Rappahannock Tributary Summary:

A summary of trends in tidal water quality and associated factors, 1985-2018.

June 7, 2021

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

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Contents

1. Purpose and Scope 3
2. Location 4
2.1 Watershed Physiography 4
2.2 Land Use 6
2.3 Tidal Waters and Stations 9
3. Tidal Water Quality Dissolved Oxygen Criteria Attainment 10
4. Tidal Water Quality Trends 13
4.1 Surface Total Nitrogen 13
4.2 Surface Total Phosphorus 16
4.3 Surface Chlorophyll *a:* Spring (March-May) 18
4.4 Surface Chlorophyll *a:* Summer (July-September) 20
4.5 Secchi Disk Depth 22
4.6 Summer Bottom Dissolved Oxygen (June-September) 24
5. Factors Affecting Trends 26
5.1 Watershed Factors 26
5.1.1 Effects of Physical Setting 26
5.1.2 Estimated Nutrient and Sediment Loads 28
5.1.3 Expected Effects of Changing Watershed Conditions 31
5.1.4 Best Management Practices (BMPs) Implementation 34
5.1.5 Flow-Normalized Watershed Nutrient and Sediment Loads 35
5.2 Tidal Factors 35
5.3 Insights on Change in the Rappahannock 39
6. Summary 40
References 41
Appendix 45

1. Purpose and Scope

The Rappahannock Tributary Summary outlines change over time in a suite of monitored tidal water quality parameters and associated potential drivers of those trends for the time period 1985 – 2018, 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), spring and summer (June, July, August)) surface chlorophyll *a*, summer bottom dissolved oxygen (DO) concentrations, and Secchi disk depth (a measure of water clarity). Results for annual surface water temperature, bottom TP, bottom TN, surface ortho-phosphate (PO4), surface dissolved inorganic nitrogen (DIN), surface total suspended solids (TSS), and summer surface DO concentrations are provided in an Appendix. 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 biological factors such as phytoplankton biomass and the presence of submersed aquatic vegetation. Continuing to track water quality response and investigating these influencing factors are important steps to understanding water quality patterns and changes in the Rappahannock River.

2. Location

The Rappahannock River watershed covers approximately 4% of the Chesapeake Bay Watershed. Its watershed spans approximately 6,530 km^2 (Table 1.). Major tributaries to the Rappahannock River include the Rapidan, Robinson, and Corrotoman rivers. The Rappahannock river watershed is contained within one state, Virginia.

Tributary Name	Watershed Area km2
MARYLAND MAINSTEM	71967
POTOMAC	36611
JAMES	25831
YORK	6537
RAPPAHANNOCK	6530
LOWER EASTERN SHORE	4532
MARYLAND UPPER EASTERN SHORE	2441
PATUXENT	2236
VIRGINIA MAINSTEM	2052
CHOPTANK	1844
PATAPSCO-BACK	1647
MARYLAND UPPER WESTERN SHORE	1523
MARYLAND LOWER WESTERN SHORE	439

Table 1. "Watershed areas for each of the thirteen tributary or tributary groups for which Tributary Trends summaries have been produced. All 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 1). 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.

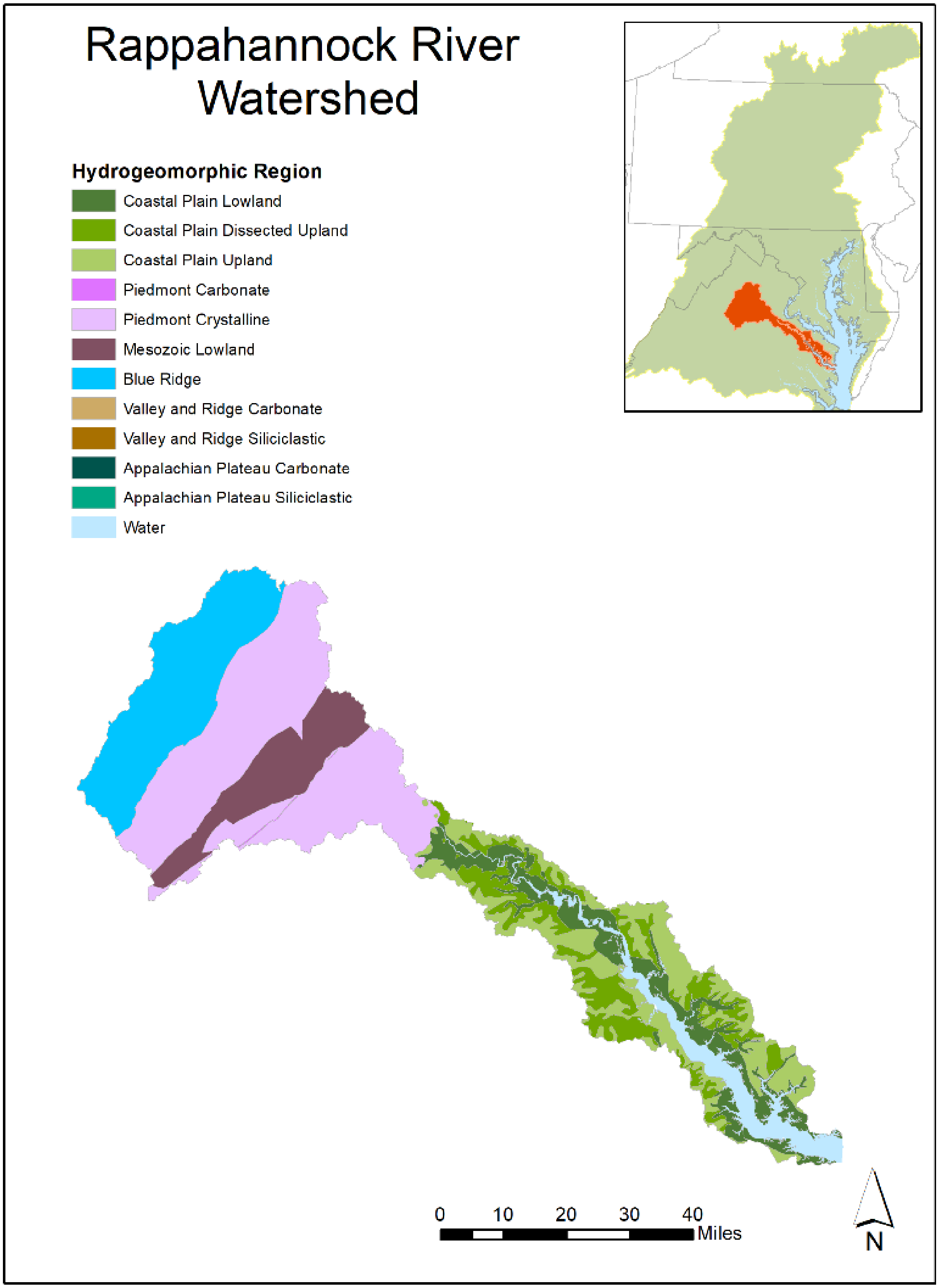

Figure 1. Distribution of physiography in the Rappahannock River watershed. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

2.2 Land Use

Land use in the Rappahannock watershed is dominated (66%) by natural areas. Urban and suburban land areas have increased by 77,361 acres since 1985, agricultural lands have decreased by 50,570 acres, and natural lands have decreased by 26,597 acres. Correspondingly, the proportion of urban land in this watershed has increased from 6% in 1985 to 10% in 2019 (Figure 2).

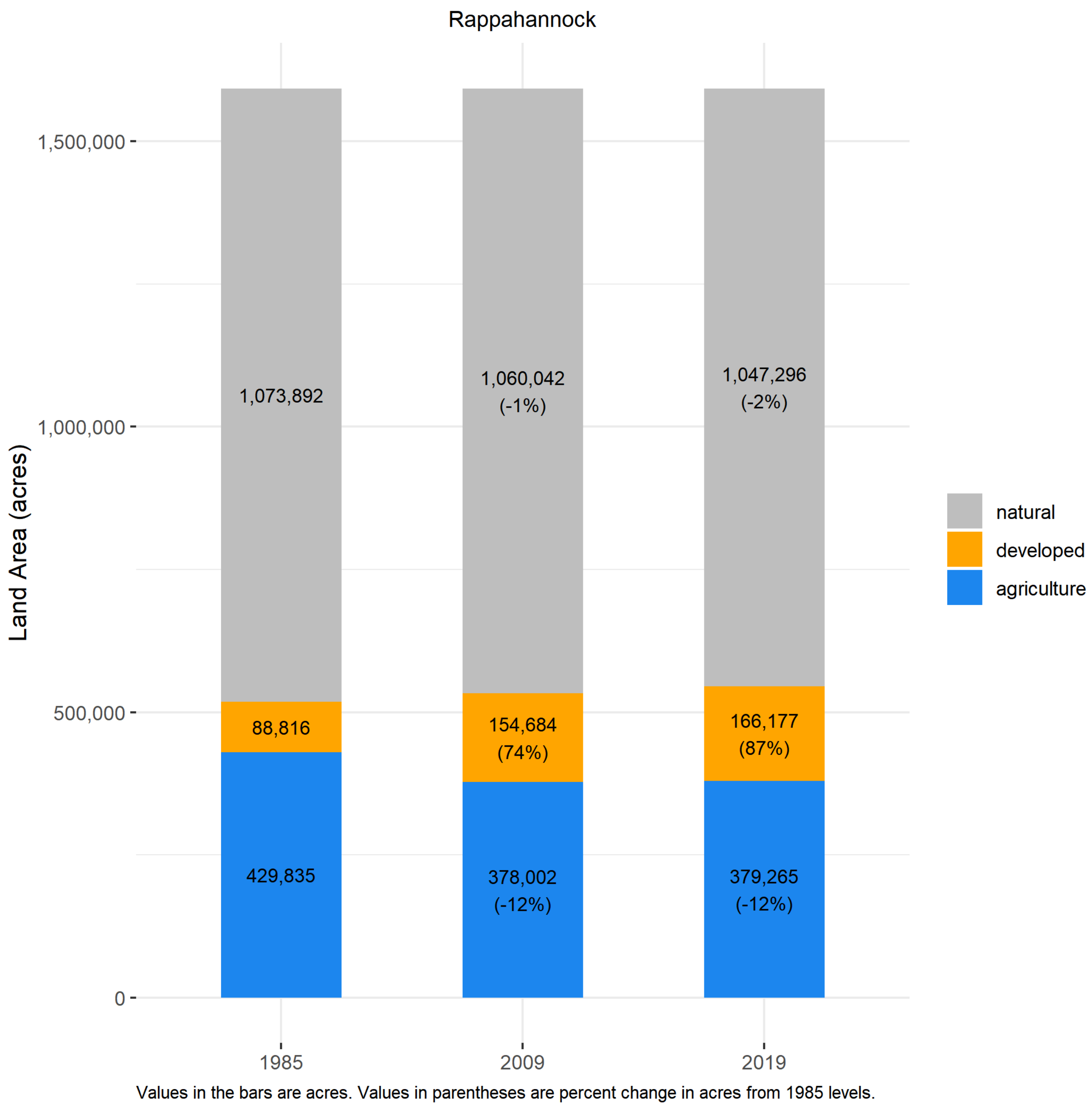

Figure 2. Distribution of land uses in the Rappahannock watershed. Percentages are the percent change from 1985 for each source sector.

In general, developed lands in the 1970s were concentrated within towns and major metropolitan areas. Since then, developed and semi-developed lands have increased around these areas, as well as expanding into previously undeveloped regions (Figure 3). 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.

