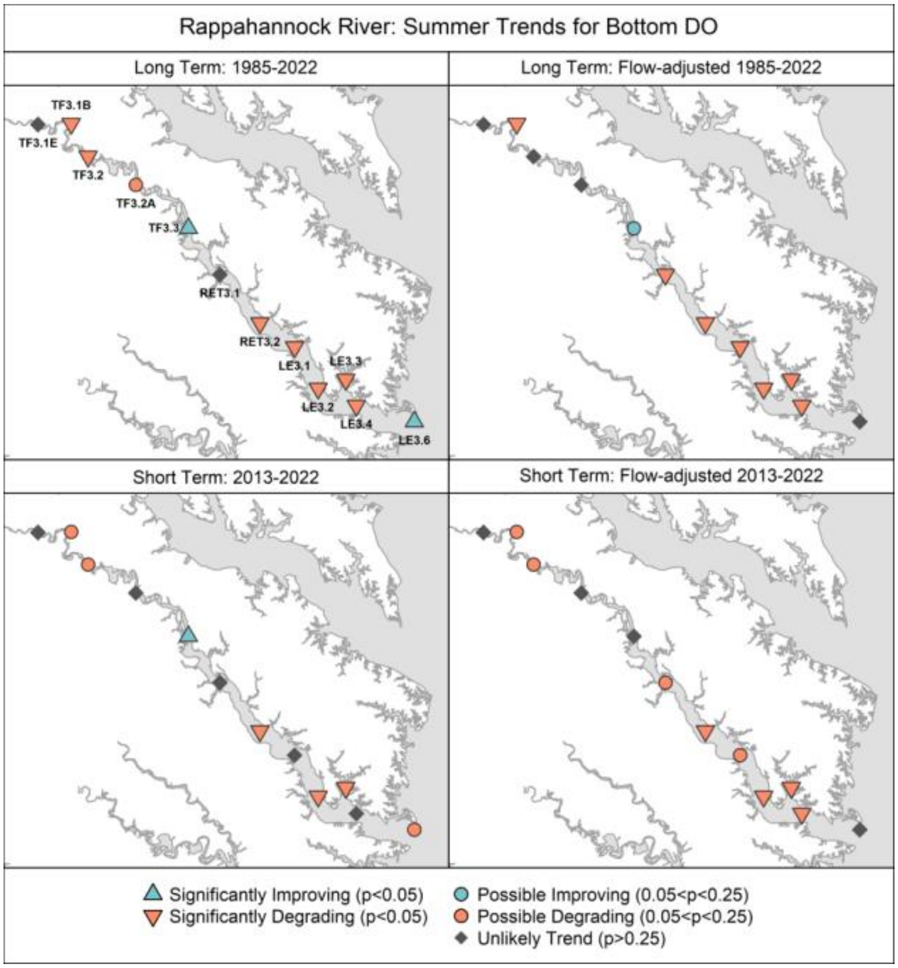


Figure 18. Flow-adjusted summer (June-September) bottom DO trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Plots of the summer data and average summer GAM estimates demonstrate the spatial variability in bottom DO concentrations (Figure 19). Tidal fresh concentrations are trending downward and periodically dip below the 5 mg/L summer Open Water 30-day mean DO criterion. Similarly, concentrations at some of the mesohaline stations dip below the Deep Channel instantaneous criterion of 1 mg/L during the summer, and many of these stations have experienced degrading trends (Figure 19). Notably, the improving long-term trend and steady short-term trend at LE3.6 is evident as well, although the concentrations are much higher at that station than others within the Rappahannock River.

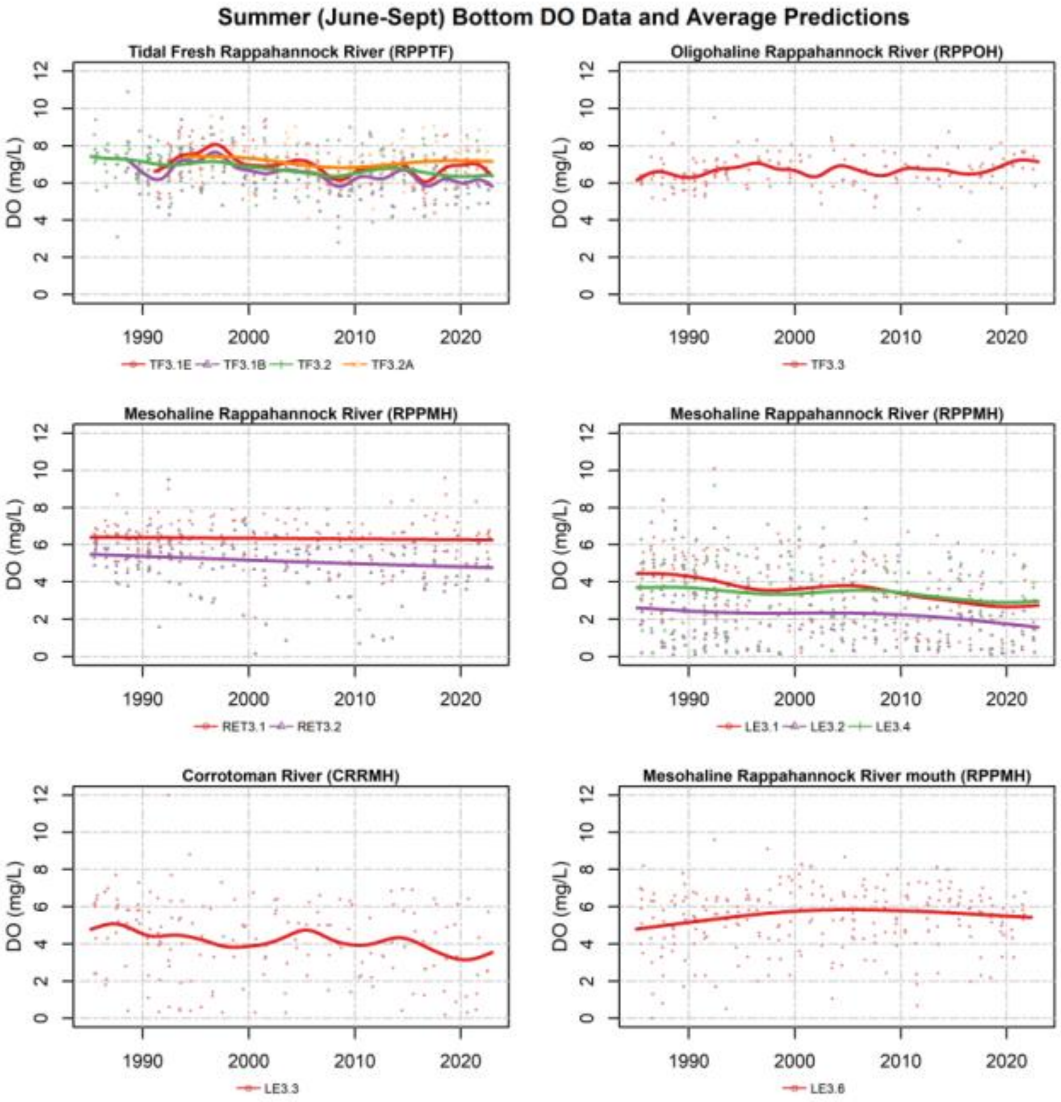


Figure 19. Summer (June-September) bottom DO data (dots) and average long-term seasonal pattern generated from non-flow adjusted Generalized Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station indicated in the legend; colored lines represent mean summer GAM estimates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

## 4.7 Surface Water Temperature

Rappahannock River 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).

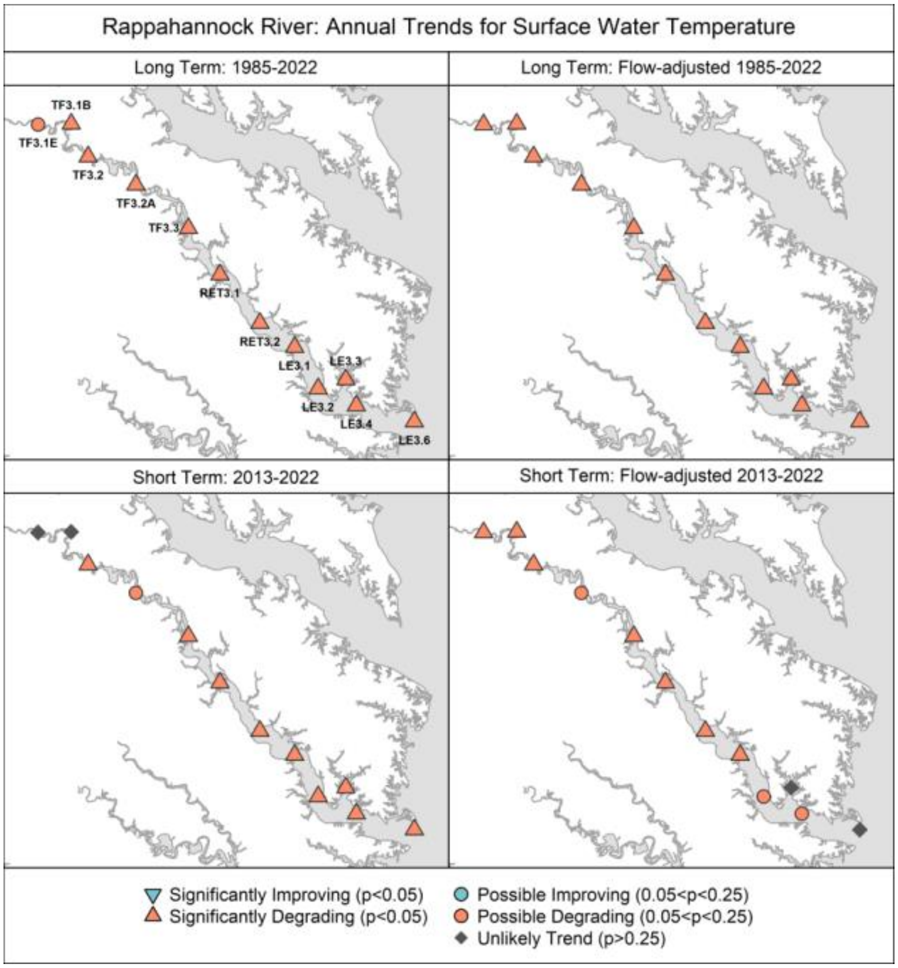


Figure 20. Annual flow-adjusted surface water temperature trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Water temperature varies seasonally in the tidal Chesapeake Bay waters, which is evident in the range of data values from almost 0 to 35 degrees Celsius (Figure 21). The mostly increasing long-term trends (Figure 20) are clear from the long-term averages of the data, even with the large seasonal variability.

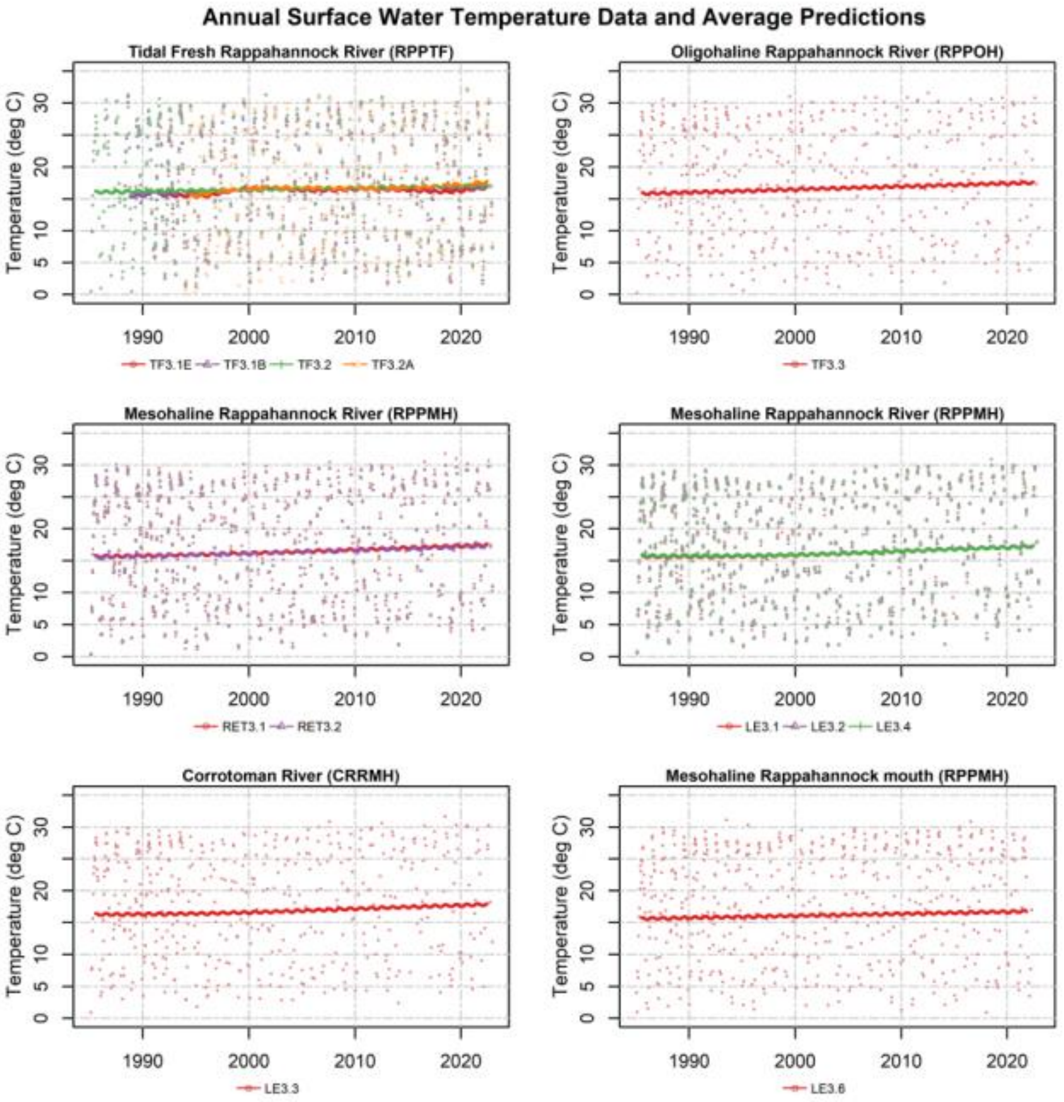


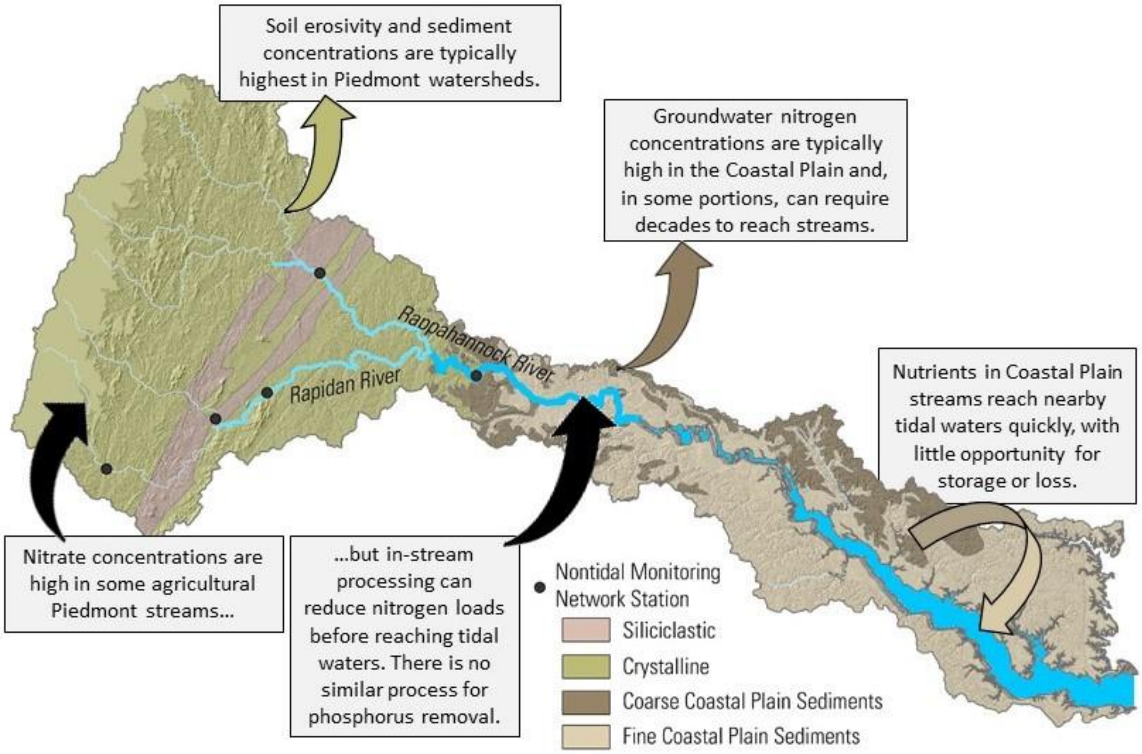
Figure 21. Annual surface water temperature data (dots) and average long-term pattern generated from non-flow adjusted Generalized Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates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

# 5. Factors Affecting Trends

## 5.1 Watershed Factors

### 5.1.1. Effects of Physical Setting

The geology of the Rappahannock River watershed and its associated land use affects the quantity and transmission of nitrogen, phosphorus, and sediment delivered to non-tidal and tidal streams (Figure 22) (Brakebill et al., 2010; Ator et al., 2011; Ator et al., 2019; Ator et al., 2020; Noe et al., 2020).