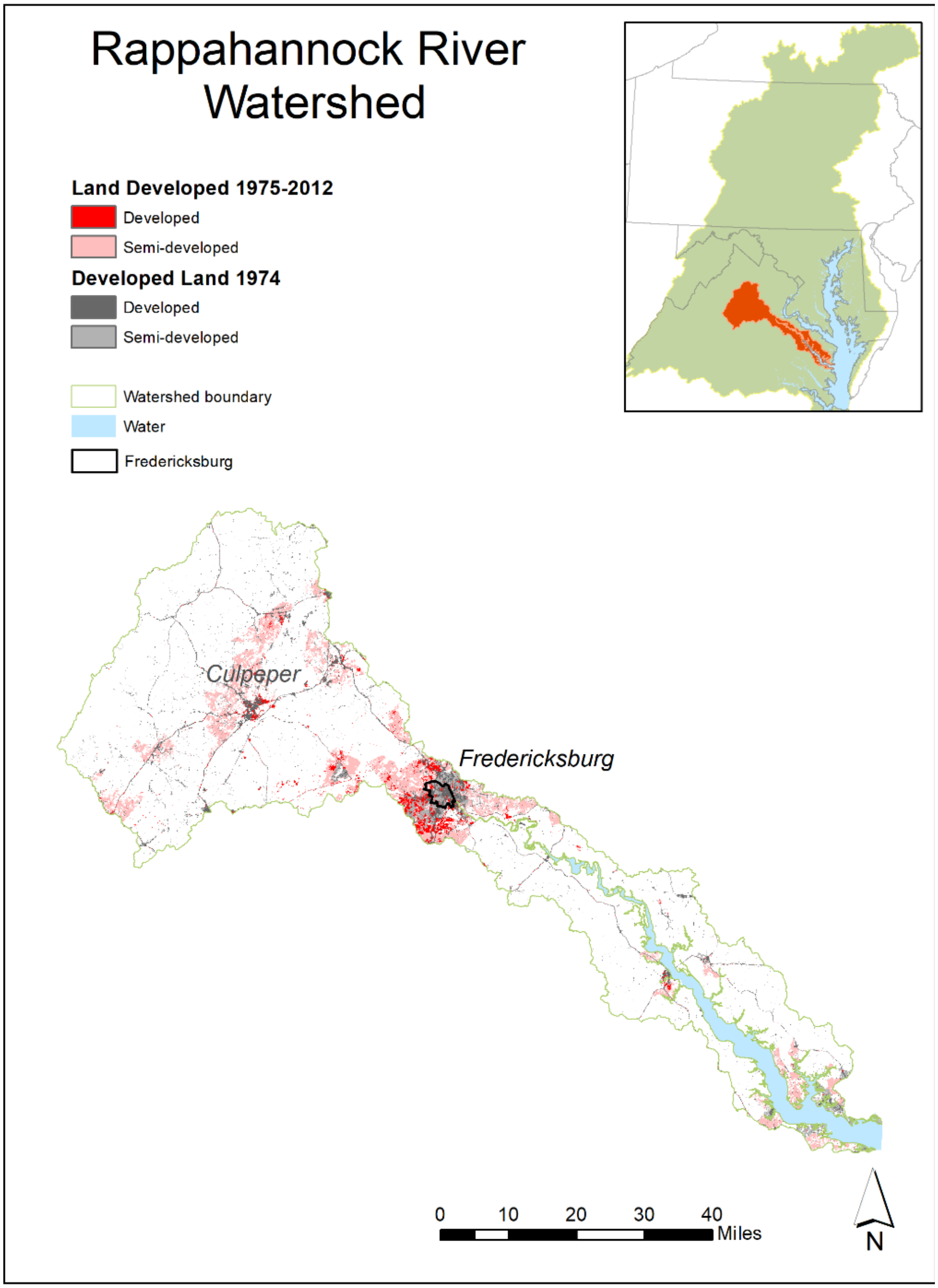

Figure 3. Distribution of developed land in the Rappahannock River watershed. Derived from Falcone (2015). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

2.3 Tidal Waters and Stations

For the purposes of water quality standards assessment and reporting, the tidal waters associated with the Rappahannock River are divided into three segments (U.S. Environmental Protection Agency, 2004): the Tidal Fresh (RPPTF), Oligohaline (RPPOH), and Mesohaline (RPPMH). One tributary of the Rappahannock – the Corrotoman River – is also represented (Figure 4).

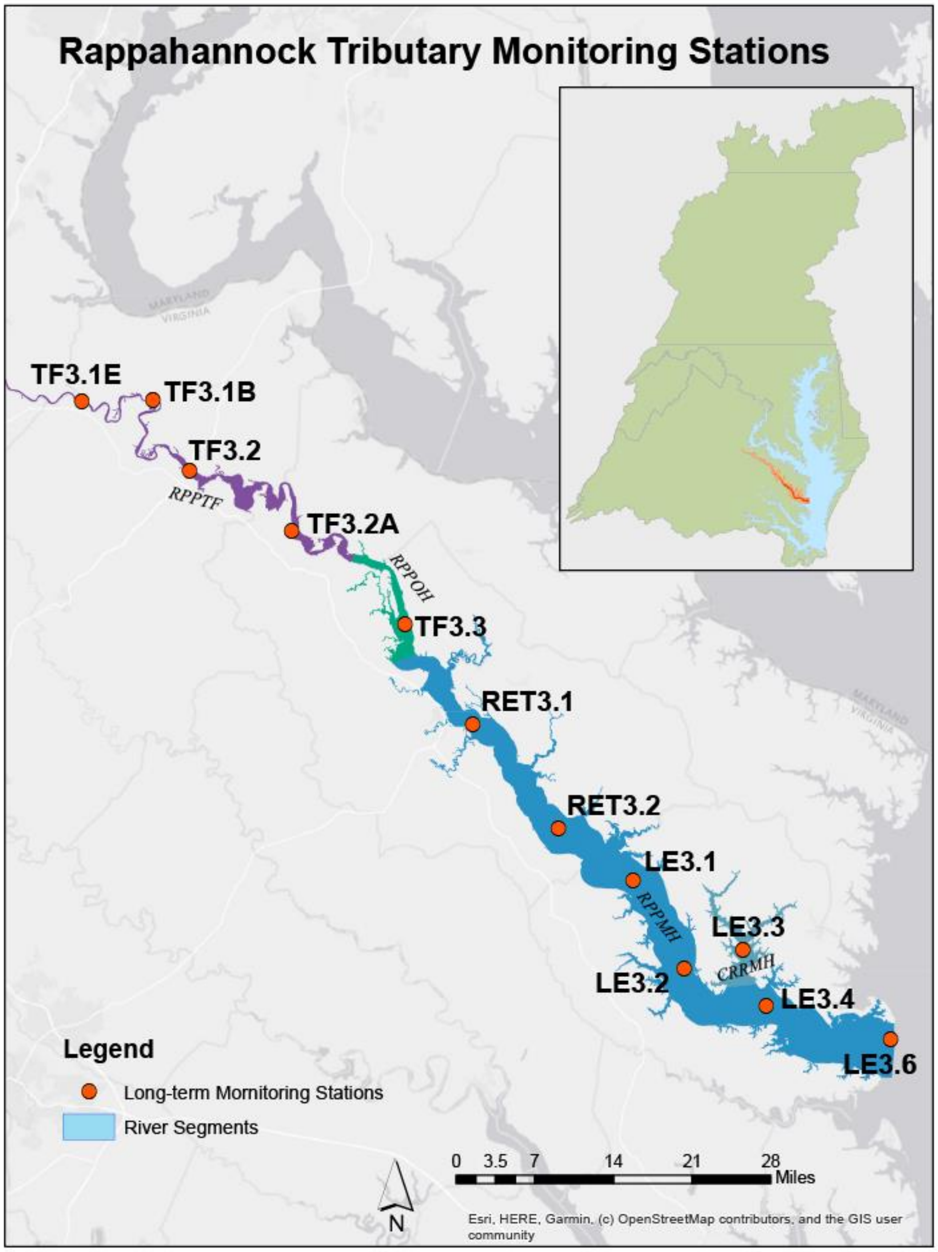

Figure 4. Map of tidal Rappahannock River segments and long-term monitoring stations. Base map credit Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community, World Geodetic System 1984.

Long-term trends in water quality are analyzed by the Virginia Department of Environmental Quality (VADEQ) and Old Dominion University (ODU) at 12 stations stretching from the tidal fresh region near Fredericksburg, VA to the mouth of the Rappahannock flowing into Chesapeake Bay (Figure 4). Water quality data at these stations are also used to assess attainment of dissolved oxygen (DO) water quality criteria. All tidal water quality data analyzed for this summary 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.

3. Tidal Water Quality Dissolved Oxygen Criteria Attainment

Multiple water quality standards were developed for the tidal Rappahannock to protect aquatic living resources (U.S. Environmental Protection Agency, 2003; Tango and Batiuk, 2013). These standards include specific criteria for dissolved oxygen (DO) and water clarity/underwater bay grasses. For the purposes of this summary, a record of the evaluation results indicating whether different Rappahannock segments have met or not met either 30-day or instantaneous Open Water (OW), Deep Water (DW), and Deep Channel (DC) DO criteria over time is shown below (Zhang *et al.*, 2018a; Hernandez Cordero *et al.*, 2020). While analysis of water quality standards attainment is not the focus of this summary, the results (Tables 2 and 3) provide context for the importance of understanding factors affecting water quality trends. For more information on water quality standards, criteria, and standards attainment, visit the CBP's "Chesapeake Progress" website at www.chesapeakeprogress.com. In the recent period (2016-2018), the only assessed criterion that was met was the 30-day mean summer open water criterion in the oligohaline segment (Zhang *et al.*, 2018b).

Table 2. Open Water summer DO criterion evaluation results (30-day mean June-September assessment period). Green indicates the criterion was met. White indicates that the criterion was not met.

time period	RPPTF	RPPOH	RPPMH	CRRMH
1985-1987				
1986-1988				
1987-1989				
1988-1990				
1989-1991				
1990-1992				
1991-1993				
1992-1994				
1993-1995				
1994-1996				
1995-1997				
1996-1998				
1997-1999				
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2001-2003				
2002-2004				

2003-2005				
2004-2006				
2005-2007				
2006-2008				
2007-2009				
2008-2010				
2009-2011				
2010-2012				
2011-2013				
2012-2014				
2013-2015				
2014-2016				
2015-2017				
2016-2018				

Table 3. Deep Water summer DO (30-day mean) and Deep Channel (Instantaneous) DO criteria evaluation results. Green indicates that the criterion was met. White indicates that the criterion was not met.

time period	Deep Water	Deep Channel
	RPPMH	RPPMH
1985-1987		
1986-1988		
1987-1989		
1988-1990		
1989-1991		
1990-1992		
1991-1993		
1992-1994		
1993-1995		
1994-1996		
1995-1997		
1996-1998		
1997-1999		
1998-2000		
1999-2001		
2000-2002		
2001-2003		
2002-2004		
2003-2005		
2004-2006		
2005-2007		
2006-2008		
2007-2009		
2008-2010		
2009-2011		
2010-2012		
2011-2013		
2012-2014		
2013-2015		
2014-2016		

2015-2017		
2016-2018		

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 the possibility that conditions are degrading even if the criteria are currently being met. To illustrate this, the 2016-2018 attainment status for the OW summer and DC instantaneous DO criteria shown in Tables 2 and 3 are overlain with the 1985-2018 change in summer surface DO concentration and the 1985-2018 change in bottom summer DO concentrations, respectively (Figure 5). The 30-day mean OW summer DO criterion was met in one of the four segments for the 2016-2018 period. Surface oxygen is increasing in that segment that met the OW criterion and in the mesohaline segments, but decreasing in the tidal fresh segment where the OW criterion was not met. The DC water quality criterion was not met in the Rappahannock mesohaline segment where bottom oxygen trends are also decreasing.

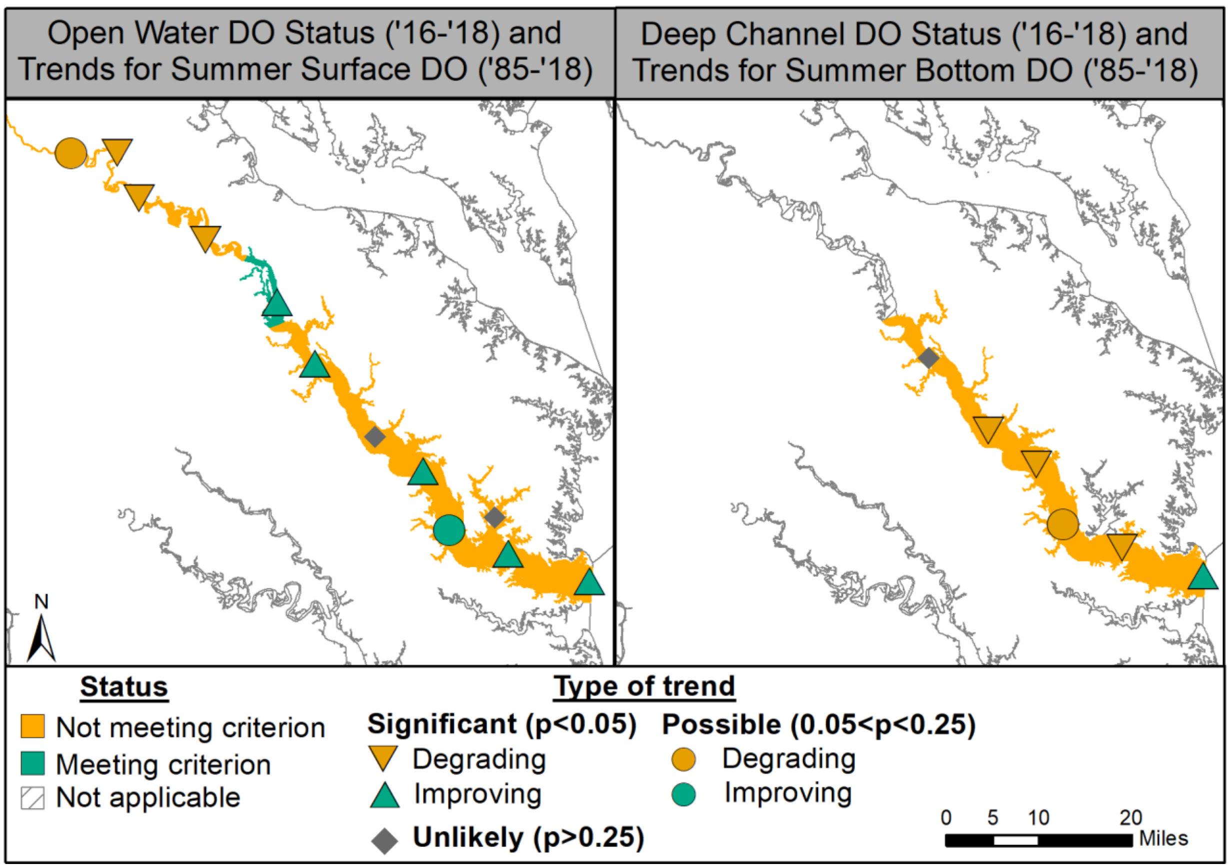


Figure 5. Pass-fail DO criterion status for 30-day OW summer DO and DC instantaneous DO designated uses in Rappahannock segments along with long-term trends in DO concentrations. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

4. Tidal Water Quality Trends

Tidal water quality trends are 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 station labeled in Figure 4. 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, see Murphy *et al.* (2019).

Results shown below in each set of maps (e.g., Figure 6) 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 the concentrations over time, as observed in the estuary. The second approach involves including monitored river flow or *in situ* salinity (as an aggregated measure of multiple river flows) in the GAM to explain some of the variation in the water quality parameter. From the results of this second approach, it is possible to estimate the "flow-adjusted" change over time, which gives a mean estimate of what the water quality parameter trend would have been if river flow had been average 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 all of these results as "flow-adjusted" for simplicity.

To determine if there has been a change over time (i.e., a trend) at a particular station for a given parameter, we compute a percent change between the estimates at beginning and end of a period of interest from the GAM fit. For each percent change computation, the level of statistical confidence can be computed as well. Change is called significant if $p < 0.05$ and possible if the p-value is up to 0.25. That upper limit is higher than usually reported for 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 7) 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.

4.1 Surface Total Nitrogen

Annual total nitrogen (TN) concentrations have decreased (improved) at almost all the mesohaline Rappahannock tidal stations over both the long-term and short-term, using both non-flow-adjusted results and adjusted results (Figure 6). There are also some improving trends at the most upstream tidal fresh stations, but in general the upper and middle estuary show no trends. Note that while the tidal monitoring program extends back to 1985, the long-term trend results shown for TN use data beginning in 1994 due to laboratory limitations in earlier years.

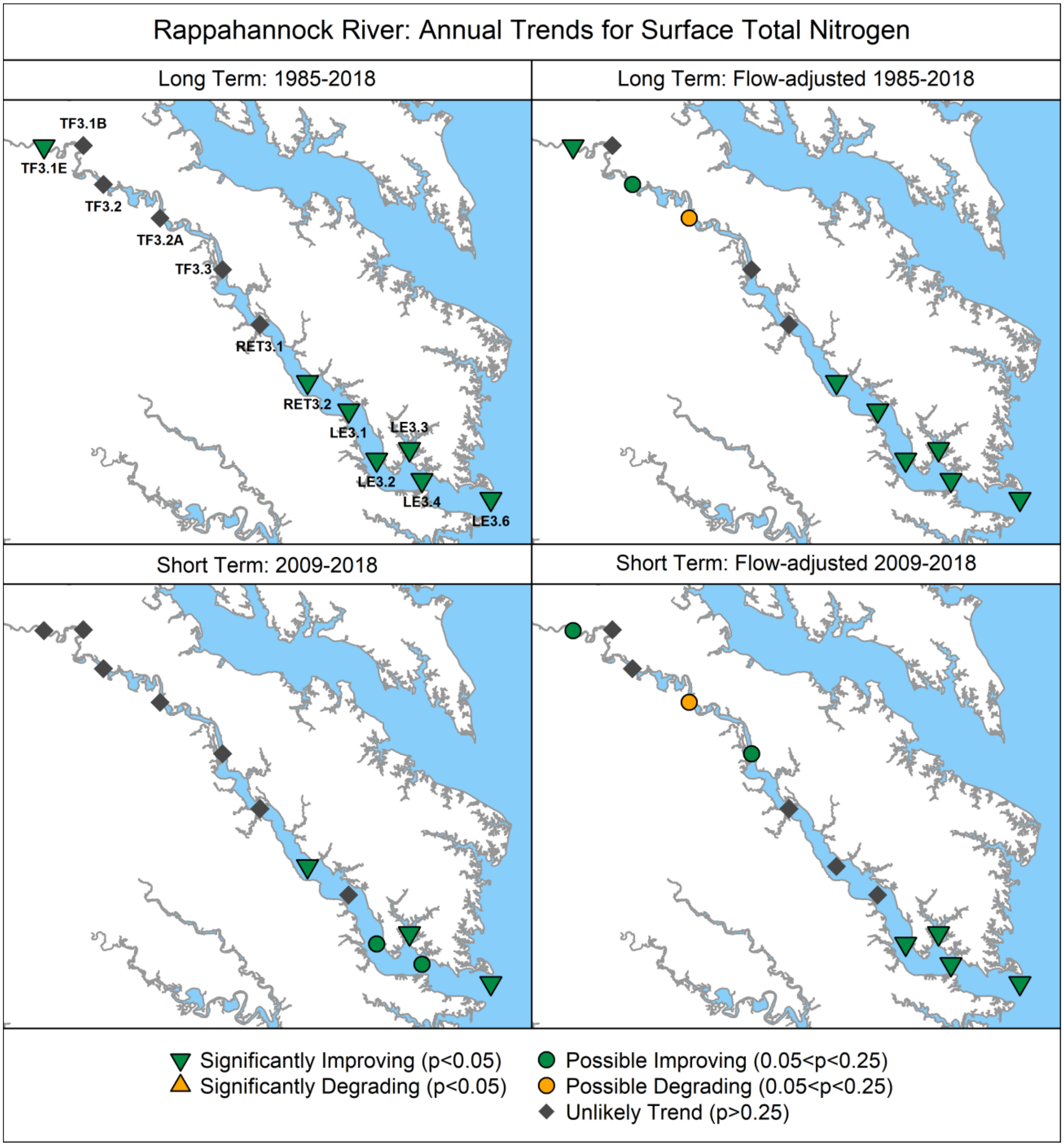


Figure 6. Surface TN trends. Note that for the Rappahannock most of these trends begin in 1994 due to data availability. Basse map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Slight decreases are apparent over the long-term at many stations in both the data and the non-flow-adjusted mean annual GAM estimates presented in Figure 7. An upswing in 2018 is clear in many of these graphs as well, which can be attributed to higher river flows in that year (Figure 7). 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.

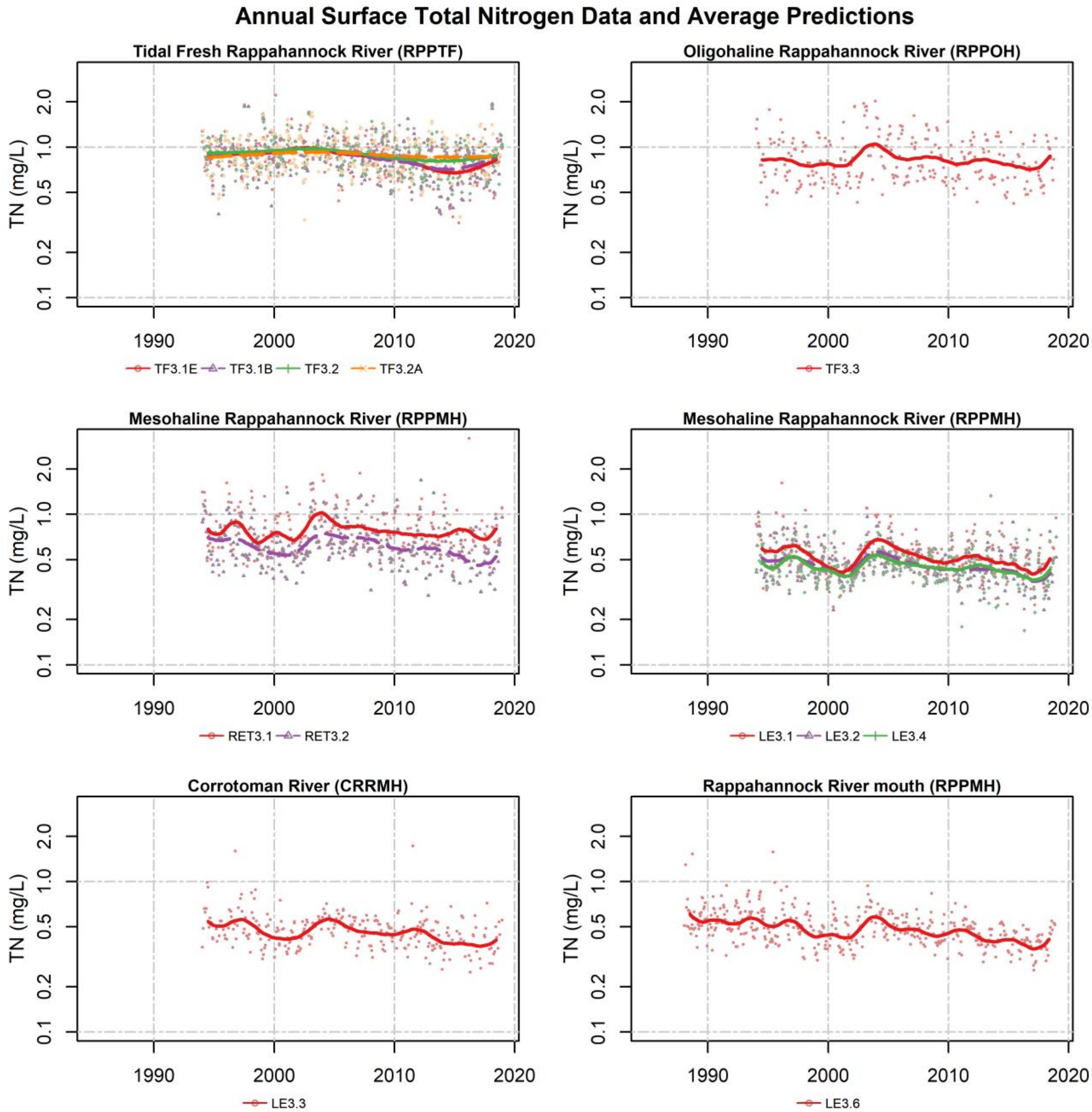


Figure 7. Surface TN data (dots) and average long-term pattern generated from non-flow adjusted GAM. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

4.2 Surface Total Phosphorus

Surface total phosphorus (TP) trends are improving consistently in the tidal fresh Rappahannock River (Figure 8). The middle and lower tributary trends are more mixed with lack of trends most common, but there are some possibly degrading and some improving trends.