Soil erosivity and sediment concentrations are typically highest in Piedmont watersheds.

Groundwater nitrogen concentrations are typically high in the Coastal Plain and, in some portions, can require decades to reach streams.

Nutrients in Coastal Plain streams reach nearby tidal waters quickly, with little opportunity for storage or loss.

Nitrate concentrations are high in some agricultural Piedmont streams...

...but in-stream processing can reduce nitrogen loads before reaching tidal waters. There is no similar process for phosphorus removal.

Figure 22: Effects of watershed hydrogeomorphology on nutrient transport to freshwater streams and tidal waters. Base map modified from (King et al., 1974) and (Ator et al., 2005), North American Datum 1983.

## Nitrogen

Groundwater is an important delivery pathway for nitrogen, as nitrate, to most streams in the Chesapeake Bay watershed (Ator and Denver, 2012; Lizarraga, 1997). The proportion of nitrogen in groundwater that reaches freshwater streams and/or tidal waters is heavily dependent on location in the watershed (Figure 22). Groundwater nitrate concentrations in the Rappahannock River watershed are highest in streams that drain Piedmont soils (Greene and others, 2005; Terziotti and others, 2017). Crystalline rocks in the upper portion of the Rappahannock River watershed (refer to Figure 1 and Figure 22) contain large amounts of oxic groundwater, which promotes nitrate transport (Tesoriero and others, 2015), but their low porosity limits the amount of surface water infiltration (Lindsey and others, 2003). The typical residence time of groundwater delivered to streams in the Chesapeake Bay watershed is about 10 years, but ages vary from less than one year to greater than 50 years based on bedrock structure, groundwater flow paths, and aquifer depths (Lindsey and others, 2003). A similar range of water ages has been measured from Piedmont crystalline springs (0 – 34 years, Phillips and others, 2016). Groundwater represents about 50% of streamflow in most Chesapeake Bay streams, with the other half composed of soil moisture and runoff, which have residence times of months to days (Phillips, 2007).

### Phosphorus

Phosphorus binds to soil particles and most phosphorus delivered to the Bay is attached to sediment (Zhang and others, 2015); however, once fully saturated with phosphorus, soils will not retain new applications, and export of dissolved phosphorus to streams from shallow soils and groundwater will increase (Staver and Brinsfield, 2001). Phosphorus sorption capacity varies based on soil particle chemical composition and physical structure, with clays typically having the highest number of sorption sites and highest average phosphorus concentrations (Sharpley, 1980). The highest soil phosphorus concentrations occur in the headwaters of the Rappahannock River watershed where inputs of manure and fertilizer applied to agricultural fields exceed crop needs (Kleinman and others, 2011). Reducing soil phosphorus concentrations can take a decade or more (Kleinman and others, 2011), and until this occurs, watershed phosphorus loads may be unresponsive to management practices (Jarvie and others, 2013; Sharpley and others, 2013).

### Sediment

The delivery of sediment from upland soil erosion, streambank erosion, and tributary loading varies throughout the Rappahannock River watershed, but in-stream concentrations are typically highest in streams that drain Piedmont geology (Brakebill and others, 2010). The erosivity of Piedmont soils results from its unique topography and from the prevalence of agricultural and urban land uses in these areas (Trimble 1975, Gellis et al. 2005, Brakebill et al. 2010). Factors affecting streambank erosion are highly variable throughout this watershed and include drainage area (Gellis and others, 2015; Gellis and Noe, 2013; Gillespie and others, 2018; Hopkins and others, 2018), bank sediment density (Wynn and Mostaghimi, 2006), vegetation (Wynn and Mostaghimi, 2006), stream valley geomorphology (Hopkins and others, 2018), and developed land uses (Brakebill and others, 2010).

### Delivery to tidal waters from the non-tidal watershed

The delivery of nitrogen, phosphorus, and sediment in non-tidal streams to tidal waters in the Rappahannock River watershed varies based on physical and chemical factors that affect in-stream retention, loss, or storage. In general, nutrient and sediment loads in tidal waters are most strongly influenced by conditions in proximal non-tidal streams that have less opportunity for denitrification and floodplain trapping of sediment sorbed phosphorus. In-stream denitrification rates vary spatially with soil moisture and temperature (Pilegaard, 2013) and are typically higher in the Rappahannock River watershed than in more northern Bay regions because of a warmer climate. More than half of the nitrogen in the uppermost reaches of the Rappahannock River is removed via denitrification before reaching tidal waters (Ator and others, 2011). 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 (Noe et al., 2022). High rates of sediment trapping by Coastal Plain nontidal floodplains and head-of-tide tidal freshwater wetlands creates a “sediment shadow,” or area with limited sediment availability for sediment accumulation and wetland accretion, in many tidal rivers and limits sediment delivery to the bay which reduces the resilience of wetlands to the impacts of sea level rise (Ensign and others, 2013; Noe and Hupp, 2009). The average age of sediment stored in-channel is typically assumed to be less than a year (Gellis et al., 2017), but delivery to tidal waters can be exponentially longer as sediment moves in and out of different storage zones during downstream transport.

### 5.1.2. Estimated Nutrient and Sediment Loads

Estimated nutrient and sediment loads to the Rappahannock River are a combination of monitored loads from its U.S. Geological Survey (USGS) River Input Monitoring (RIM) station (USGS station number 01668000; USGS, 2022) located at the nontidal-tidal interface and below-RIM simulated loads from the Chesapeake Bay Program Watershed Model. Nitrogen and suspended sediment loads to the tidal Rappahannock River were primarily from the below-RIM areas, whereas phosphorus loads were primarily from the RIM areas (Figure 23). Over the period of 1985-2022, 0.15, 0.016, and 22 million tons of nitrogen, phosphorus, and suspended sediment loads were exported through the Rappahannock River watershed, with 47%, 66%, and 37% of those loads from the RIM areas, respectively. 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 10 ton/yr in the period between 1985 and 2022, although this increase is not statistically significant ($p = 0.62$). This increase reflects a combination of increases in RIM loads (4 ton/yr; $p = 0.67$) and below-RIM loads (7 ton/yr; $p = 0.55$). The below-RIM increase is driven by below-RIM nonpoint sources (11 ton/yr; $p = 0.34$). In contrast, long-term reductions were observed with the below-RIM point sources (-2.4 ton/yr; $p < 0.01$) and atmospheric deposition to tidal waters (-2.4 ton/yr; $p < 0.01$). The significant below-RIM 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 4.2 ton/yr in the period between 1985 and 2022, although this increase is not statistically significant ($p = 0.11$). This increase in TP is largely driven by the RIM loads (3.7 ton/yr; $p < 0.05$). Within the below-RIM loads, nonpoint sources showed a statistically significant increase (1.2 ton/yr; $p < 0.05$), whereas point sources showed a statistically significant decline (-0.56 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 2,000 ton/yr in the period between 1985 and 2022, although this increase is not statistically significant ($p = 0.38$). Both the RIM and below-RIM loads showed long-term increases, but neither is statistically significant. Like TP and TN, the below-RIM point source load of SS showed a statistically significant decline in this period (-4.1 ton/yr; $p < 0.01$).

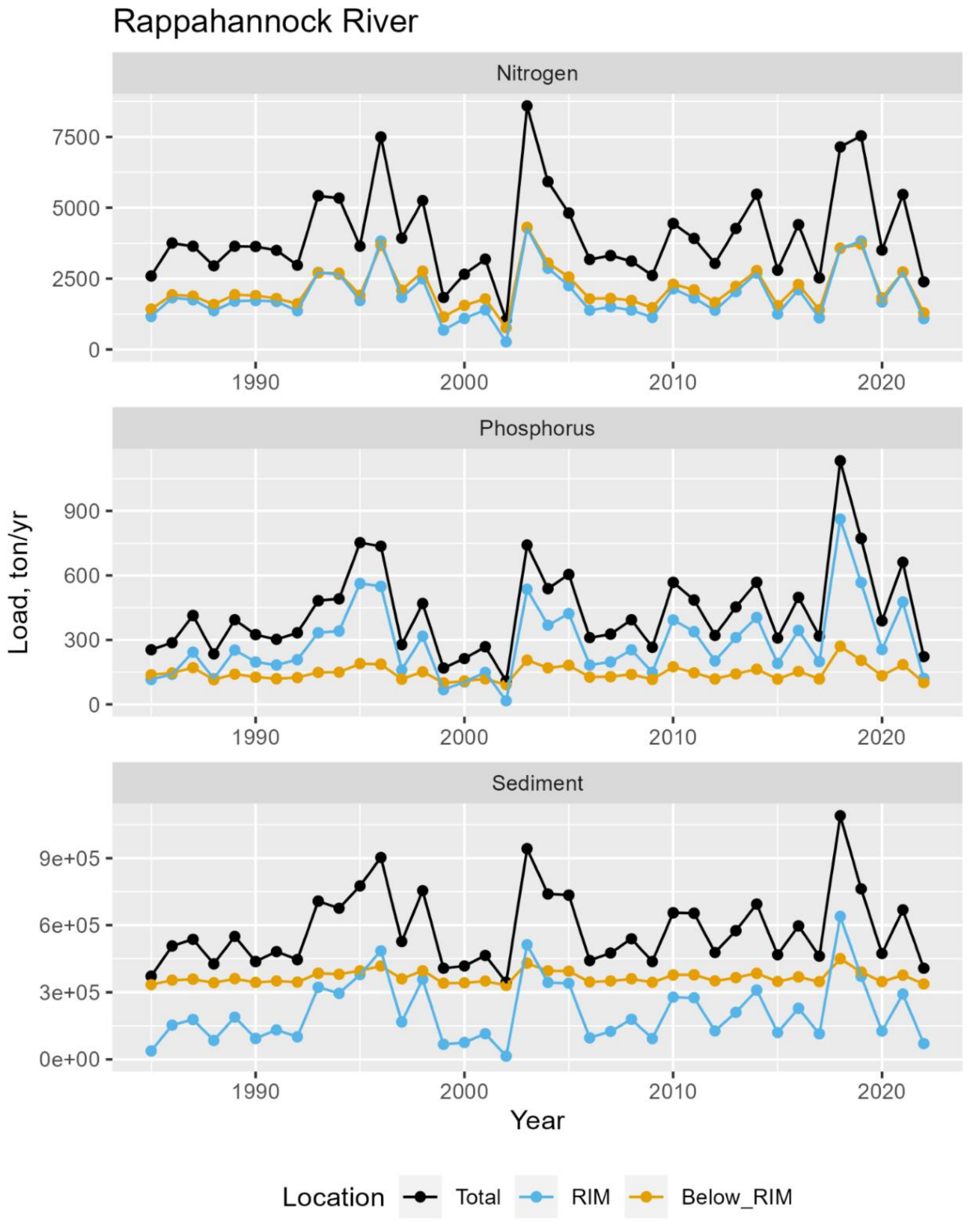


Figure 23. Estimated total loads (sum of RIM and Below-RIM) of nitrogen (TN), phosphorus (TP), and suspended sediment (SS) from the RIM and below-RIM areas of the Rappahannock River. RIM refers to the USGS River Input Monitoring site located just above the head of tide of this tributary, which includes upstream point source loads. Below-RIM estimates are a combination of simulated non-point and reported point-source loads.

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 to the Rappahannock River.

| Categories | TN | | TP | | SS | |
|---|---|---|---|---|---|---|
| | Trend, metric ton/yr | p-value | Trend, metric ton/yr | p-value | Trend, metric ton/yr | p-value |
| Total watershed | 10 | 0.62 | 4.2 | 0.11 | 2,000 | 0.38 |
| RIM watershed [1] | 4 | 0.67 | 3.7 | < 0.05 | 1,700 | 0.35 |
| Below-RIM watershed [2] | 7 | 0.55 | 0.26 | 0.55 | 270 | 0.41 |
| *Below-RIM point source* | -2.4 | < 0.01 | -0.56 | < 0.01 | -4.1 | < 0.01 |
| *Below-RIM nonpoint source* [3] | 11 | 0.34 | 1.2 | < 0.05 | 270 | 0.41 |
| *Below-RIM tidal deposition* | -2.4 | < 0.01 | - | - | - | - |

[1] Loads for the RIM watershed were estimated loads at the USGS RIM station 01668000 (Rappahannock River near Fredericksburg, Va.; https://cbrim.er.usgs.gov/loads_query.html).

[2] Loads for the below-RIM watershed were obtained from the Chesapeake Bay Program Watershed Model (https://cast.chesapeakebay.net/).

[3] Below-RIM nonpoint source loads were obtained from the Chesapeake Bay Program Watershed Model's progress runs specific to each year from 1985 and 2022, which were adjusted to reflect actual hydrology using the method of the Chesapeake Bay Program's Loads to the Bay indicator (refer to https://www.chesapeakeprogress.com/clean-water/water-quality).

### 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, version Phase 6 - 7.6.0), changes in population size, land use, and pollution management controls between 1985 and 2022 would be expected to change long-term average nitrogen, phosphorus, and sediment loads to the tidal Rappahannock River by -17%, -33%, and -13%, 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. 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 natural were the two largest sources of nitrogen loads. By 2022, agriculture remained the largest nitrogen source; however, natural nitrogen loads had changed by -7%, and the developed sector had taken its place as the second largest nitrogen source. Overall, decreasing nitrogen loads from agriculture (-32%), natural (-7%), stream bed and bank (-15%), and wastewater (-34%) sources were partially counteracted by increases from developed (80%) and septic (66%) sources.

The two largest sources of phosphorus loads as of 2022 were the agriculture and developed sectors. Overall, expected declines from agriculture (-51%), natural (-8%), stream bed and bank (-33%), and wastewater (-78%) sources were partially counteracted by increases from developed (100%) sources.

For sediment, the largest sources are shoreline and stream bed and bank areas: these two sources changed by -1% and -25%, respectively, between 1985 and 2022. Sediment loads from the agriculture sector changed by -58%, whereas sediment load from developed areas increased by 39%.

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 2022, whereas the developed sectors are expected to increase in nitrogen, phosphorus, and sediment loads.