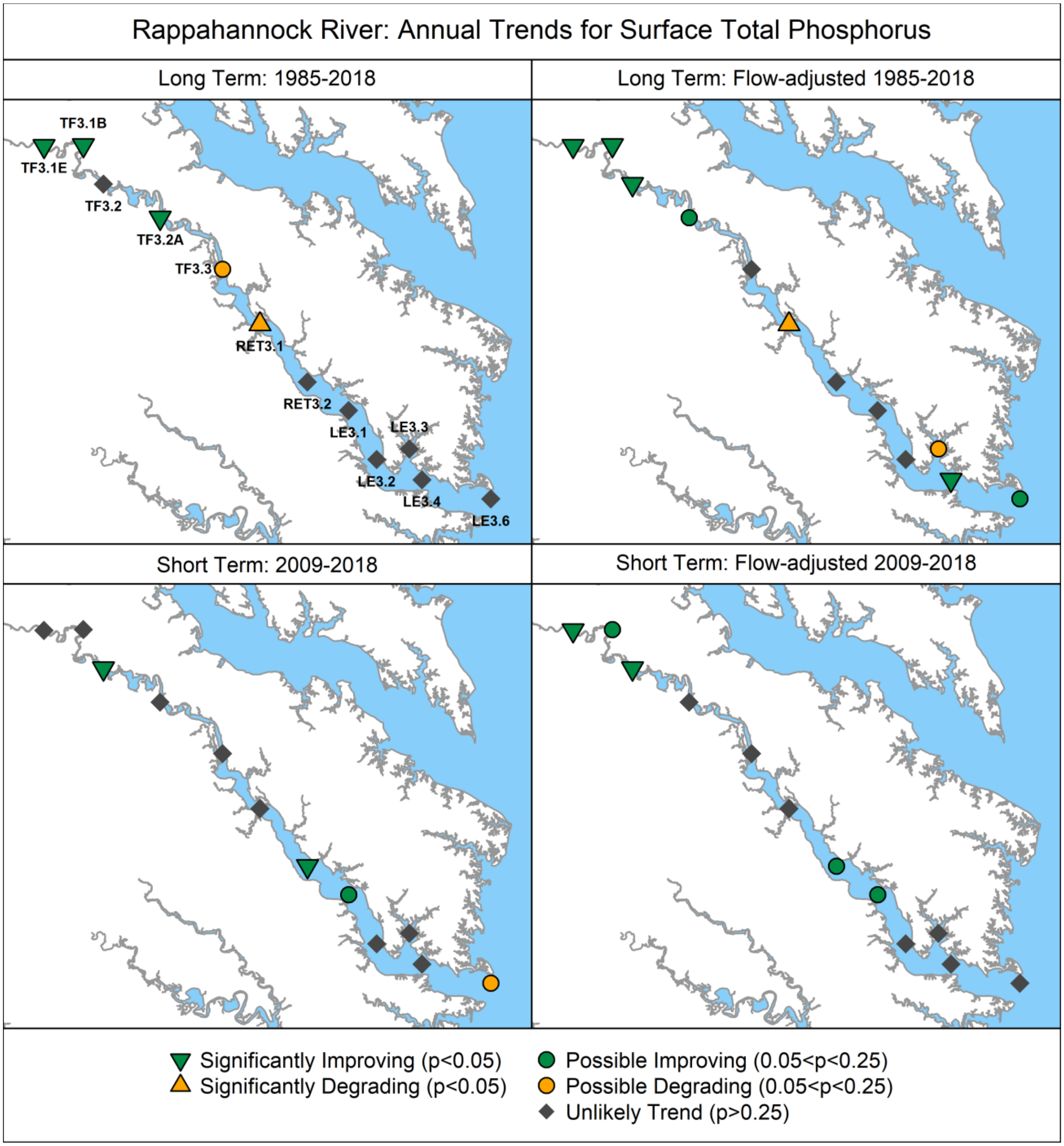


Figure 8. Surface TP trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

The most noticeable decrease in TP concentrations occurred at the tidal fresh stations (top left panel, Figure 9). Data and GAM estimates are fairly flat at other stations, consistent with the limited trends in TP beyond the tidal fresh (Figure 8).

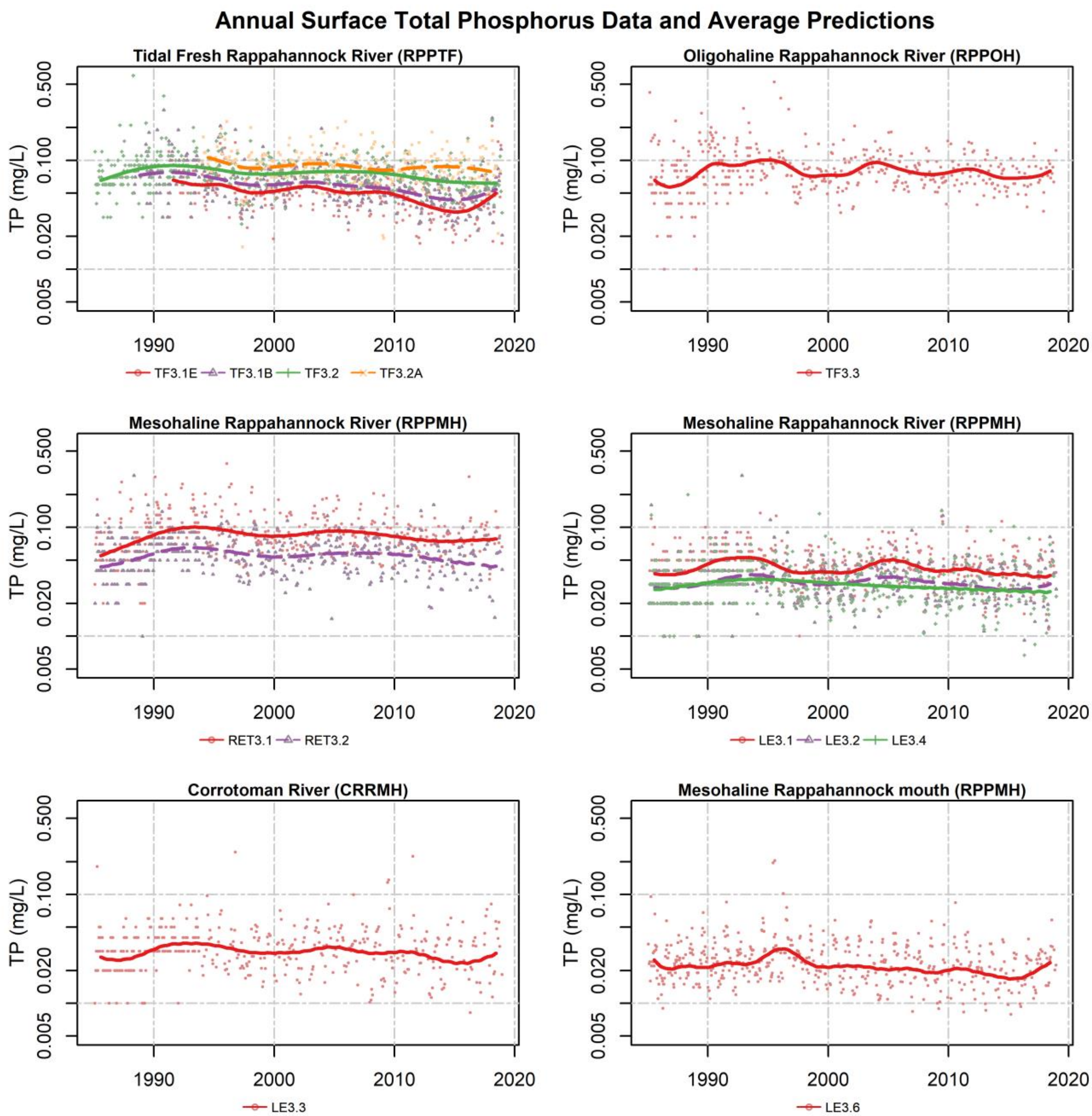


Figure 9. Surface TP data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

4.3 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 10) are mixed, with some significant degradations in the middle tributary stations over the long-term, and improvements in the tidal fresh and mesohaline. In the last 10 years, the possible improvements in the tidal fresh spring chlorophyll *a* persist, and otherwise possibly degrading or no trends were found at other stations.

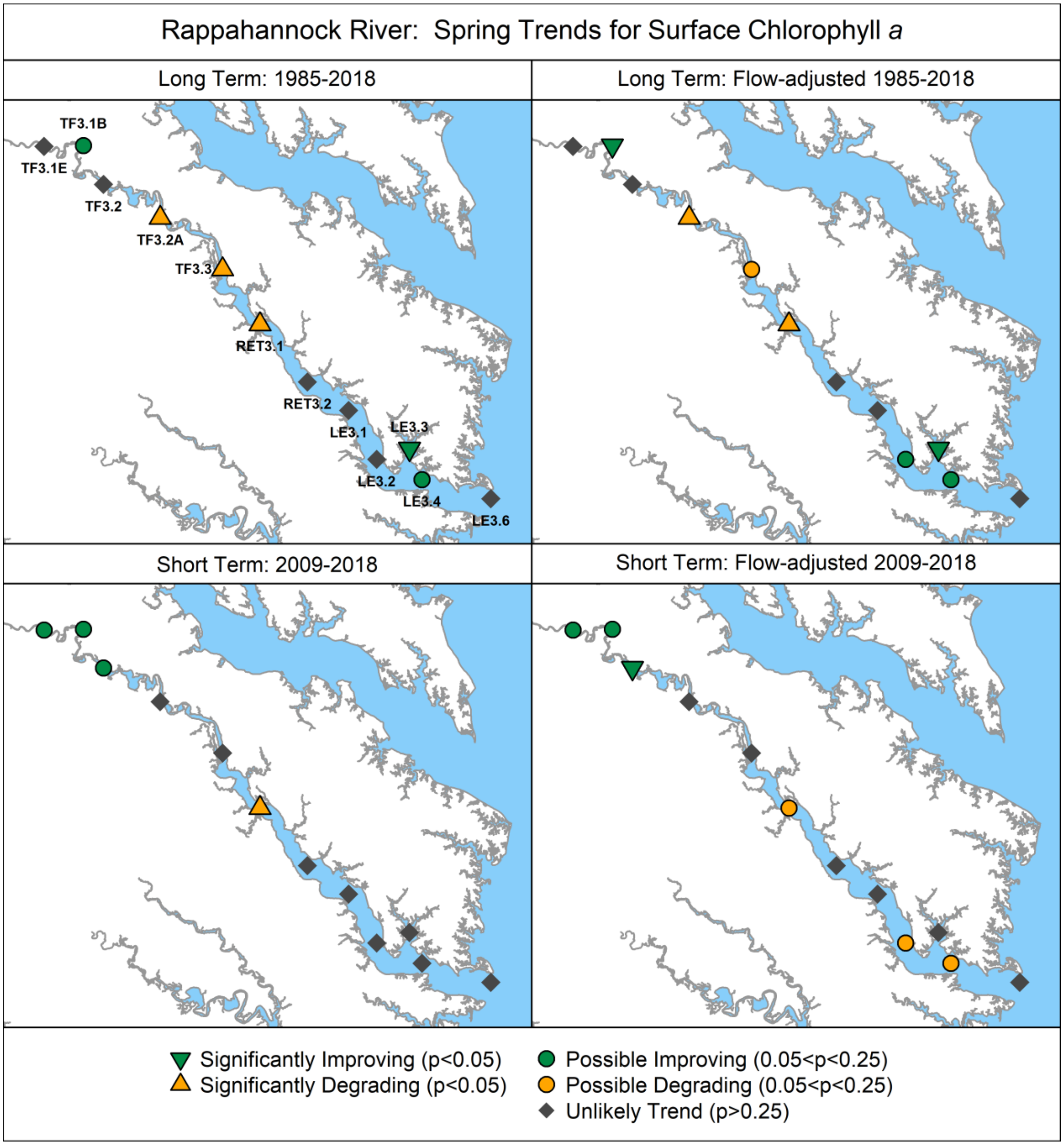


Figure 10. Surface spring (March-May) chlorophyll *a* trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

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 11). The increases in TF3.3 and RET3.1 are clear from the GAM graphics.