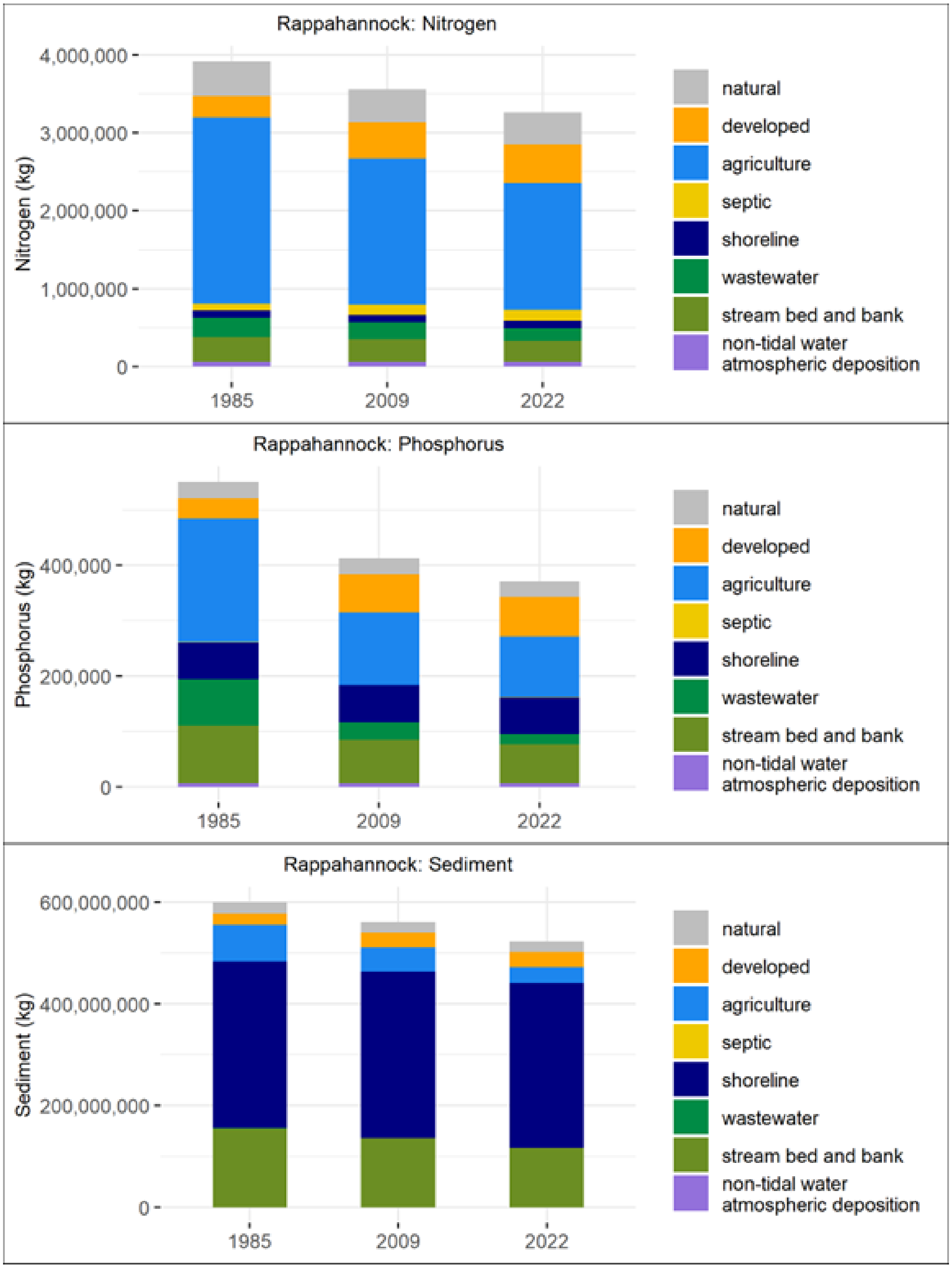
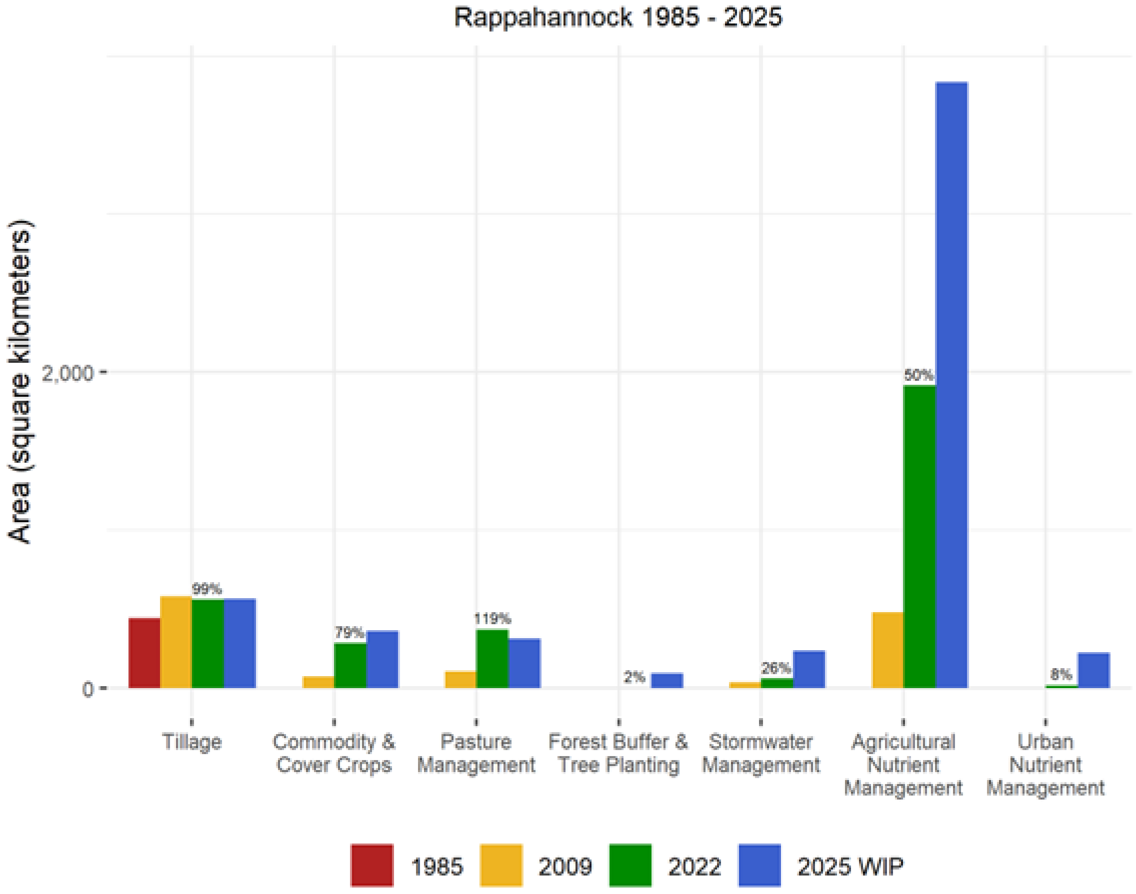


Figure 24. Expected long-term average loads of nitrogen, phosphorus, and sediment from different sources to the tidal Rappahannock River based on watershed conditions in 1985, 2009, and 2022. Data

are from the Chesapeake Assessment Scenario Tool (CAST; https://cast.chesapeakebay.net/About/UpgradeHistory, version Phase 6 - 7.6.0).

### 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, version Phase 6 - 7.6.0). Reported BMP implementations on the ground as of 1985, 2009, and 2022 are compared to planned 2025 implementation levels in Figure 25 for a subset of major BMP groups measured in square kilometers. As of 2022, tillage, cover crops, pasture management, forest buffer and tree planting, stormwater management, agricultural nutrient management, and urban nutrient management were credited for 560, 285, 371, 1.7, 62, 1,915, and 18 square kilometers, respectively. Implementation levels for some practices are already close to achieving their planned 2025 levels: for example, 119% of planned acres for pasture management had been achieved as of 2022. In contrast, about 8% of planned urban nutrient management implementation had been achieved as of 2022.



Values above the 2022 bars are the percent of the 2025 goal achieved.

Figure 25. Best management practice (BMP) implementation and watershed implementation plan (WIP) goals in the Rappahannock River watershed. Data are from the Chesapeake Assessment Scenario Tool (CAST; https://cast.chesapeakebay.net/About/UpgradeHistory, version Phase 6 - 7.6.0).

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) had increased from 0 meters in 1985 to 126 meters in 2022. Over the same period, animal waste management systems treated 0 animal units in 1985 and 2,011 animal units in 2022 (one animal unit represents 1,000 pounds of live animal). These implementation levels represent 1% and 7% of their planned 2025 implementation levels, respectively.

### 5.1.5. Flow-Normalized Watershed Nutrient and 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 long term (1985-2020) and short term (2011-2020) at nontidal network stations throughout the watershed and can be found at the USGS National Water Information System (NWIS; Mason et al., 2023; USGS, 2022) (Table 3). These trends result from variability in nutrient applications, the delivery of nutrients and sediment from the landscape to streams, and from processes that affect in-stream loss or retention of nutrients and sediment.

Table 3. Long-term (1985 - 2020) and short-term trends (2011 - 2020) of flow-normalized total nitrogen (TN), total phosphorus (TP), and suspended-sediment (SS) loads for nontidal network monitoring locations in the Rappahannock River watershed. A more detailed summary of flow-normalized loads and trends measured at all USGS Chesapeake Bay Nontidal Network stations can be found at usgs.gov/CB-wq-loads-trends.

| **USGS Station ID** | **USGS Station Name** | **Trend start water year** | **Percent change in FN load, through water year 2020** | | |
|---|---|---|---|---|---|
| | | | **TN** | **TP** | **SS** |
| 01664000 | RAPPAHANNOCK RIVER AT REMINGTON, VA | 1985 | **8.63** | - | - |
| | | 2011 | -0.681 | - | - |
| 01665500 | RAPIDAN RIVER NEAR RUCKERSVILLE, VA | 2011 | **6.08** | - | - |
| 01666500 | ROBINSON RIVER NEAR LOCUST DALE, VA | 1985 | 2.98 | - | - |
| | | 2011 | 6.13 | - | - |
| 01667500 | RAPIDAN RIVER NEAR CULPEPER, VA | 2011 | **-10.8** | -2.21 | 0.557 |
| 01668000 | | 1985 | **-15.7** | **35.1** | **56.8** |

| | | | | | |
|---|---|---|---|---|---|
| | RAPPAHANNOCK RIVER NEAR FREDERICKSBURG, VA | 2011 | **5.5** | 13.7 | **16.1** |

Decreasing trends listed in green, increasing trends listed in orange, results reported as “no trend” listed in black. TN = total nitrogen, TP = total phosphorus, SS = suspended sediment.

## 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 (Bukaveckas et al., 2011; Keisman et al., 2019; Testa et al., 2019). DO 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).

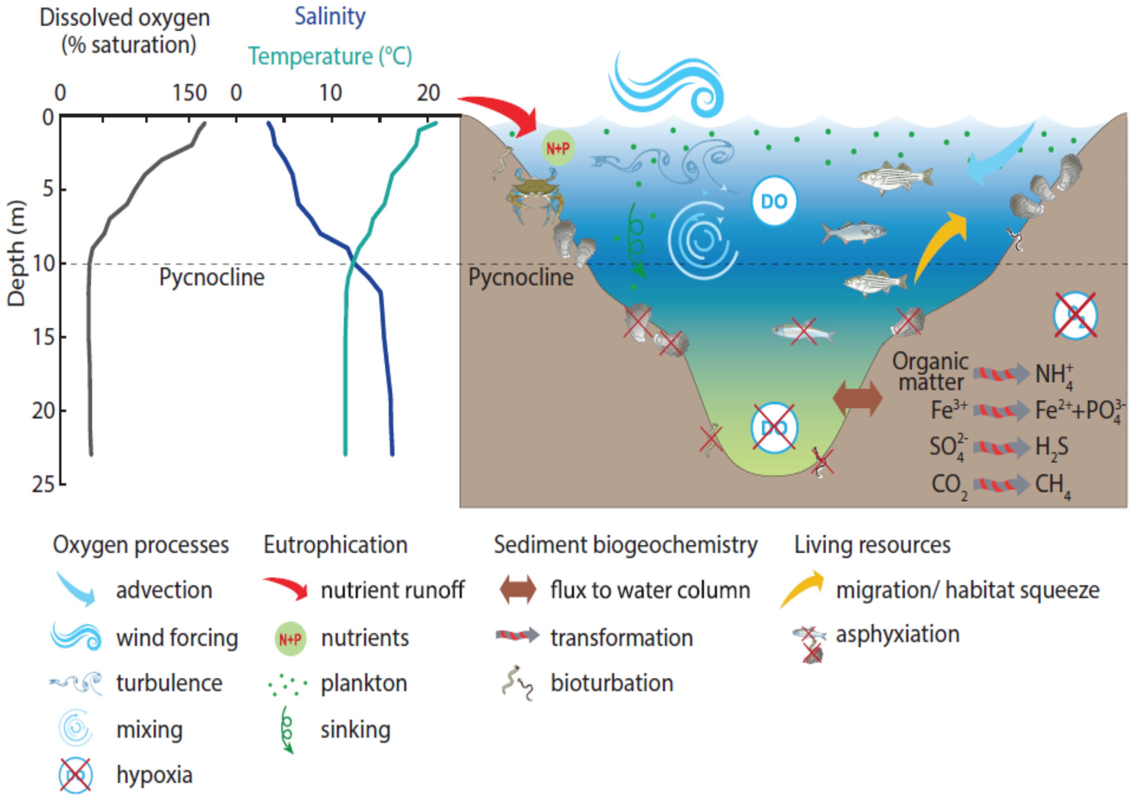


Figure 26. Conceptual diagram illustrating how hypoxia is driven by eutrophication and physical forcing, while affecting sediment biogeochemistry and living resources. From (Testa et al., 2017).

### 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; however, it would also correlate with a higher flow rate and decreased flushing time (Bricker et al., 2008). Figure 27 is a comparison of watershed area 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 Potomac River contains monitoring segments in the tidal fresh, oligohaline, and mesohaline sections of the river as well as the entire Anacostia River and other sub-estuaries. 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. Table 4 shows the associated tributary name for the abbreviated name and group name represented in the watershed and estuarine volume figures.

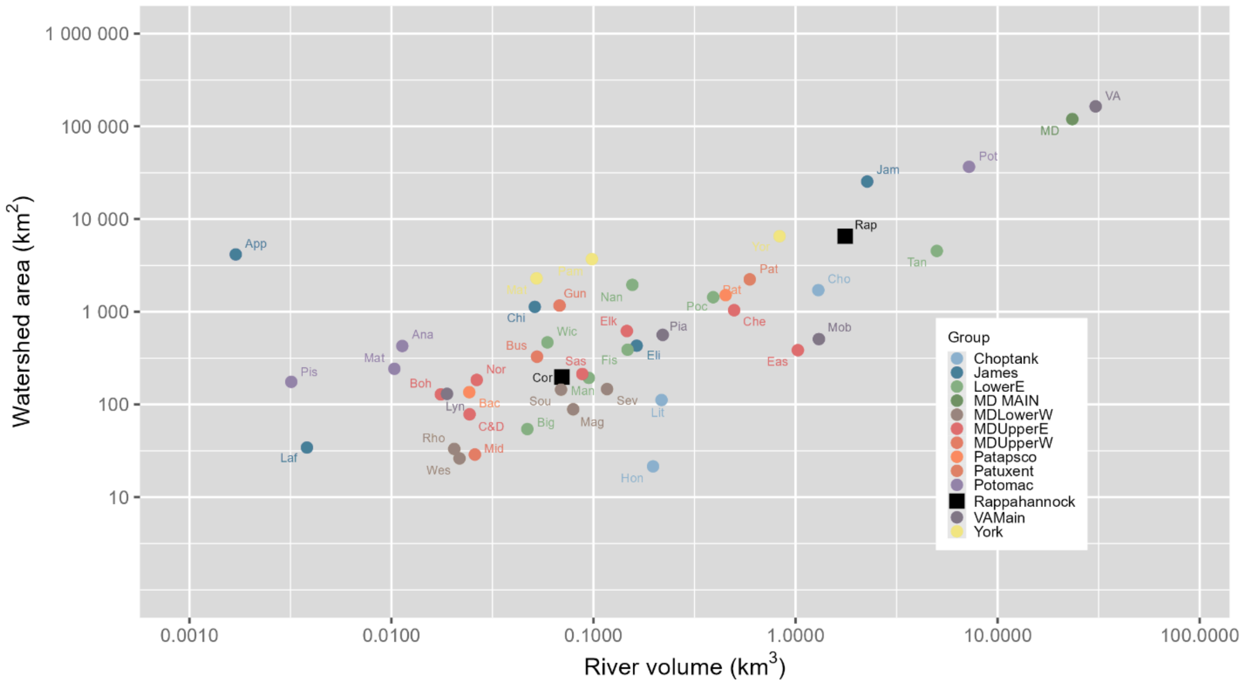


Figure 27. A comparison of watershed area (km$^2$) vs estuarine volume (km$^3$) for each tributary. The table of tributary names and their abbreviations can be found below.

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#tributaryRptsSection).

| Abbreviated tributary name | Full tributary name | Group name | Abbreviated tributary name | Full tributary name | Group name |
|---|---|---|---|---|---|
| Ana | Anacostia River | Potomac | Mat | Mattaponi River | York |
| App | Appomattox River | James | MD | MD MAINSTEM | MD Main |
| Bac | Back River | Patapsco | Mid | Middle River | MDUpperW |
| Big | Big Annemessex River | LowerE | Mob | Mobjack Bay | VAMain |
| Boh | Bohemia River | MDUpperE | Nan | Nanticoke River | LowerE |
| Bus | Bush River | MDUpperW | Nor | North East River | MDUpperE |
| C&D | Chesapeake & Delaware Canal | MDUpperE | Pam | Pamunkey River | York |
| Che | Chester River | MDUpperE | Pat | Patapsco River | Patapsco |
| Chi | Chickahominy River | James | Pat | Patuxent River | Patuxent |
| Cho | Choptank River | Choptank | Pia | Piankatank River | VAMain |
| Cor | Corrotoman River | Rappahannock | Pis | Piscataway Creek | Potomac |
| Eas | Eastern Bay | MDUpperE | Poc | Pocomoke River | LowerE |
| Eli | Elizabeth River | James | Pot | Potomac River | Potomac |
| Elk | Elk River | MDUpperE | Rap | Rappahannock River | Rappahannock |
| Fis | Fishing Bay | LowerE | Rho | Rhode River | MDLowerW |
| Gun | Gunpowder River | MDUpperW | Sas | Sassafras River | MDUpperE |
| Hon | Honga River | Choptank | Sev | Severn River | MDLowerW |
| Jam | James River | James | Sou | South River | MDLowerW |
| Laf | Lafayette River | James | Tan | Tangier Sound | LowerE |

| | | | | | |
|---|---|---|---|---|---|
| Lit | Little Choptank River | Choptank | VA | VA MAINSTEM | VAMain |
| Lyn | Lynnhaven River | VAMain | Wes | West River | MDLowerW |
| Mag | Magothy River | MDLowerW | Wes | Western Branch Patuxent River | Patuxent |
| Man | Manokin River | LowerE | Wic | Wicomico River | LowerE |
| Mat | Mattawoman Creek | York | Yor | York River | York |

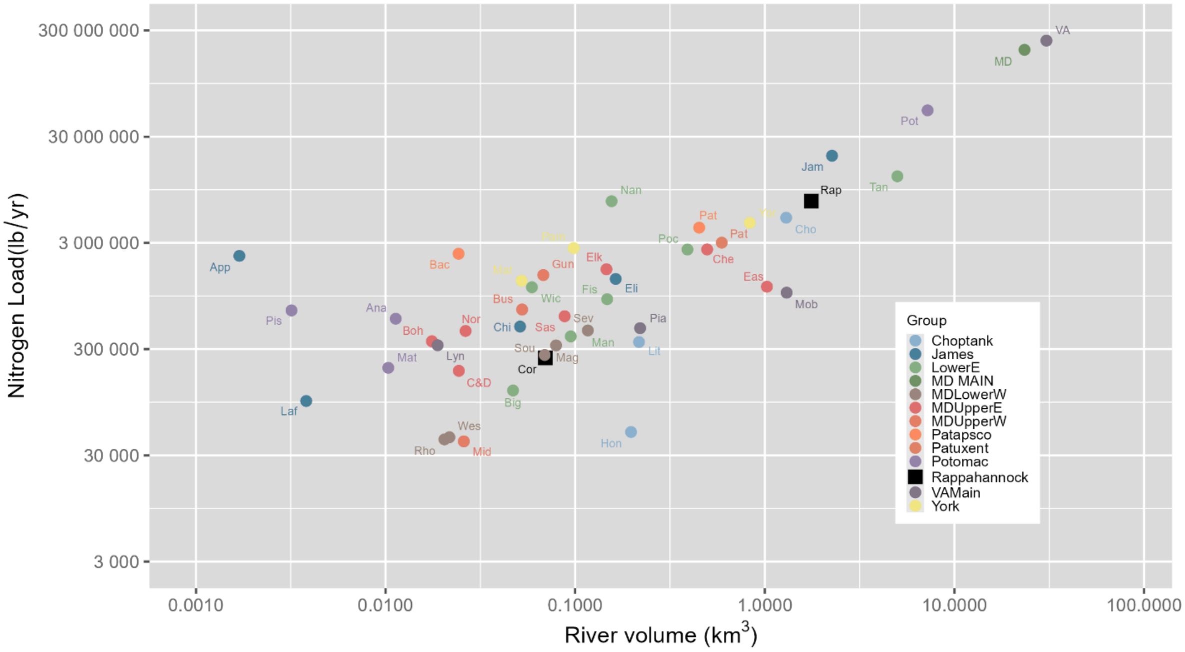


Figure 28. Annual average expected nitrogen loads versus estuarine volume. Nitrogen loads are from the 2021 progress scenarios in CAST (Chesapeake Bay Program, 2020), which is an estimate of nitrogen loads under long-term average hydrology given land use and reported management as of 2021.

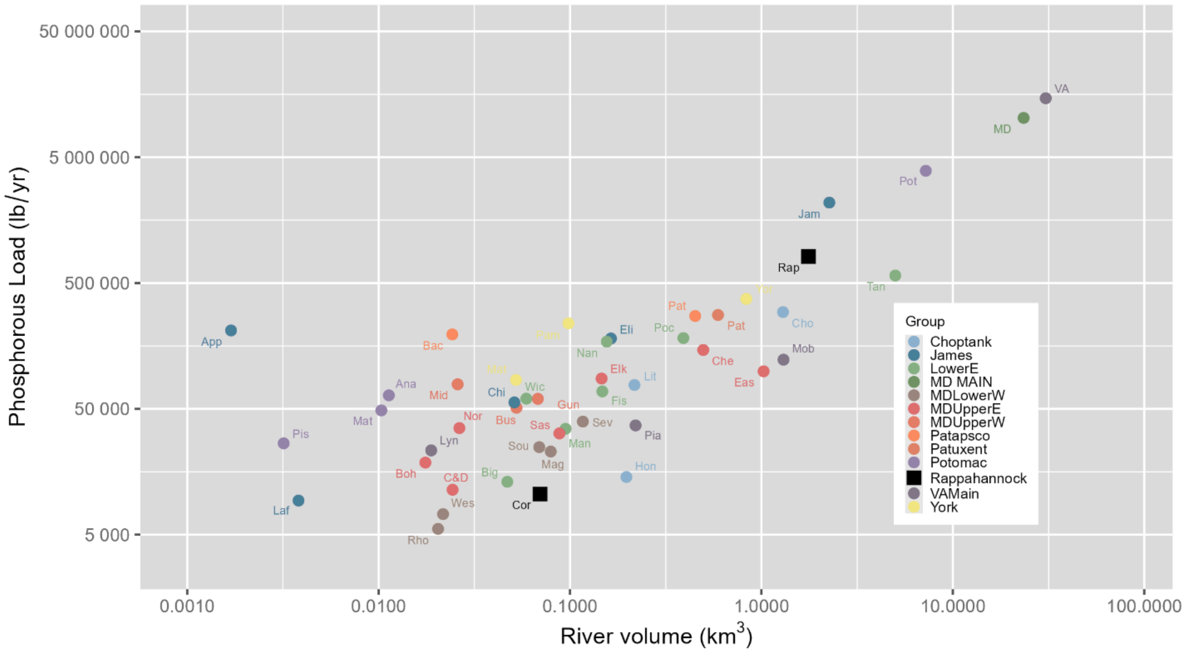


Figure 29. Annual average expected phosphorus loads versus estuarine volume. Phosphorus loads are from the 2021 progress scenarios in CAST (Chesapeake Bay Program, 2020), which is an estimate of phosphorus loads under long-term average hydrology given land use and reported management as of 2021.

The Rappahannock River estuary volume and watershed contain approximately 2% of the total volume and 4% of the total watershed of the Chesapeake Bay, respectively. This ranks the mainstem Rappahannock River as the 6th largest volume and 6th largest watershed area aggregated tributary in this summary (Figures 27, 28, and 29). The Corrotoman River, a smaller tributary within the Rappahannock River system, follows the same trend as the mainstem Rappahannock River. The ratios of watershed area, nitrogen loading, and phosphorus loading to estuarine volume in the Rappahannock River watershed are generally consistent with other estuaries in the Chesapeake Bay system. This indicates a moderate level of susceptibility to eutrophication.

### 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 Rappahannock River 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. Cluster analysis is used to group years according to similarity of longitudinal profiles. The profiles of the same color represent years with similar upstream to downstream trends across all the stations in the Rappahannock River. Comparing these groups allow for assessment of both spatial and temporal patterns for a given parameter, and comparisons among parameters allows for assessment of associations of parameters.

In the Rappahannock River, TN shows a spatial pattern of decreasing TN from RET3.1 and RET3.1 to the estuary mouth. This pattern follows typical patterns shown in western shore tributaries to the Chesapeake Bay (Figure 30).

Over time, the second most recent years (2012-2018, purple) have lower TN than prior years over the entire Rappahannock River estuary, apart from the most recent years (2019-2022, cyan) which have slightly higher TN in the RET stations and most of the lower estuary upstream of the mouth of the tributary. The greatest improvements in TN during the 2012-2018 period (purple) occur in the RET stations and upper portion of the lower estuary, and the degree of improvement is somewhat less near the estuary mouth. A comparison of the high flow years shown in red versus the normal flow years in cyan suggests that increased flow did result in a higher export of TN into the lower estuary.

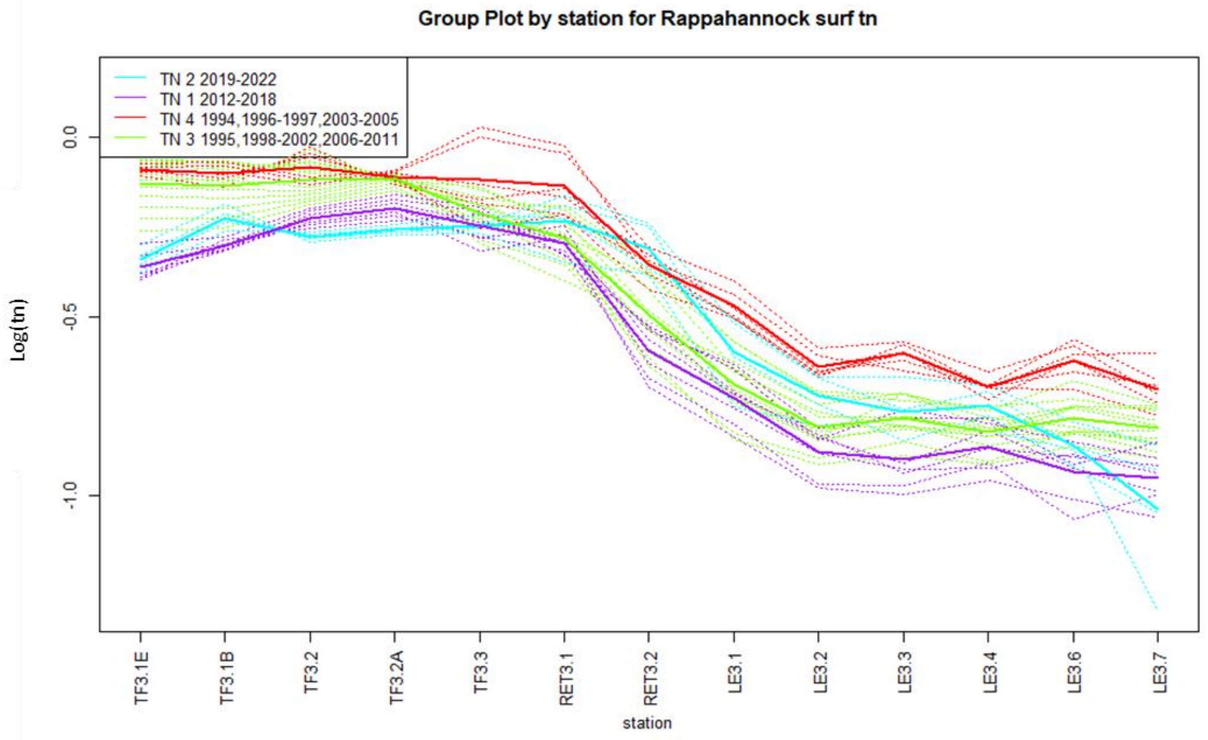


Figure 30: Station means of Total Nitrogen (TN) from upstream to downstream plotted with year groups segregated by color. Multiple dashed line traces within group show variability among years within groups.

In the Rappahannock River, TP shows a spatial pattern of increasing TP down to the first RET station (RET3.1) and then decreasing toward the estuary mouth (Figure 31). This pattern of increasing to a plateau in the turbidity maximum zone of the estuary and then decreasing is typical of the western shore tributaries to the Chesapeake Bay. It is attributed to the close association of TP and suspended particles. The estuarine mixing that occurs in the RET section of the estuary keeps particulate matter suspended in the water column.

The recent period from 2010-2018 (purple) have lower TP than prior years over most of the Rappahannock River estuary. The greatest improvements in TP occur in the lower tidal fresh. The three most recent years, 2019-2020 (cyan) show slightly higher TP than 2010-2018 (purple). This is likely due to 2019 being a record-high flow year. The years 1994-1997 (red) are also mostly above average flow years and stand out as having high levels of TP estuary wide.

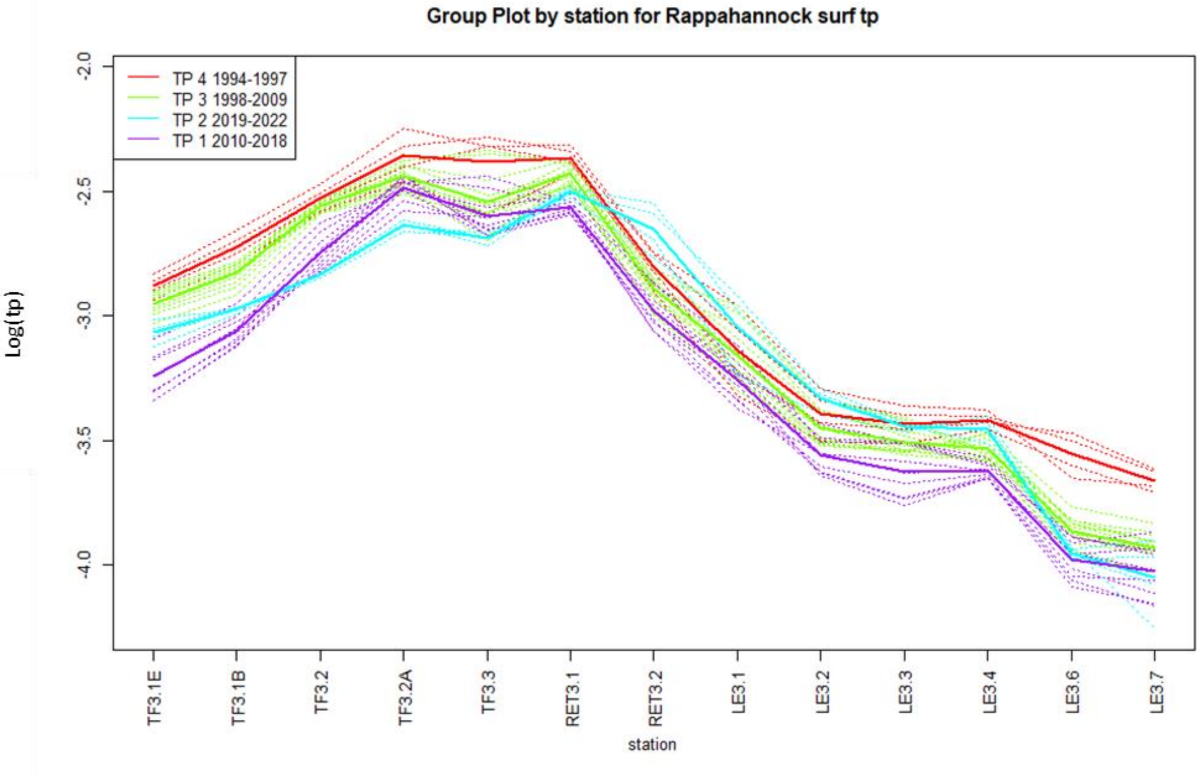


Figure 31: Station means of Total Phosphorus from upstream to downstream plotted with year groups segregated by color. Multiple dashed line traces within group show variability among years within groups.

The highest levels of surface chlorophyll *a* are typically observed in the lower tidal fresh down through the RET stations (Figure 32). An exception occurs in 1994-1995 (purple) where the highest levels are in the lower estuary. Station TF3.3 has relatively lower levels of surface chlorophyll *a* compared to its neighboring upstream and downstream stations.

Over time, surface chlorophyll *a* does not exhibit the consistent decrease that is shown by the nutrients TN and TP. In the tidal fresh, the highest levels of surface chlorophyll *a* occur in 1998-2002 and 2007-2011 (red), which are mostly low or normal flow years. In the lower Rappahannock River estuary, the highest levels of surface chlorophyll *a* occur in 2011-2020 (green) which are mostly high flow years. The years 2004-2005 have the longitudinal profile that is least similar to other years: 2004 is a high flow year while 2005 is a below average flow year. There is no ready explanation for similarity between these two years or the disparity between these years and others.

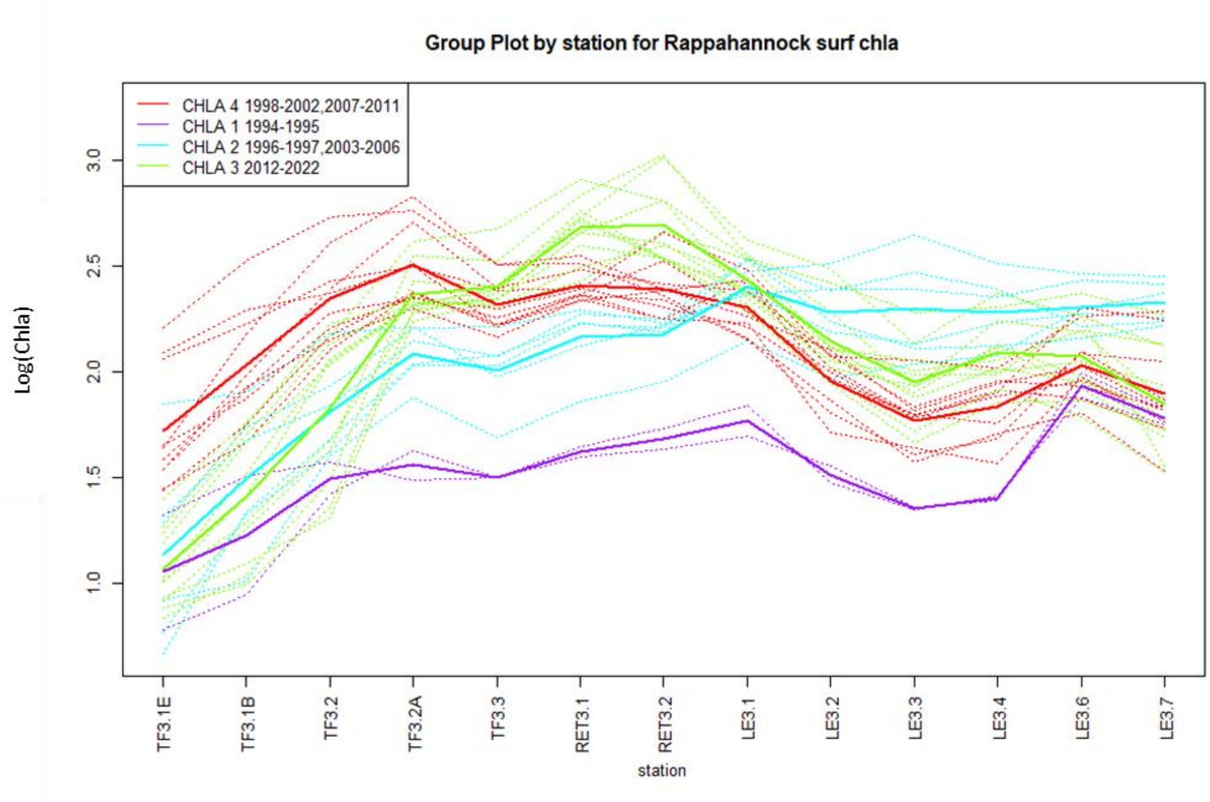


Figure 32: Station means of surface chlorophyll *a* plotted from upstream to downstream with year groups segregated by color. Multiple dashed line traces within groups show variability among years within groups.