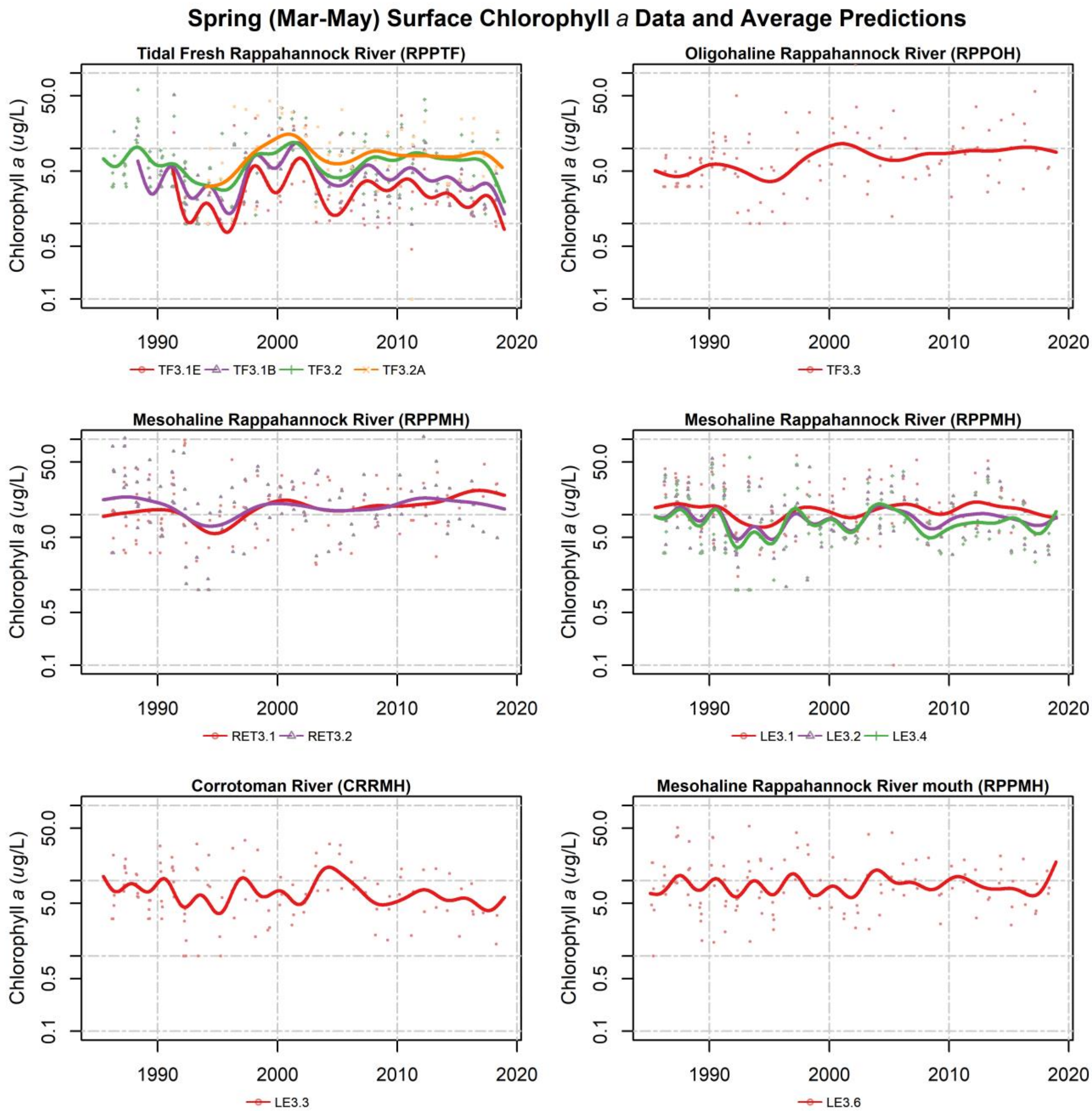


Figure 11. Surface spring Chlorophyll *a* data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent March-May data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean spring GAM estimates for the noted monitoring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

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

Summer long-term chlorophyll *a* trends show a distinct spatial pattern (Figure 12), with more degrading or likely degrading trends than in the spring. The three most upstream tidal fresh stations are consistently improving in over both the short- and long-term, with and without flow-adjustment. At almost all other stations, however, summer chlorophyll *a* concentrations have degraded. These degrading trends are more likely over the long- than the short-term.

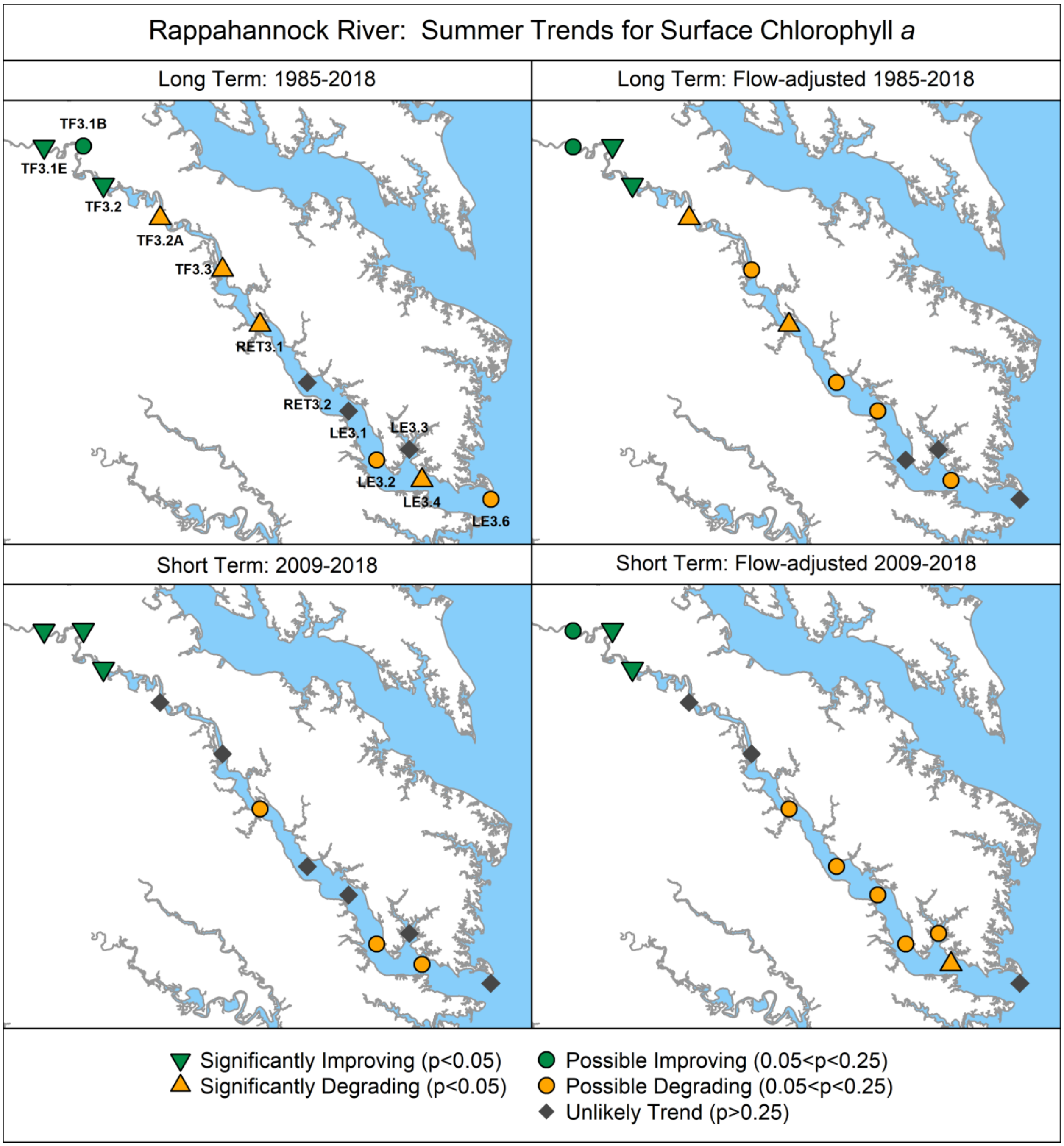


Figure 12. Surface summer (July-September) chlorophyll *a* trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

The magnitude of the summer tidal fresh chlorophyll *a* concentrations (Figure 13, top left panel) is much higher than it is in spring (Figure 11). The decreases at the tidal fresh stations are also clear, despite the large fluctuations. The increases at the more downstream stations are readily apparent, especially at TF3.3 and RET3.1.

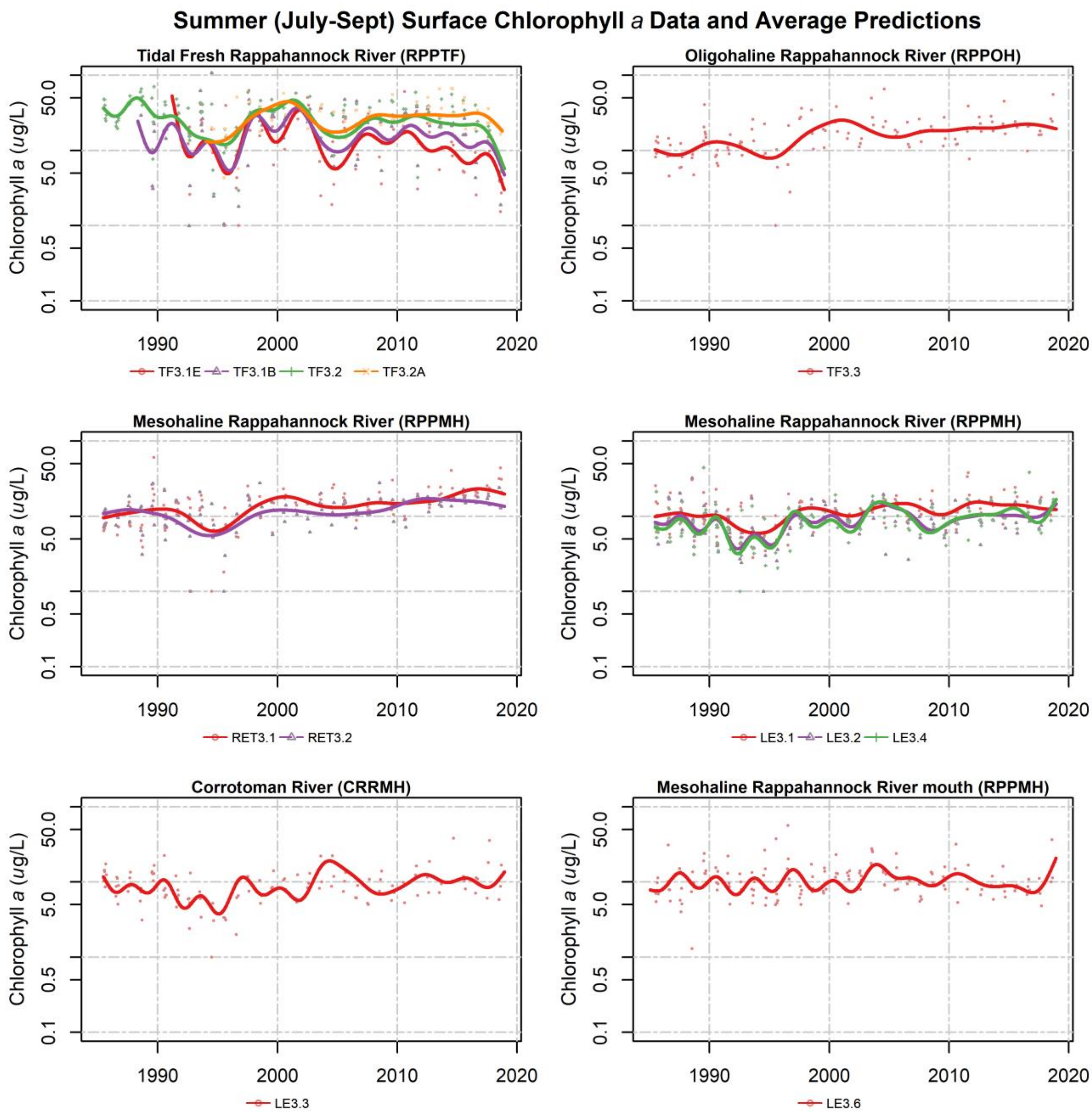


Figure 13. Surface summer chlorophyll *a* data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent July-September data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean summer GAM estimates for the noted 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 14). This spatial pattern is somewhat similar to summer chlorophyll *a* (Figure 12) with improvements in the tidal fresh and degradations or no trends elsewhere. The tidal fresh improvements are consistent over the long- and short-term, but degradations only appear at one station (TF3.3) over the short-term.