The longitudinal pattern for water clarity as measured by the Secchi disk, as shown in Figure 33, is almost the inverse of the pattern exhibited by TP (Figure 31). In the lower tidal fresh through the RET water clarity is lowest (TF3.1E – RET3.1). In the lower estuary, clarity improves with proximity to Chesapeake Bay. This pattern is primarily due to estuarine mixing associated with riverine flows/inputs maintaining suspended particles in the water column, thus reducing water clarity in the lower tidal fresh and RET. It should also be noted that lower tidal fresh and RET form a zone where phytoplankton are abundant, which also tends to reduce water clarity (Figure 33).

Like chlorophyll *a*, Secchi depth does not exhibit the consistent improvement over time that is shown by the nutrients TN and TP. From the lower tidal fresh down to the mouth of the Rappahannock River estuary, the poorest water clarity occurs in 2019-2020 (purple). This corresponds to a period of high chlorophyll *a* in the lower estuary, but chlorophyll *a* was lower than average in the tidal fresh (Figure 32). The lower estuary appears to have improved clarity in recent years (2019-2020, purple), but the lower tidal fresh does not show improvement in this period.

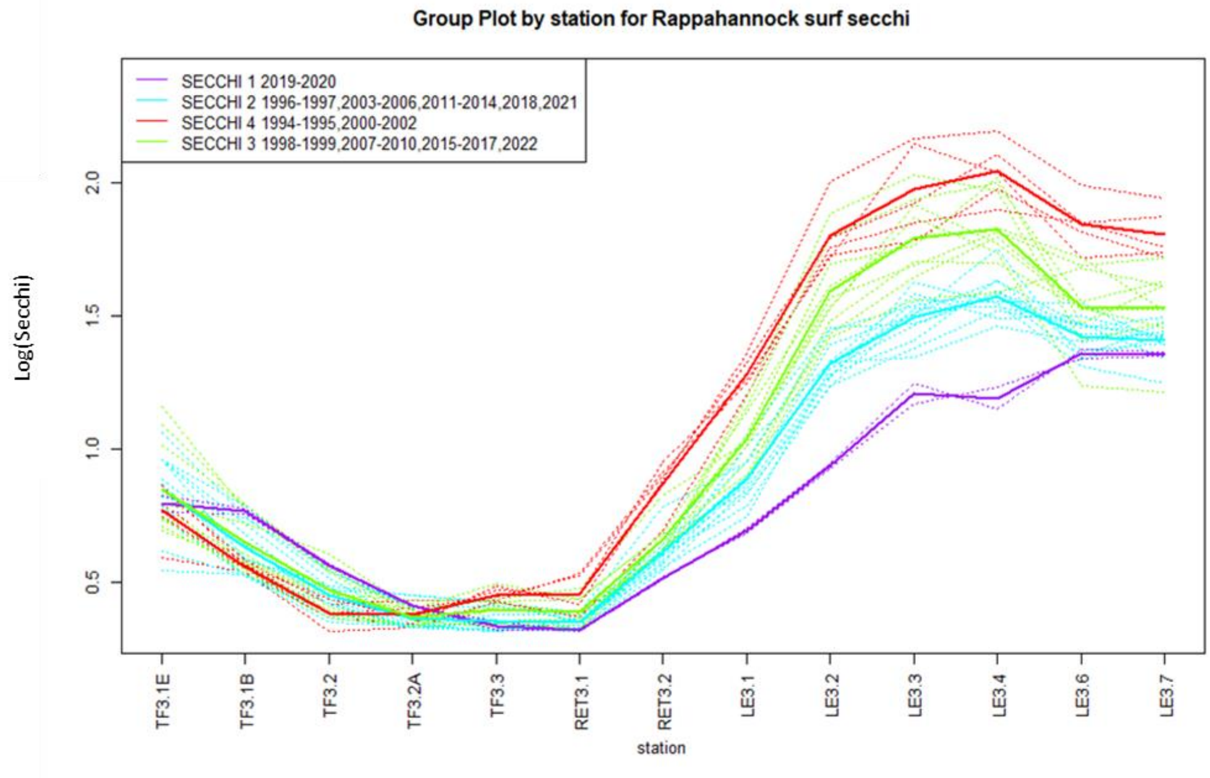


Figure 33: Station means of Secchi depth plotted from upstream to downstream with year groups segregated by color. Multiple dashed line traces within group show variability among years within groups.

Trends in summer bottom DO for the Rappahannock River, as shown in Figure 34, exhibit high DO in the lower tidal fresh and a decrease from the RET to the lower estuary (LE3.2), showing hypoxic conditions at LE3.2 in more recent years (2007-2017, green, and 2018-2022, red). Low bottom DO trends in the lower estuary are largely influenced by the bathymetry at these stations, as these are deepest areas of the Rappahannock and classified as the deep channel designated use (U.S. Environmental Protection Agency, 2003). Bottom DO trends improve moving from the lower estuary to the main Bay. It seems that DO conditions in the lower estuary are below average in recent years with the exception of the stations at the mouth of the estuary, LE3.6 and LE3.7 (2018-2022, red).

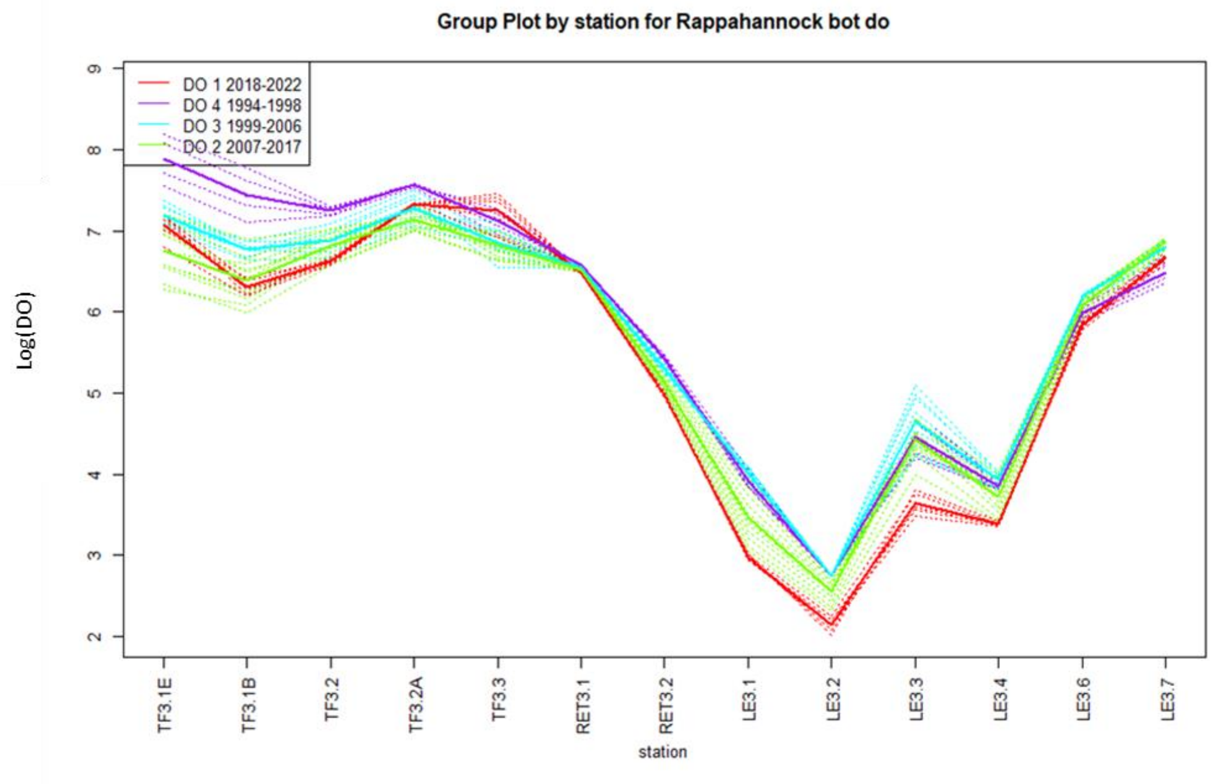


Figure 34: Station means of summer bottom Dissolved Oxygen plotted from upstream to downstream with year groups segregated by color. Multiple dashed line traces within group show variability among years within groups.

## 5.3 Climate Change Factors

The existence and influence of climate change is well demonstrated both globally (IPCC, 2014) and in the Chesapeake Bay (Hinson et al., 2022). As one of the most vulnerable areas in the nation, all aspects of the Chesapeake Bay watershed and tributaries are at risk from the effects of climate change, and the impacts are already being observed. Overall, the watershed is experiencing increases in precipitation, temperatures, and climatic variability, which shape Chesapeake Bay tributary water quality trends (Najjar et al., 2010). These trends differ spatially and temporally throughout the watershed, and climate impacts are exacerbated by local non-climate 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 climate change is influencing water quality in Chesapeake Bay tributaries but instead is an acknowledgement of the influence of climate change on the trends discussed in this report. Efforts aimed to increase understanding of climate change impacts on water quality patterns can help explain the actual 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 Chesapeake Bay ecosystem. During large rain events, river flows increase, delivering more fresh water into Chesapeake Bay and decreasing the salinity (Murphy et al., 2019). Stormwater runoff delivers nitrogen, phosphorus, and sediment into rivers and Chesapeake 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. More information capturing the extreme weather events occurring in the Chesapeake Bay watershed is shared seasonally by the Mid-Atlantic Regional Integrated Sciences and Assessments in the regional climate summaries (MARISA, 2023).

The correlation of water quality with extreme weather events is seen through the Chesapeake Bay Water Quality Standards Attainment Indicator (Fig 35) (Chesapeake Bay Program, 2023). The attainment indicator presently 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 the 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 Chesapeake Bay.

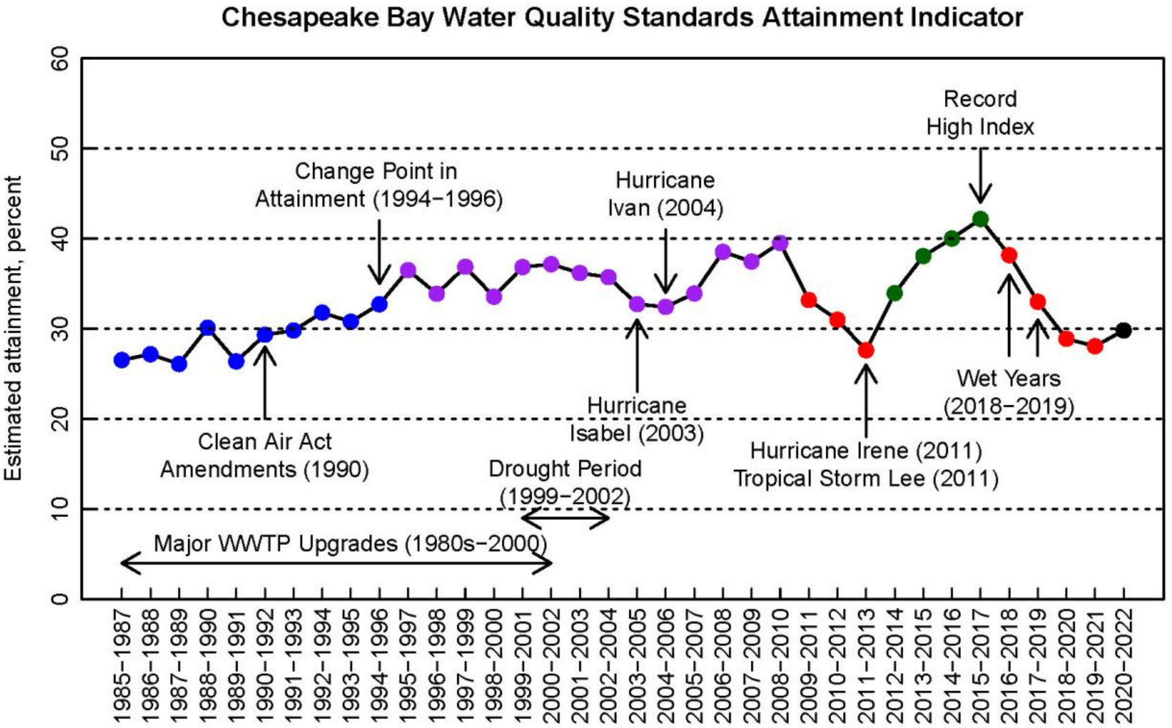
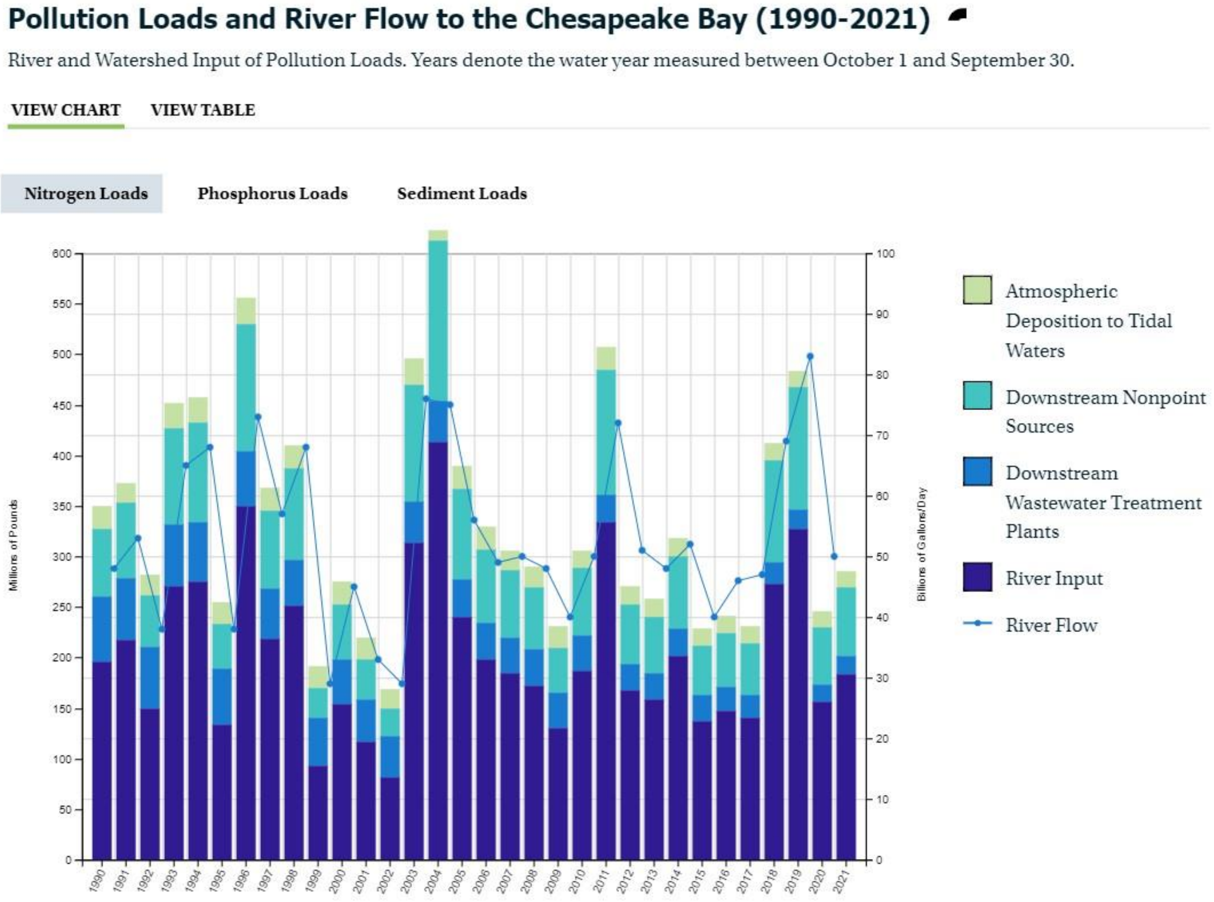


Figure 35. Chesapeake Bay Water Quality Standards Attainment Indicator evaluated using three parameters from 1985 – 2022: dissolved oxygen, water clarity or submerged aquatic vegetation abundance, and chlorophyll *a.* Colors represent a different period: blue represents period before the change point, 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. Figure from (Zhang et al., 2018).

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 the Bay, delivering high pollutant loads during that period (Fig 36). 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 (Chesapeake Bay Program, 2023).


Pollution Loads and River Flow to the Chesapeake Bay (1990-2021)

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

Figure 36. Pollution Loads and River Flow to the Chesapeake Bay (1990-2021): River and Watershed Input of Pollution Loads. Years denote the water year measured between October 1 and September 30. Figure from (Chesapeake Bay Program, 2023).

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 help understand patterns in regional streamflows, but local assessments of climate change and variability are still needed for determining climate vulnerability for the Bay (St. Laurent et al., 2021). Figure 37 shows Parameter-Elevation Relationship on Independent Slope Model (PRISM Climate Group, 2020) precipitation data at the land-river scale spatially aggregated to the Rappahannock River watershed. Mean annual precipitation for the Rappahannock Tributary watershed from 1981 to 2020 shows a gradual increase over the period of record.