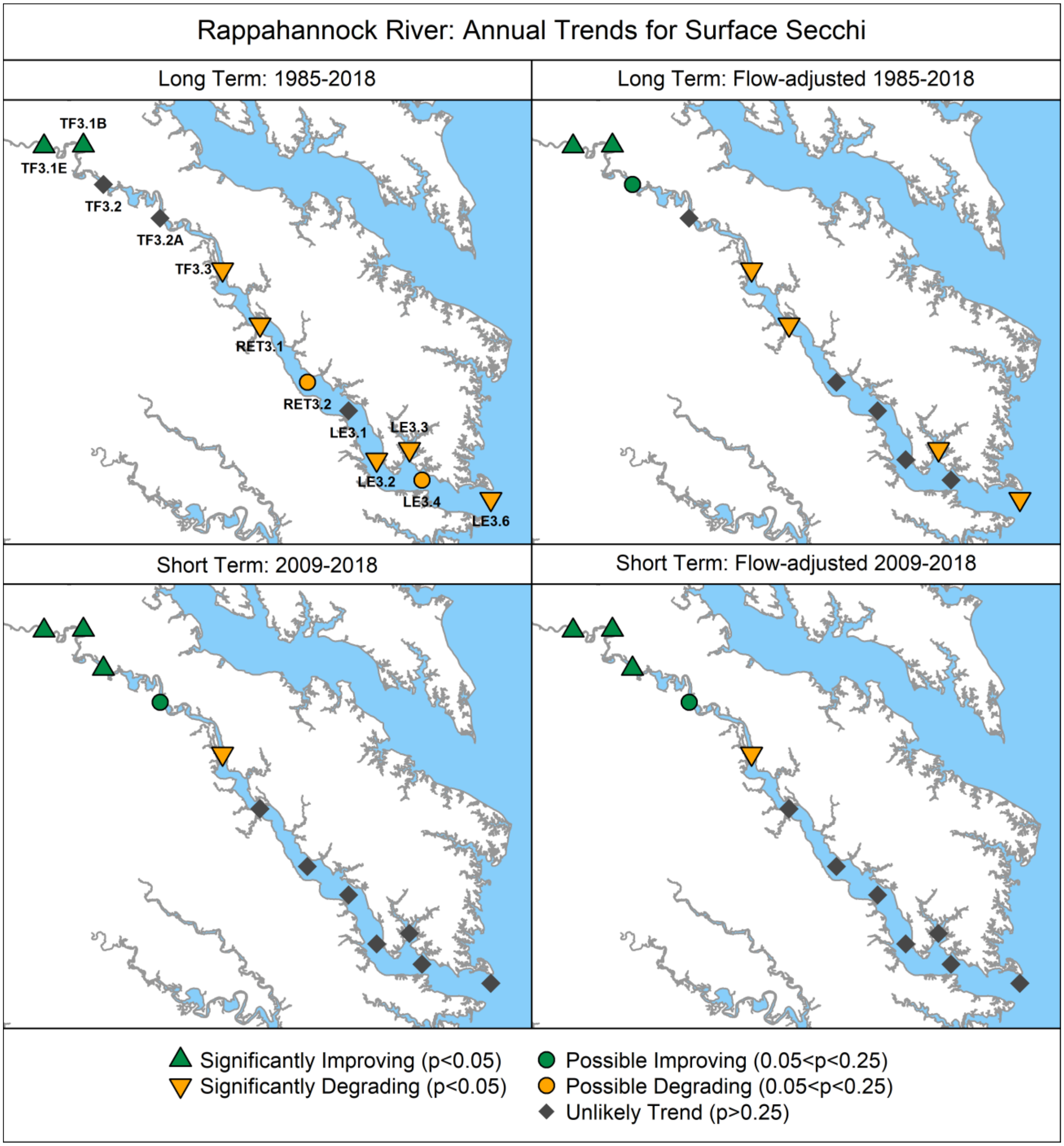


Figure 14. Annual Secchi depth trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Secchi depth is clearly deeper at the mesohaline stations than at the tidal fresh or oligohaline stations in the Rappahannock (Figure 15). The different trends in Secchi along the tributary are apparent here with improvements (i.e., increases in depth) at the tidal fresh stations and degradations elsewhere. These patterns are similar to chlorophyll *a*, and likely related.

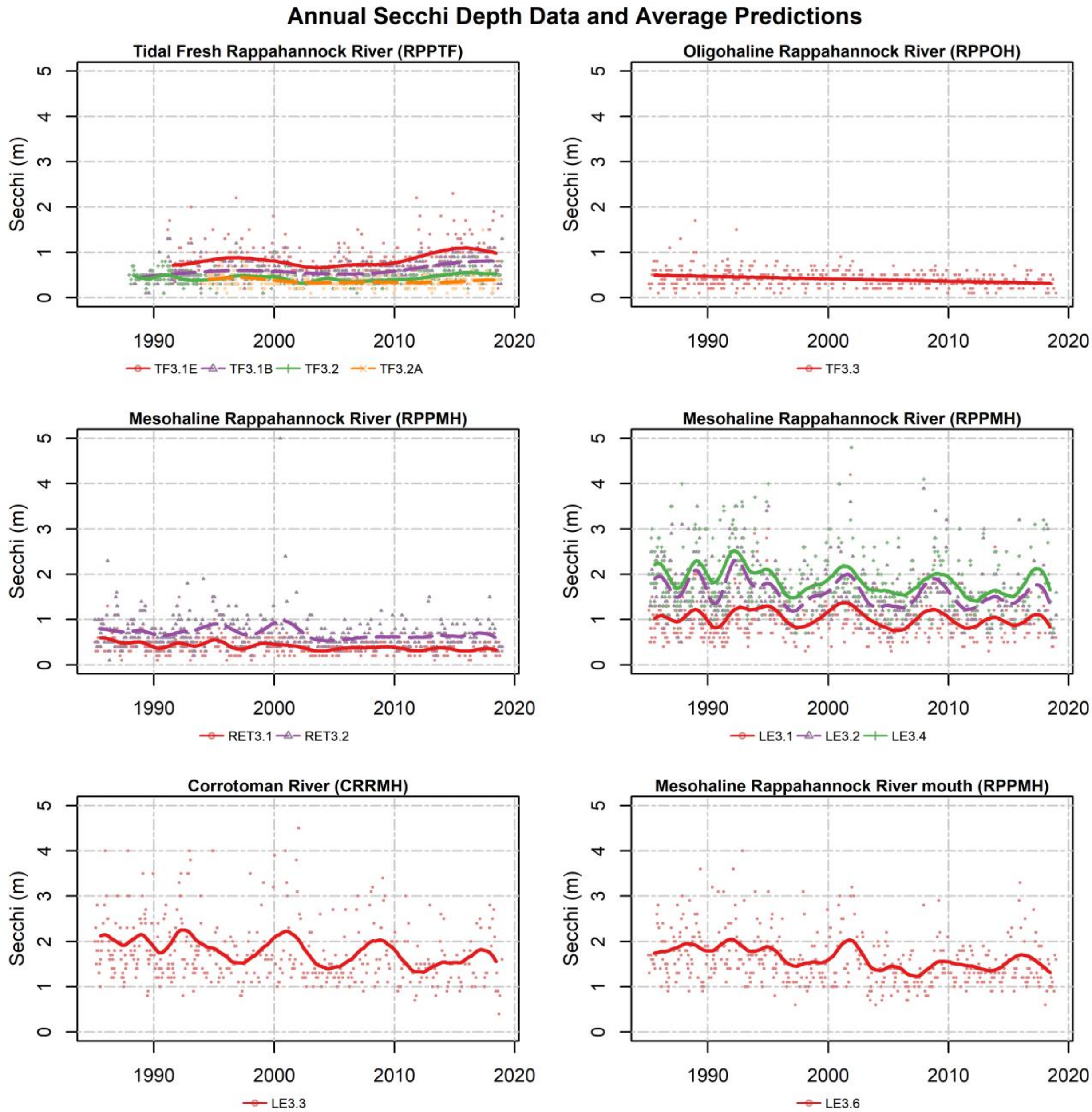


Figure 15. Annual Secchi depth data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

4.6 Summer Bottom Dissolved Oxygen (June-September)

Long-term Rappahannock bottom oxygen concentrations have degraded at almost all stations, except the middle two stations (Figure 16). Over the short-term, the only degradations are in the lower Rappahannock, with flow-adjustment making these less likely. Station LE3.6, which is within the mainstem of the Bay, shows a clearly different long-term pattern than the mesohaline Rappahannock.