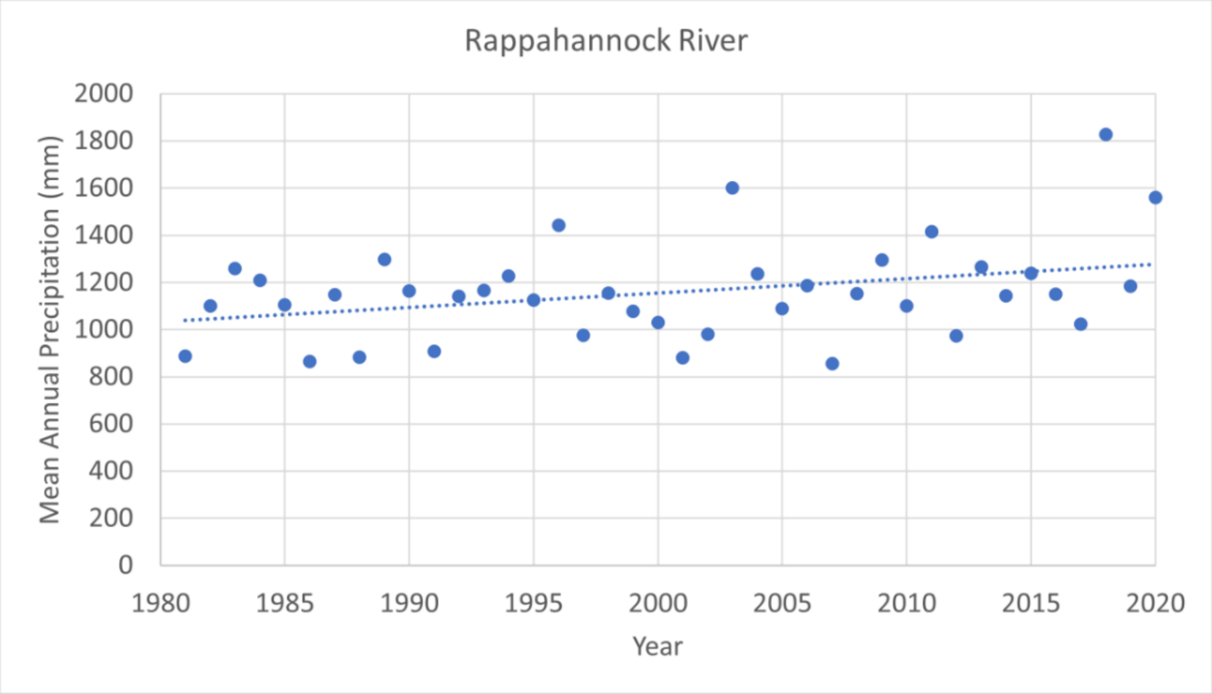


Figure 37. Rappahannock River mean annual precipitation from 1981 – 2020 from the Parameter-Elevation Relationship on Independent Slope Model (PRISM).

### 5.3.2. Warming Water Temperatures

Chesapeake Bay is shallow, with a mean depth of 6.5 m, so atmospheric variability has a large influence on water column temperatures (St. Laurent et al., 2021). As described in Section 4.7, both long-term and short-term surface water temperature trends across the tidal areas of the Rappahannock River are experiencing statistically significant warming (Figure 38). Increased atmospheric temperatures are forcing factors that contribute to warmer water temperatures. Trend analyses of 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).

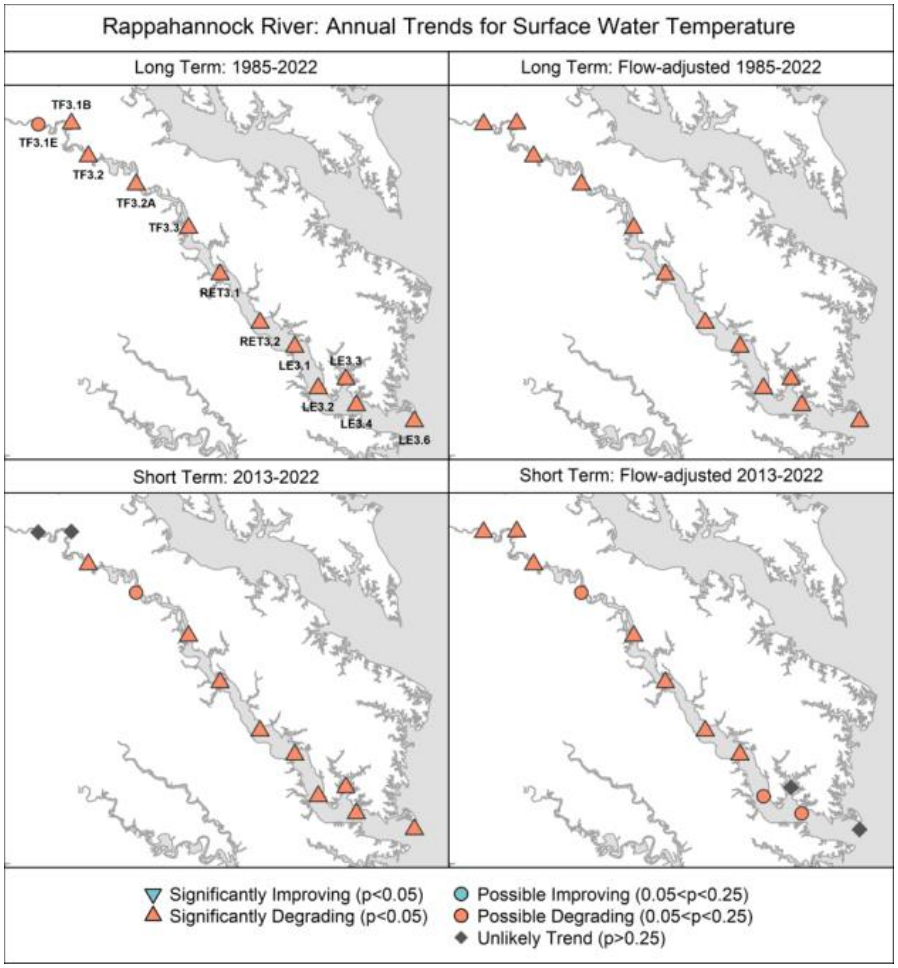


Figure 38. Annual flow-adjusted surface water temperature trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

### 5.3.3. Sea-Level Rise

Sea-level rise and climate are closely linked. As the climate has warmed, 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 one 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. Windmill Point is at the mouth of the Rappahannock tributary and shows an increasing sea-level trend of 7.01 mm/year (Figure 39).

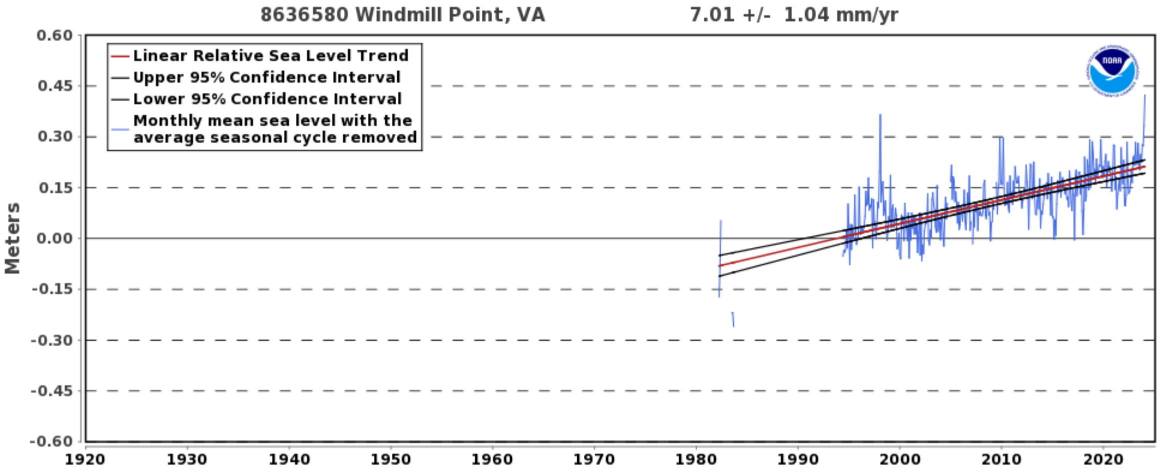


Figure 39. Windmill Point, Virginia monthly mean sea levels without the regular seasonal fluctuations from coastal ocean temperatures, salinity, wind, atmospheric pressure, and ocean currents. The relative sea level trend also shows the 95% confidence interval (NOAA, 2023b).

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 integrate changing climate 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 climate change impacts on water quality is critical, it is also important to understand these influences in the context of the living resources water quality standards were designed to protect. Warming water temperatures reduce the solubility of oxygen in water (Tian et al., 2021). With both higher water temperature averages and extremes, 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 water column (Parham et al., 2023). Another consideration is that warming waters in Chesapeake Bay favor pathogenic bacteria like *Vibrio vulnificus*, which threaten human health directly and indirectly through key living resources that are valued for human consumption, such as oysters (Archer et al., 2023; Wright et al., 1996). Additionally, phenological shifts due to warmer water temperatures threaten decoupling of predator-prey relationships and 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 climate change impacts 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 (National Oceanic and Atmospheric Association, 2023c).

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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 µg/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 Cyanophycea that are procaryotic 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 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 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.

**Eucaryote** - organisms the cells of which have 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 value 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 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 kg/yr or lbs/yr.

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

**Mesohaline** - refers to waters with salinity values ranging between 0.5 and 18.0 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 instead of being at a fixed location (e.g., run-off from residential and agricultural land).

**Oligohaline** - refers to waters with salinity values ranging between 0.5 and 5.0 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 m and 1.0 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.

**Picoplankton** - phytoplankton with a diameter between 0.2 and 2.0 µm. Picoplankton consist primarily of cyanobacteria, and high concentrations of picoplankton are generally considered to be indicative of poor water quality conditions.

**Pielou's evenness** - an estimate of the distribution of proportional abundances of individual species within a community. Evenness ($J$) is calculated as follows: $J=H'/\ln S$ where $H'$ is the Shannon - Weiner diversity index and $S$ is the number of species.

**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 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.

**Procaryote** - 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 either changes in salinity or water temperature.

**Random Station** - a station selected randomly within a stratum. In every succesive 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 serves to: 1) reduce excess amounts of sediment, organic matter, nutrients, and other pollutants in surface runoff, 2) reduce soluble pollutants in shallow ground water flow, 3) create shade along water bodies to lower aquatic temperatures, 4) provide a source of detritus and large woody debris for aquatic organisms, 5) provide riparian habitat and corridors for wildlife, and 6) reduce erosion of streambanks and shorelines.

**Salinity** - the concentration of dissolved salts in the water column measured in mg/L, ppt or 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.

**Shannon Weiner diversity index** - a measure of the number of species within a community and the relative abundances of each species.

**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* (widgeon grass), *Stuckenia pectinata* (sago pondweed)) that grow in shallow water areas. SAV are important in marine environments because they serve as major food source, provide refuge for juvenile crabs and fish, stabilize sediments preventing shoreline erosion and excessive suspended materials in the water column, and produce 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 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 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 are considered to 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 mg/L. Phosphorus is a required nutrient for cellular metabolism and for 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 are considered to 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 mg/L. The composition of total suspended solids includes both inorganic (fixed) and organic (volatile) compounds. The fixed suspended solids component is comprised of sediment particles while the volatile suspended solids component is comprised 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 in a separate Appendix document for:

- Bottom Total Nitrogen

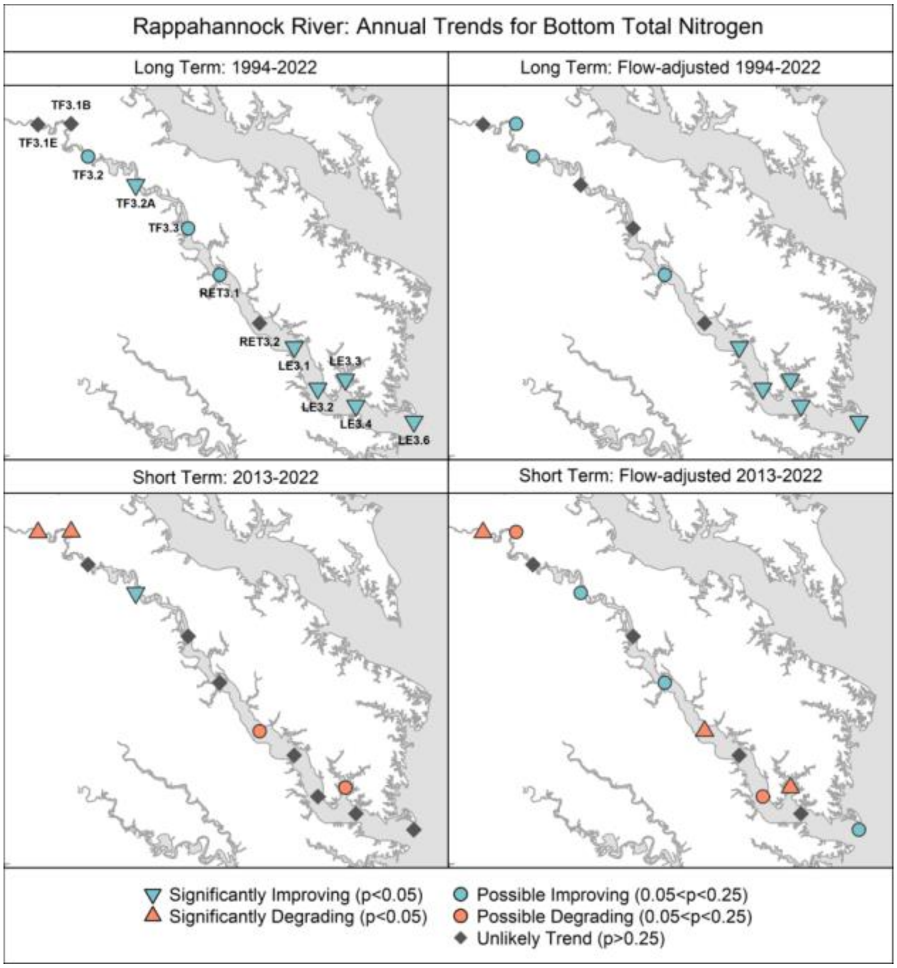

Figure A1. Annual flow-adjusted surface total nitrogen trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

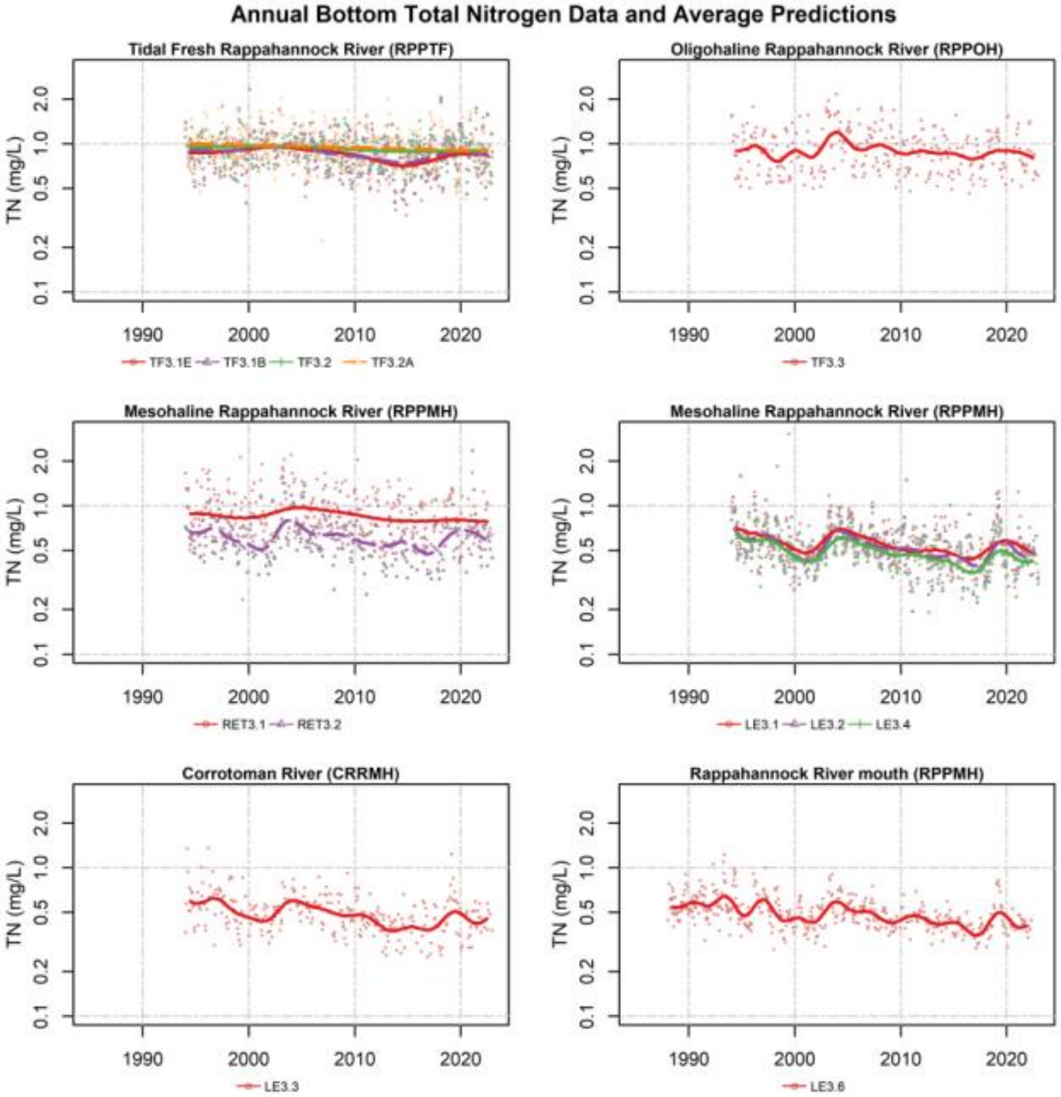

Figure A2. Annual bottom total nitrogen data (dots) and average long-term pattern generated from non-flow adjusted Generative Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