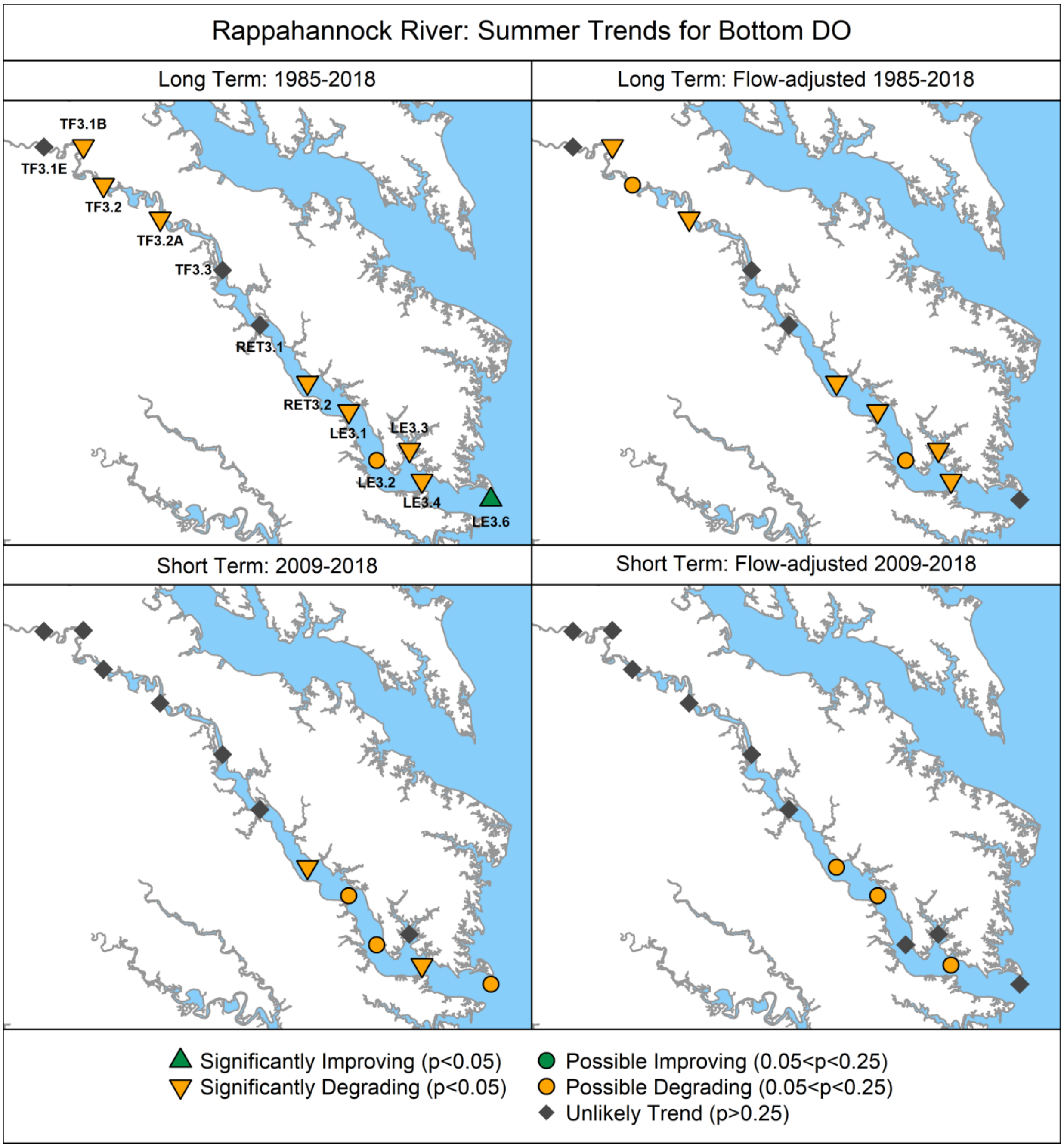


Figure 16. Summer (June-September) bottom DO trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Plots of the summer data and average summer GAM estimates demonstrate the spatial variability in bottom DO concentrations (Figure 17). Concentrations in the tidal fresh and middle Rappahannock are higher than the lower Rappahannock, but the tidal fresh concentrations are trending downward and go below the 5 mg/L summer Open Water 30-day mean DO criterion occasionally. Concentrations at some of the mesohaline stations go below the Deep Channel instantaneous criterion of 1 mg/L during the summer, and many of these stations have degrading trends (Figure 16). Notably, the improving trend at LE3.6 is evident as well, although the concentrations are much higher at that station than others within the Rappahannock.

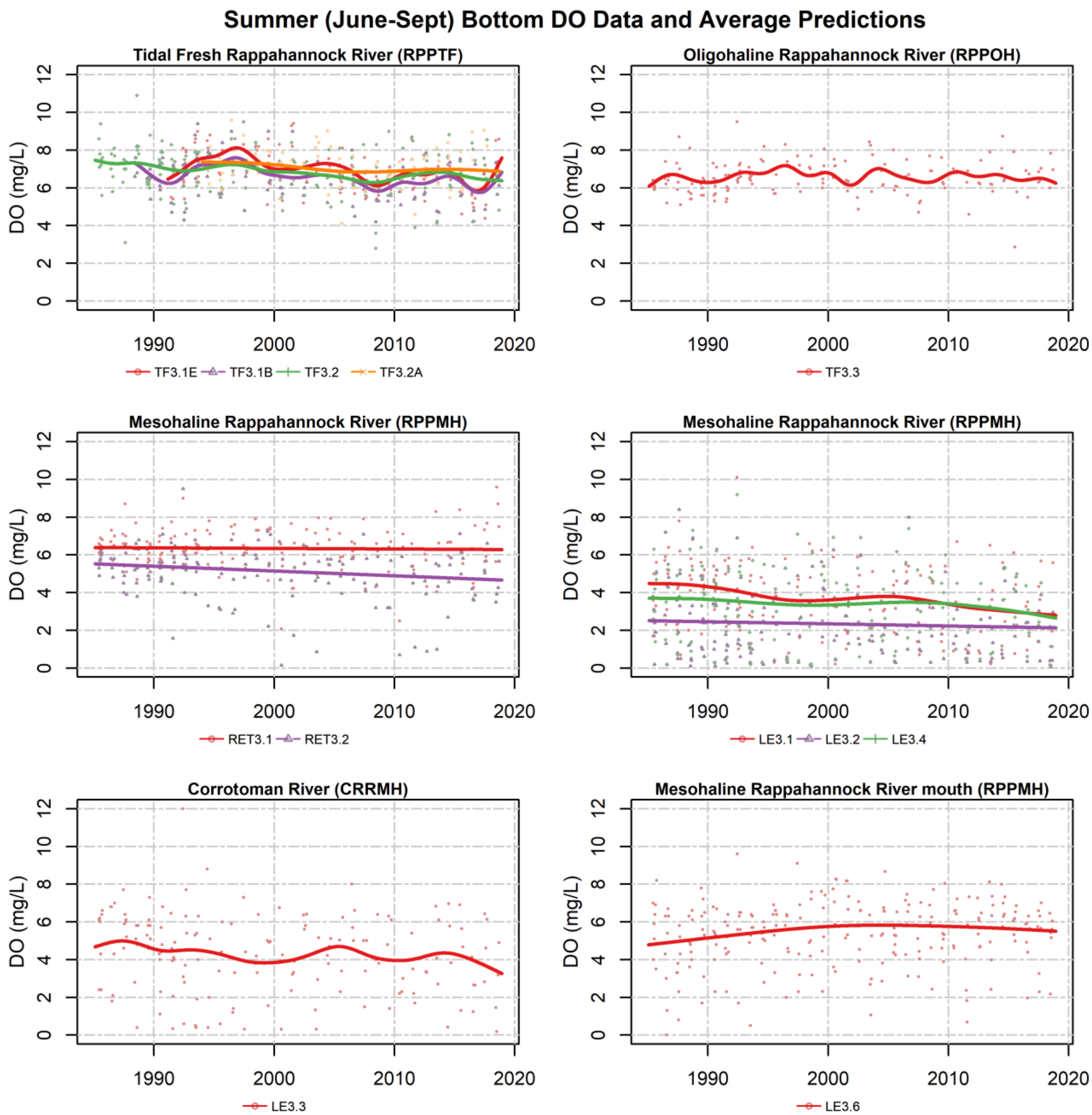


Figure 17. Summer (June-September) bottom DO data (dots) and average long-term seasonal pattern generated from non-flow adjusted GAMs. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean summer GAM estimates for the noted monitoring 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 transfer of nitrogen, phosphorus, and sediment delivered to non-tidal and tidal streams (Figure 18) (Brakebill *et al.*, 2010; Ator *et al.*, 2011; Ator *et al.*, 2019; Ator *et al.*, 2020; Noe *et al.*, 2020).

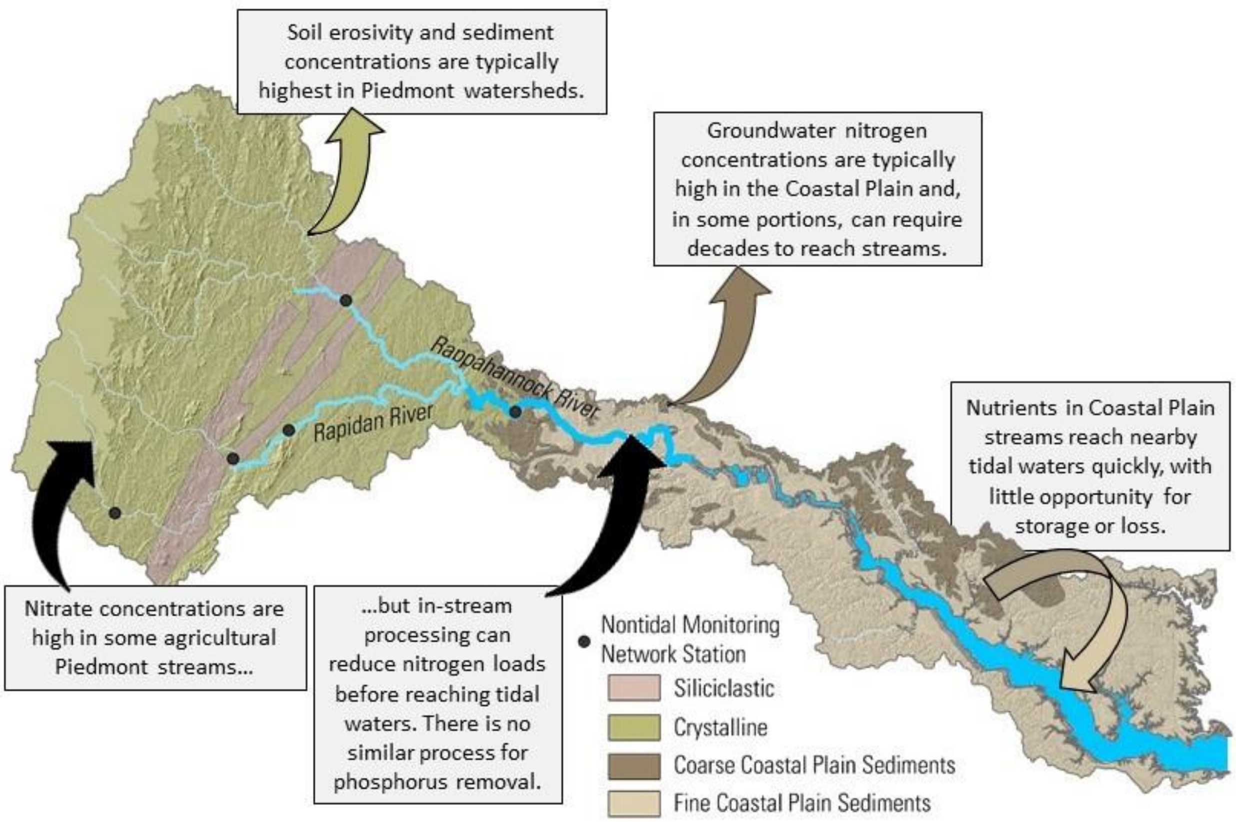


Figure 18. Effects of watershed hydrogeomorphology on nutrient transport to freshwater streams and tidal waters. Base map modified from King *et al.* (1974) and Ator *et al.* (2005), North American Datum 1983.

Nitrogen

Groundwater is an important delivery pathway of nitrogen 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. 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 (see Figure 1 and Figure 18) 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 – 33 years, Phillips and others, 1999). 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 *et al.*, 2015); however, once fully phosphorus saturated, 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 greatest 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. Reducing soil phosphorus concentrations can take a decade or more (Kleinman *et al.*, 2011) and, until this occurs, watershed phosphorus loads may be unresponsive to management practices (Jarvie *et al.*, 2013; Sharpley *et al.*, 2013).

Sediment

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 (Jarvie *et al.*, 2013; Sharpley *et al.*, 2013). 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 (Trimble, 1975; Gellis *et al.*, 2005; Brakebill *et al.*, 2010), bank sediment density (Wynn and Mostaghimi, 2006), vegetation (Wynn and Mostaghimi, 2006), stream valley geomorphology (Hopkins *et al.*, 2018), and developed land uses (Brakebill *et al.*, 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 associated 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 *et al.*, 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. High rates of sediment trapping by Coastal Plain nontidal floodplains and head-of-tide tidal freshwater wetlands creates a sediment shadow in many tidal rivers and limits sediment delivery to the bay (Ator *et al.*, 2011). 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 loads to tidal portions of Chesapeake Bay tributaries are a combination of monitored fluxes from U.S. Geological Survey (USGS) River Input Monitoring (RIM) stations 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 were primarily from the below-RIM areas, whereas phosphorus loads were primarily from the RIM areas (Figure 19). Over the period of 1985-2018, 0.14, 0.016, and 21 million tons of nitrogen, phosphorus, and suspended sediment loads were exported through the Rappahannock River watershed, with 47%, 68%, and 40% of those loads from the RIM areas, respectively.