- Bottom Total Phosphorus

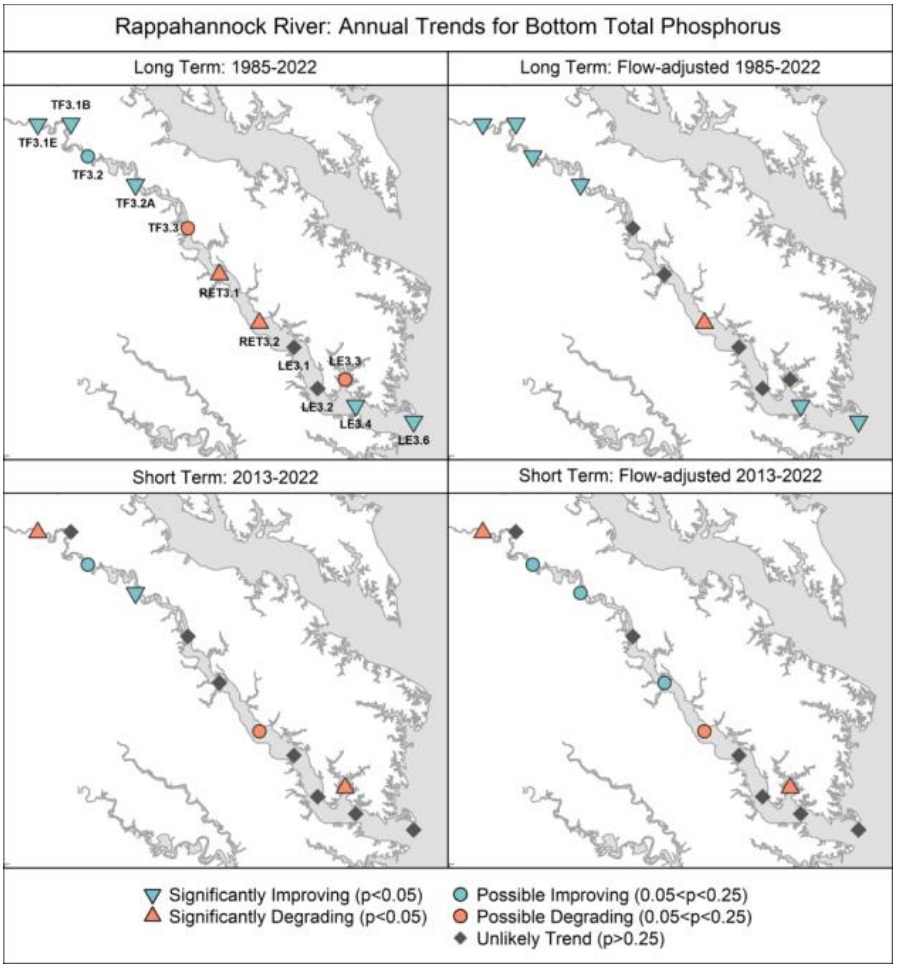

Figure A3. Annual flow-adjusted surface total phosphorus trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

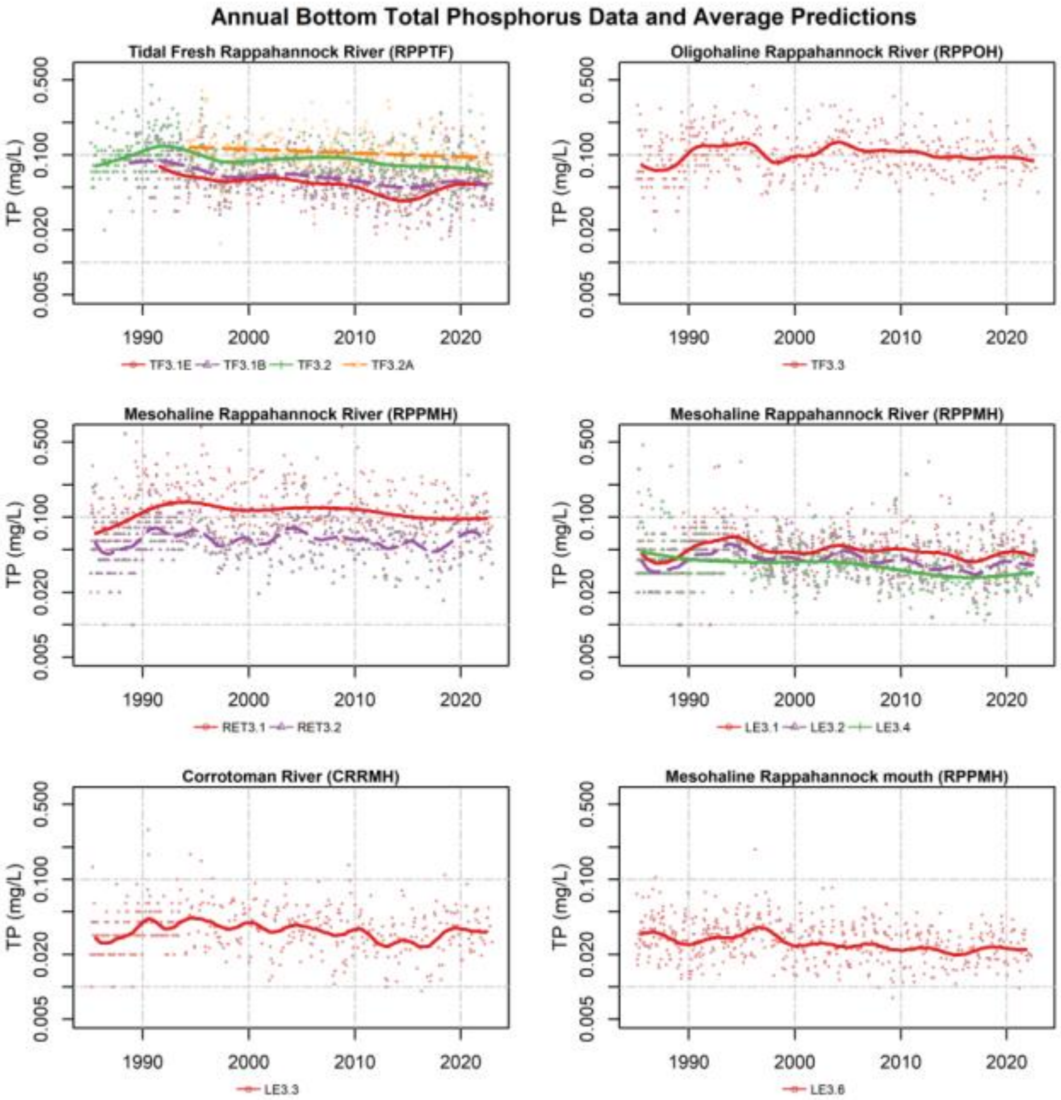

Figure A4. Annual bottom total phosphorus data (dots) and average long-term pattern generated from non-flow adjusted Generative Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

- Surface Dissolved Inorganic Nitrogen

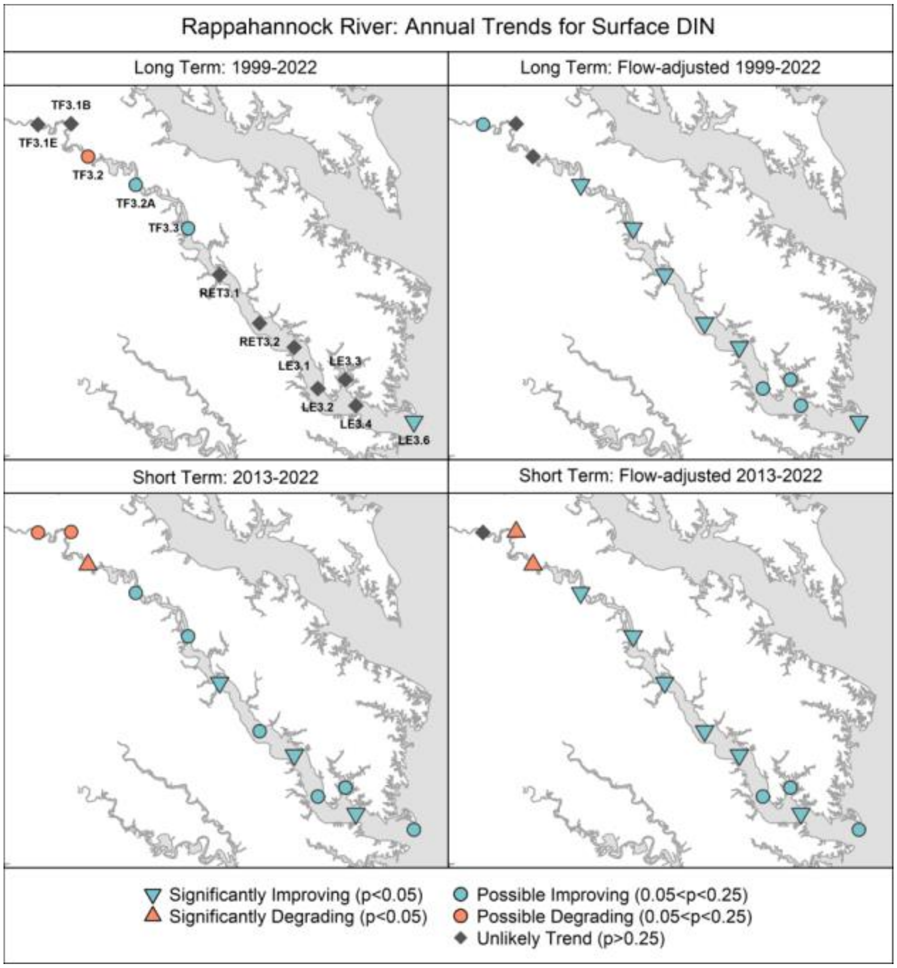

Figure A5. Annual flow-adjusted surface dissolved inorganic nitrogen trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

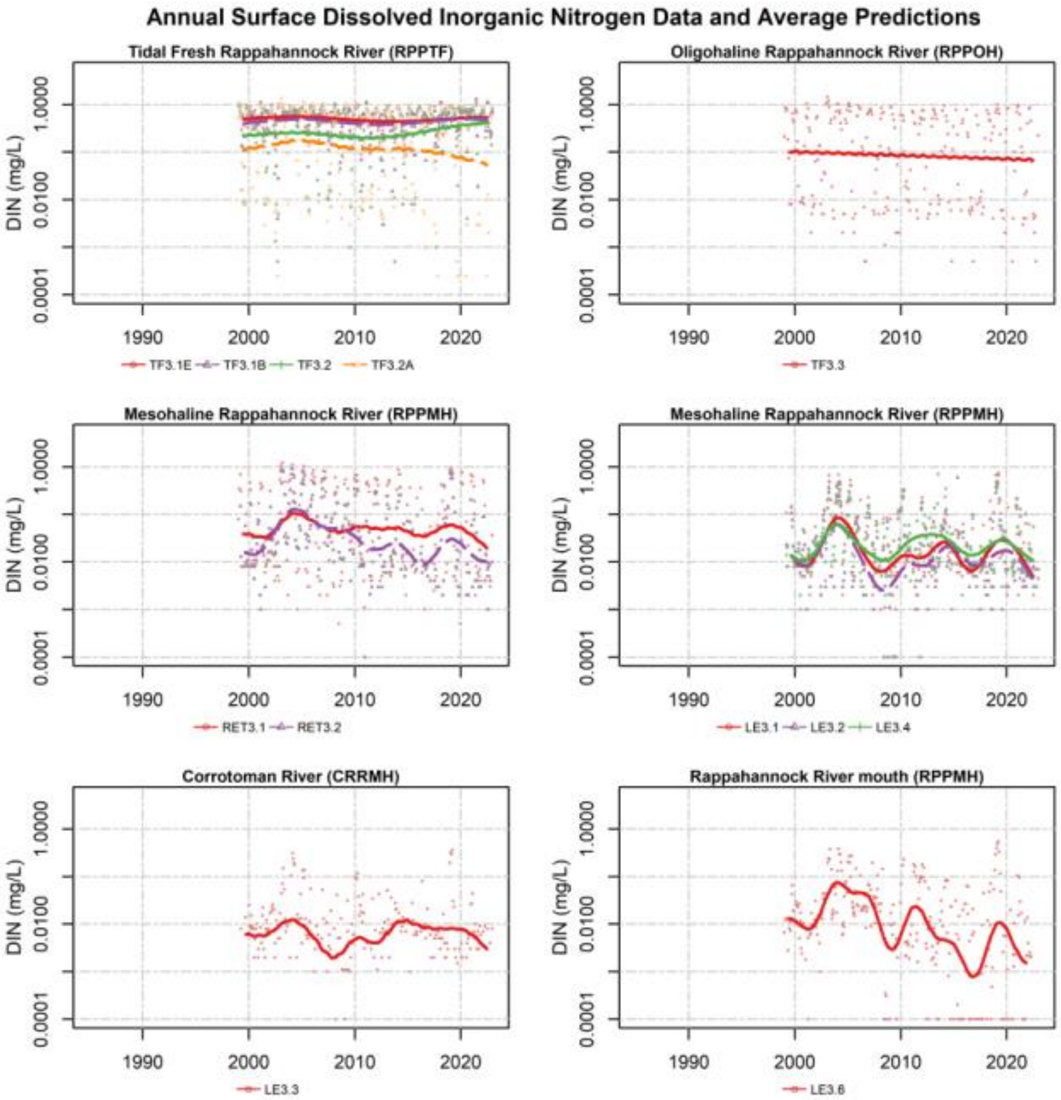

Figure A6. Annual surface dissolved inorganic nitrogen data (dots) and average long-term pattern generated from non-flow adjusted Generative Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

- Surface Orthophosphate

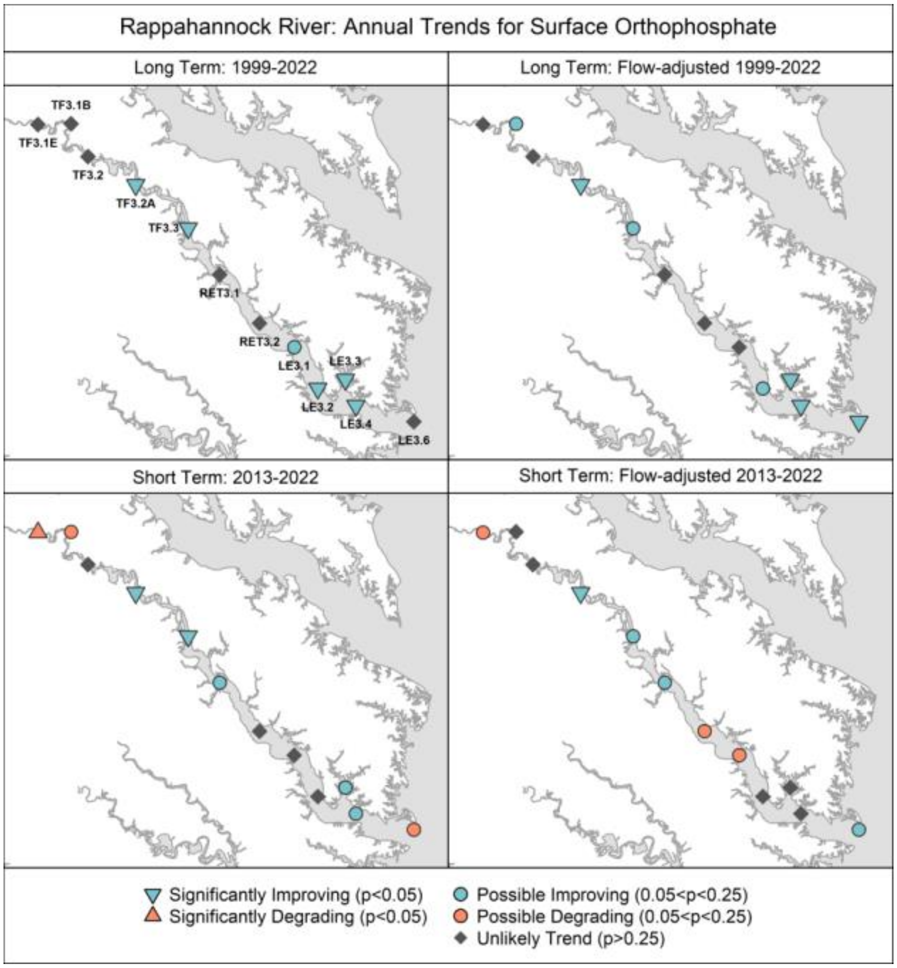

Figure A7. Annual flow-adjusted surface orthophosphate trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

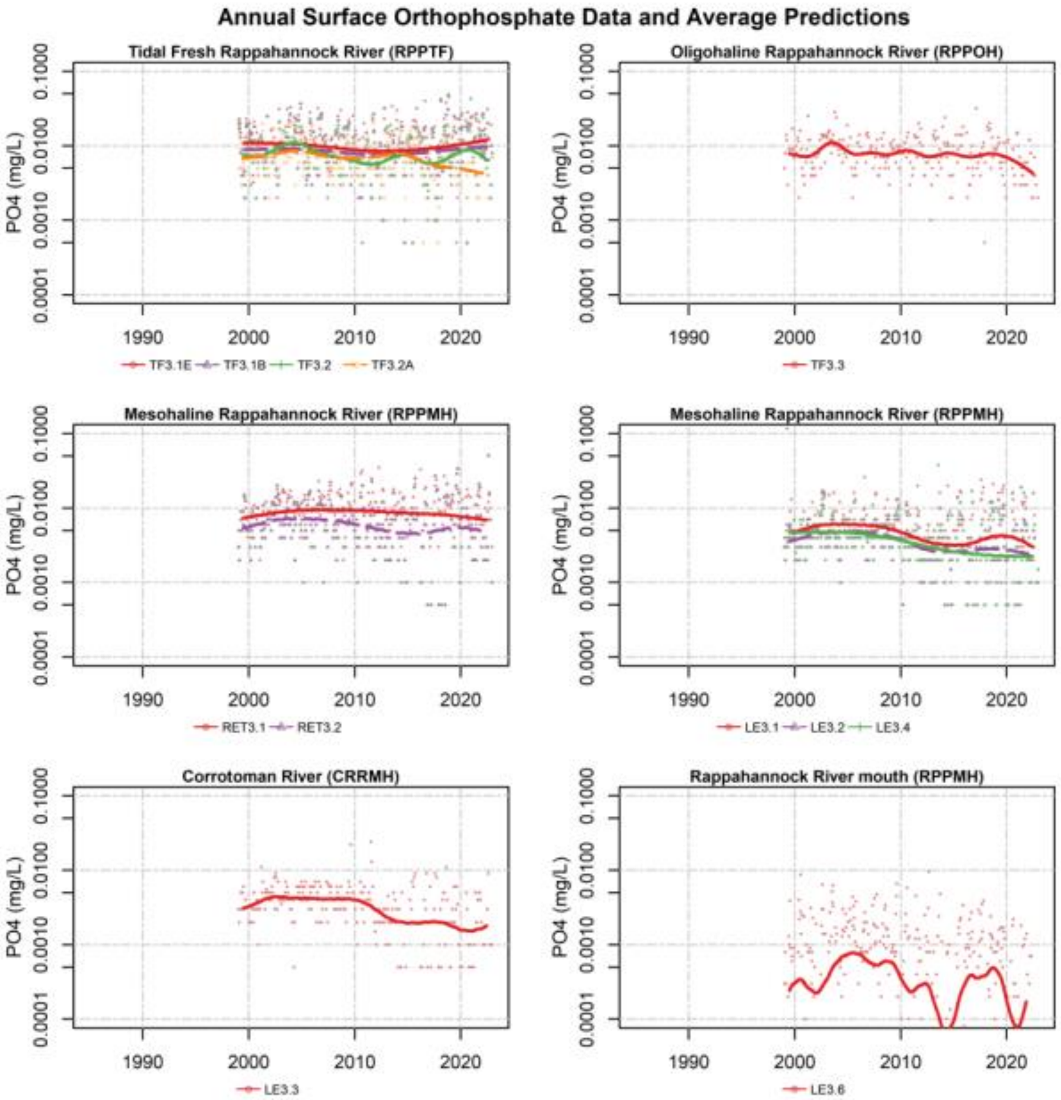

Figure A8. Annual surface orthophosphate data (dots) and average long-term pattern generated from non-flow adjusted Generative Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

- Surface Total Suspended Solids

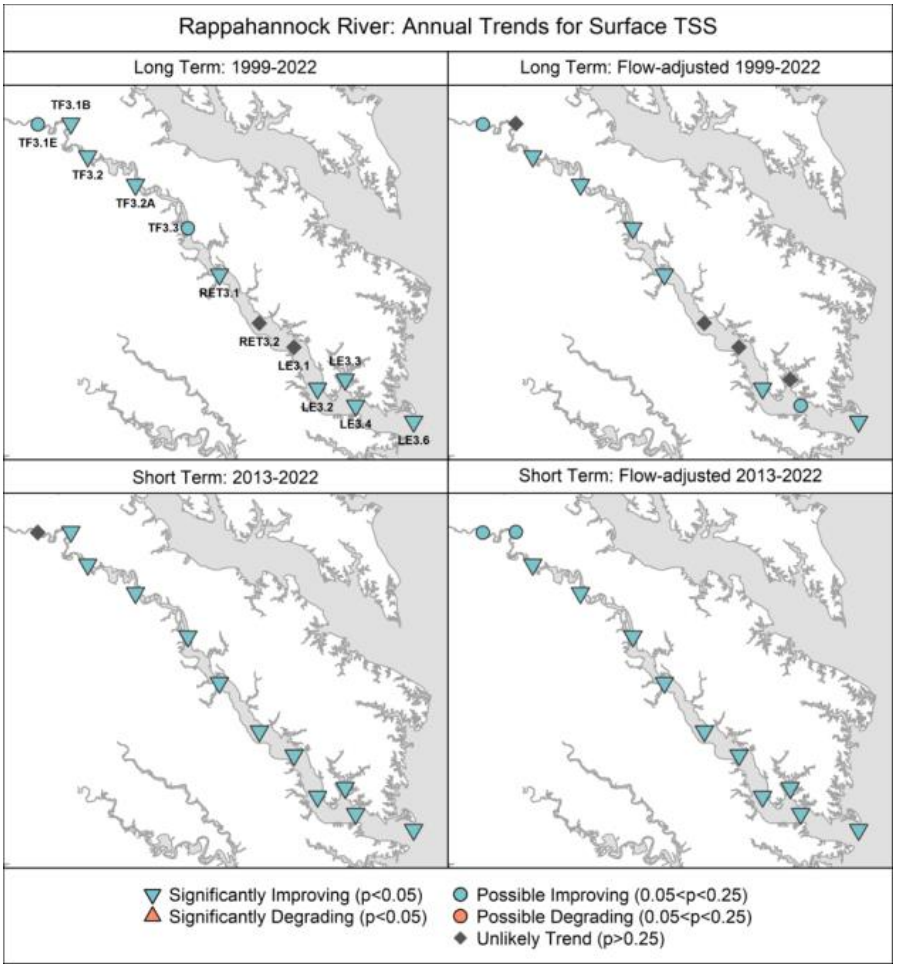

Figure A9. Annual flow-adjusted surface total suspended solids trends as calculated using Generalized Additive Models (Murphy et al. 2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

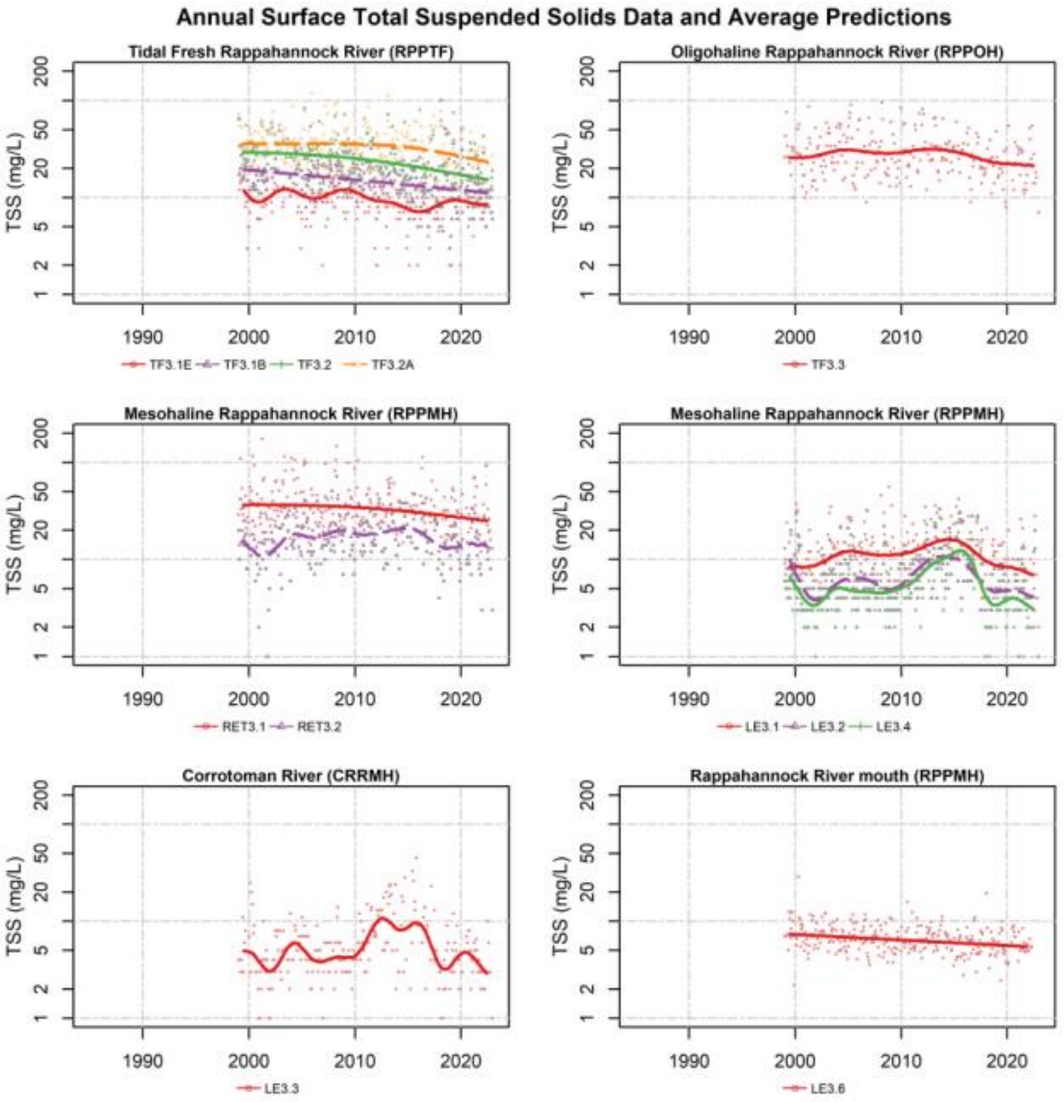

Figure A10. Annual surface total suspended solids (dots) and average long-term pattern generated from non-flow adjusted Generative Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

- Summer Surface Dissolved Oxygen

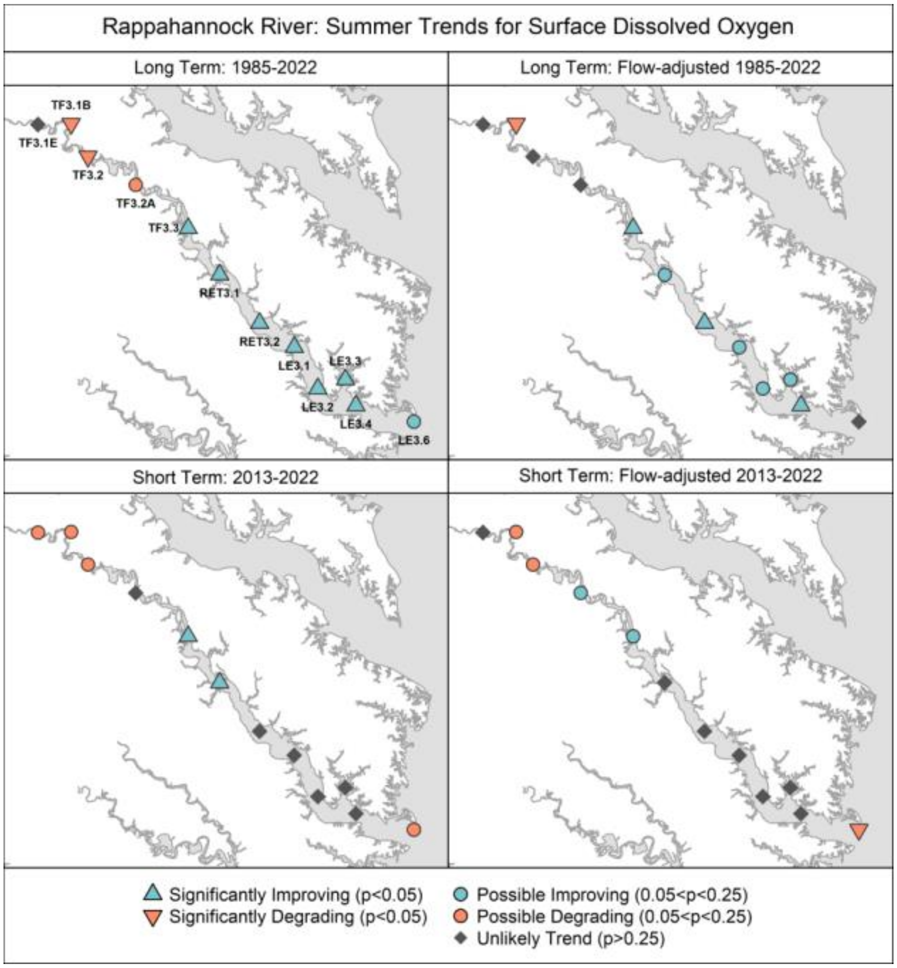

Figure A11. Annual flow-adjusted surface summer dissolved oxygen trends as calculated using Generalized Additive Models (Murphy et al. 2019. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

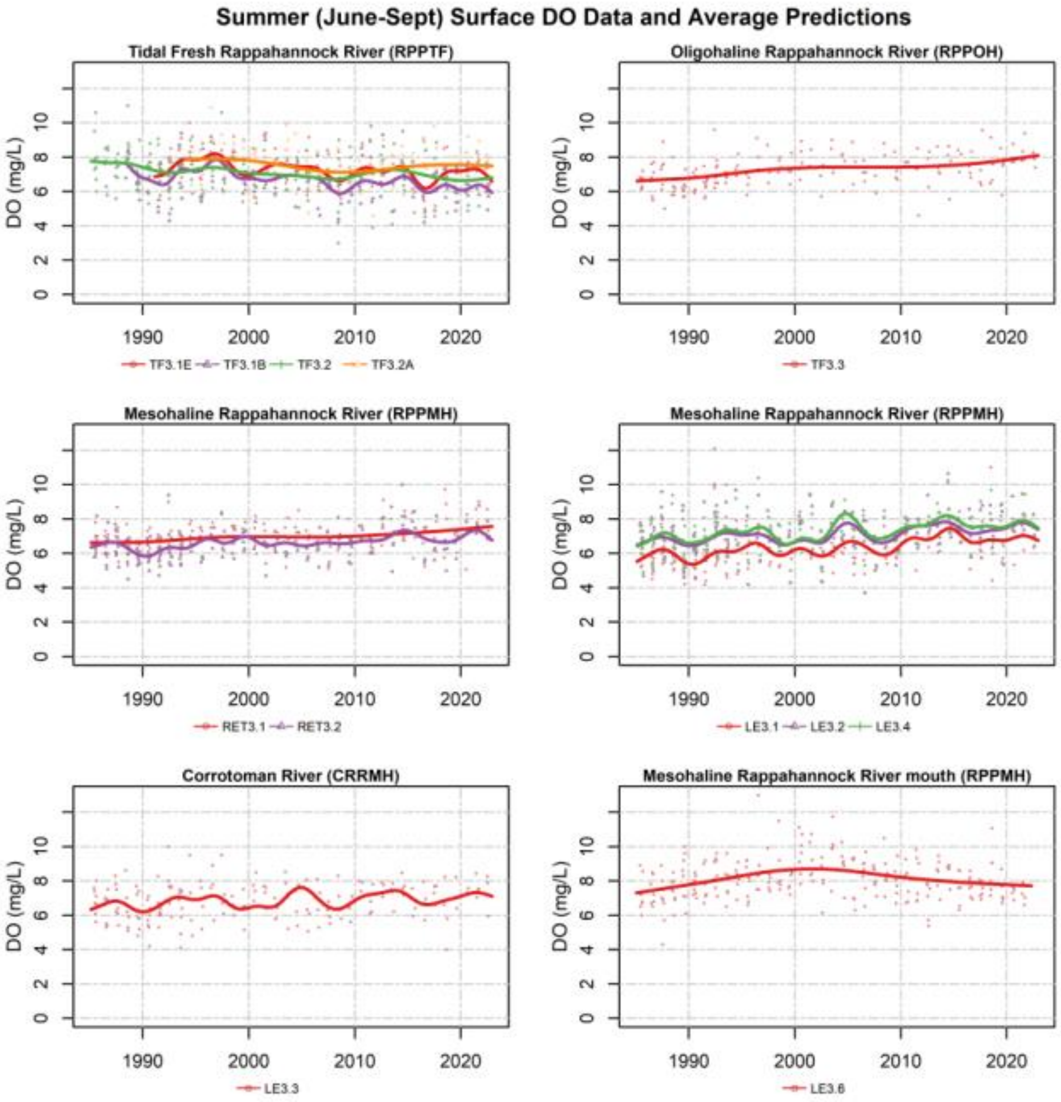

Figure A12. Annual surface dissolved oxygen data (dots) and average long-term pattern generated from non-flow adjusted Generative Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.