Mann-Kendall trends and Sen's slope estimates are summarized for each loading source in Table 4.

<u>Nitrogen</u>

Estimated TN loads showed an overall increase of 12 ton/yr in the period between 1985 and 2018, although it is not statistically significant ($p = 0.70$). This increase reflects a combination of increases in RIM loads (4.5 ton/yr; $p = 0.73$) and below-RIM loads (6.7 ton/yr; $p = 0.55$). The below-RIM increase is driven by below-RIM nonpoint sources (13 ton/yr, $p = 0.30$). In contrast, long-term reductions were observed with the below-RIM point sources (-2.5 ton/yr, $p < 0.01$) and the atmospheric deposition to tidal waters (-2.0 ton/yr, $p < 0.05$). 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).

<u>Phosphorus</u>

Estimated TP loads showed an overall increase of 5.4 ton/yr in the period between 1985 and 2018, although it is not statistically significant ($p = 0.15$). This increase in TP is largely driven by the RIM loads

(5.0 ton/yr, $p = 0.12$). Within the below-RIM load, nonpoint sources showed a statistically significant increase (1.4 ton/yr, $p < 0.05$), whereas point sources showed a statistically significant decline (-0.58 ton/yr; $p < 0.01$). This 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).

Sediment

Estimated suspended sediment (SS) loads showed an overall increase of 4,158 ton/yr in the period between 1985 and 2018, although it is not statistically significant ($p = 0.18$). Both the RIM and below-RIM loads showed increases, but both are not statistically significant. Like TP and TN, the below-RIM point source load of SS showed a statistically significant decline in this period (-4.0 ton/yr; $p < 0.01$).

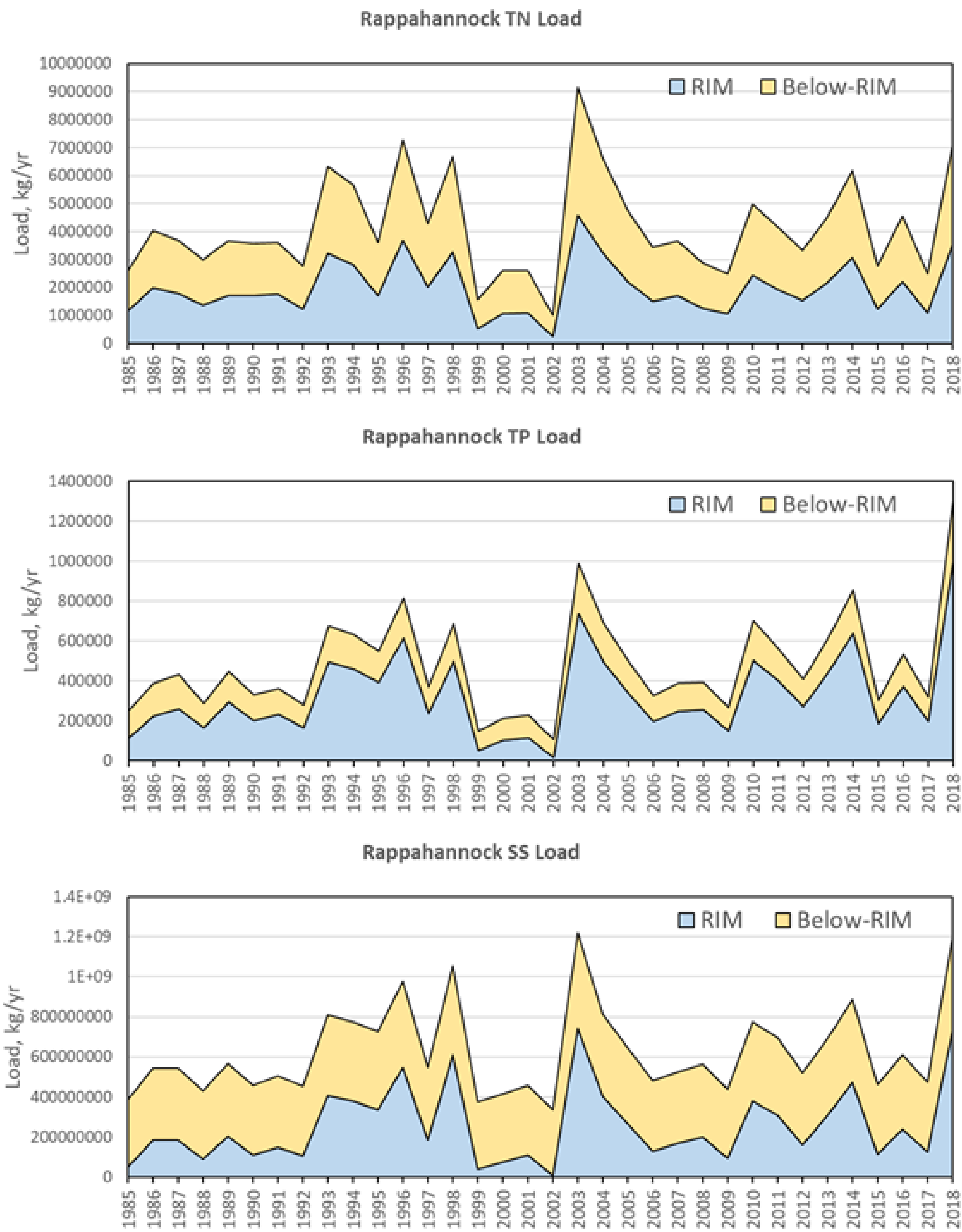


Figure 19. Estimated total loads of nitrogen (TN), phosphorus (TP), and suspended sediment (SS) from the RIM and below-RIM areas of the Rappahannock River. RIM refers to the USGS River Input Monitoring site located just above the head of tide of this tributary, which includes upstream point source loads. Below-RIM estimates are a combination of simulated non-point source, atmospheric deposition, and reported point-source loads.

Table 4. Summary of Mann-Kendall trends for the period of 1985-2018 for total nitrogen (TN), total phosphorus (TP), and suspended sediment (SS) loads from the Rappahannock River watershed.

Variable	**Trend, metric ton/yr**	**Trend p-value**
TN		
Total watershed	12	0.70
RIM watershed [1]	4.5	0.73
Below-RIM watershed [2]	6.7	0.55
Below-RIM point source	-2.5	< 0.01
Below-RIM nonpoint source [3]	13	0.30
Below-RIM tidal deposition	-2.0	< 0.05
TP		
Total watershed	5.4	0.15
RIM watershed	5.0	0.12
Below-RIM watershed	0.51	0.50
Below-RIM point source	-0.58	< 0.01
Below-RIM nonpoint source	1.4	< 0.05
SS		
Total watershed	4,158	0.18
RIM watershed	3,484	0.21
Below-RIM watershed	680	0.19
Below-RIM point source	-4.0	< 0.01
Below-RIM nonpoint source	678	0.19

[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 2018, which were adjusted to reflect actual hydrology using the method of the Chesapeake Bay Program's Loads to the Bay indicator (see https://www.chesapeakeprogress.com/clean-water/water-quality).

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, version CAST-2019), changes in population size, land use, and pollution management controls between 1985 and 2019 would be expected to change long-term average nitrogen, phosphorus, and sediment loads to the tidal Rappahannock River by -12%, -33%, and -13%, respectively (Figure 20). 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 2019, 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 (-25%), natural (-7%), stream bed and bank (-10%), and wastewater (-28%) sources were partially counteracted by increases from developed (78%) and septic (65%) sources.

The two largest sources of phosphorus loads as of 2019 were the agriculture and developed sectors. Overall, expected declines from agriculture (-51%), natural (-7%), stream bed and bank (-34%), and wastewater (-78%) sources were partially counteracted by increases from developed (95%) 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 2019. Sediment loads from the agriculture sector changed by -57%, whereas sediment load from developed areas changed by 38%.

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 2019, whereas the developed sectors are expected to increase in nitrogen, phosphorus, and sediment loads.

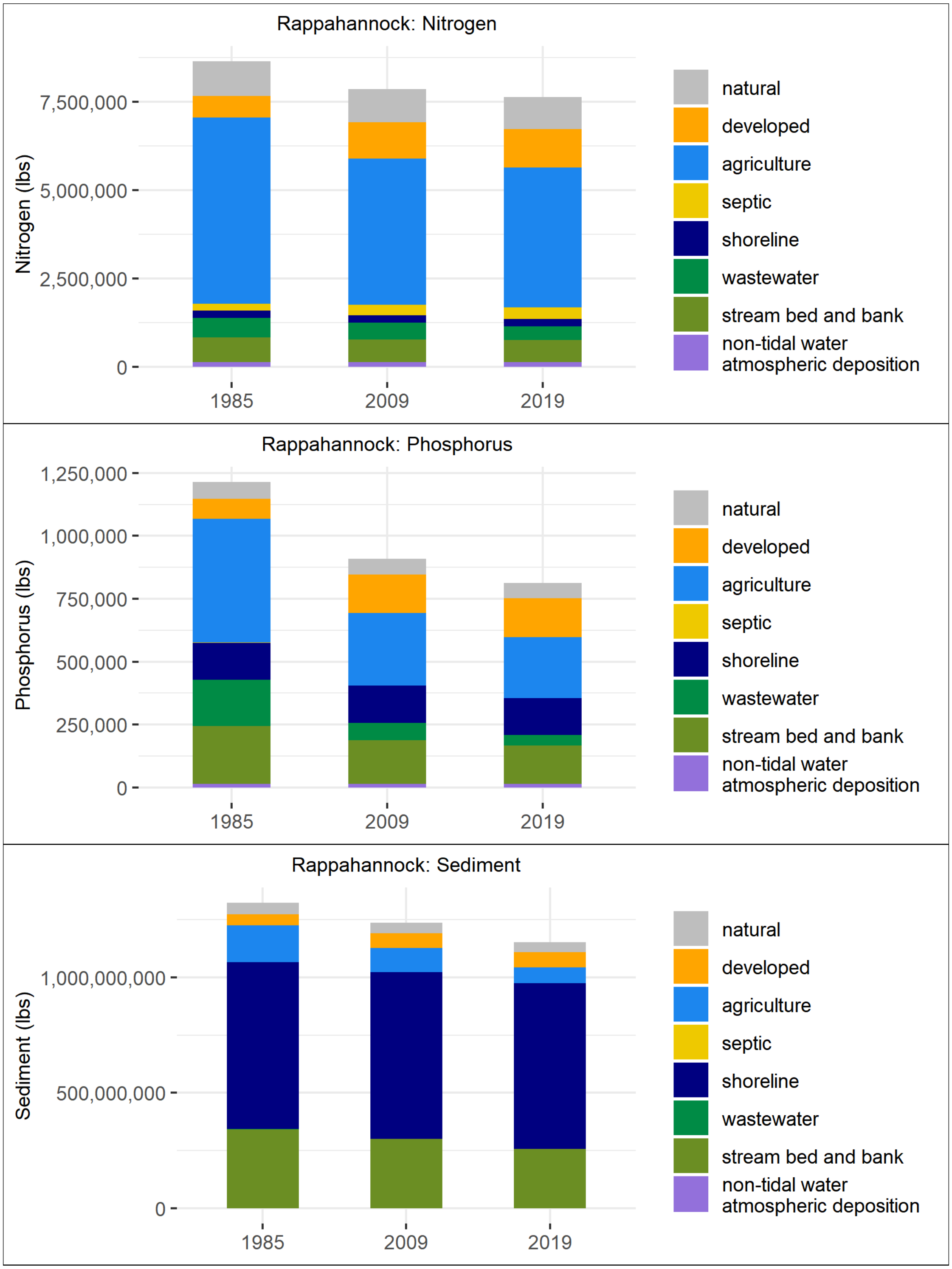
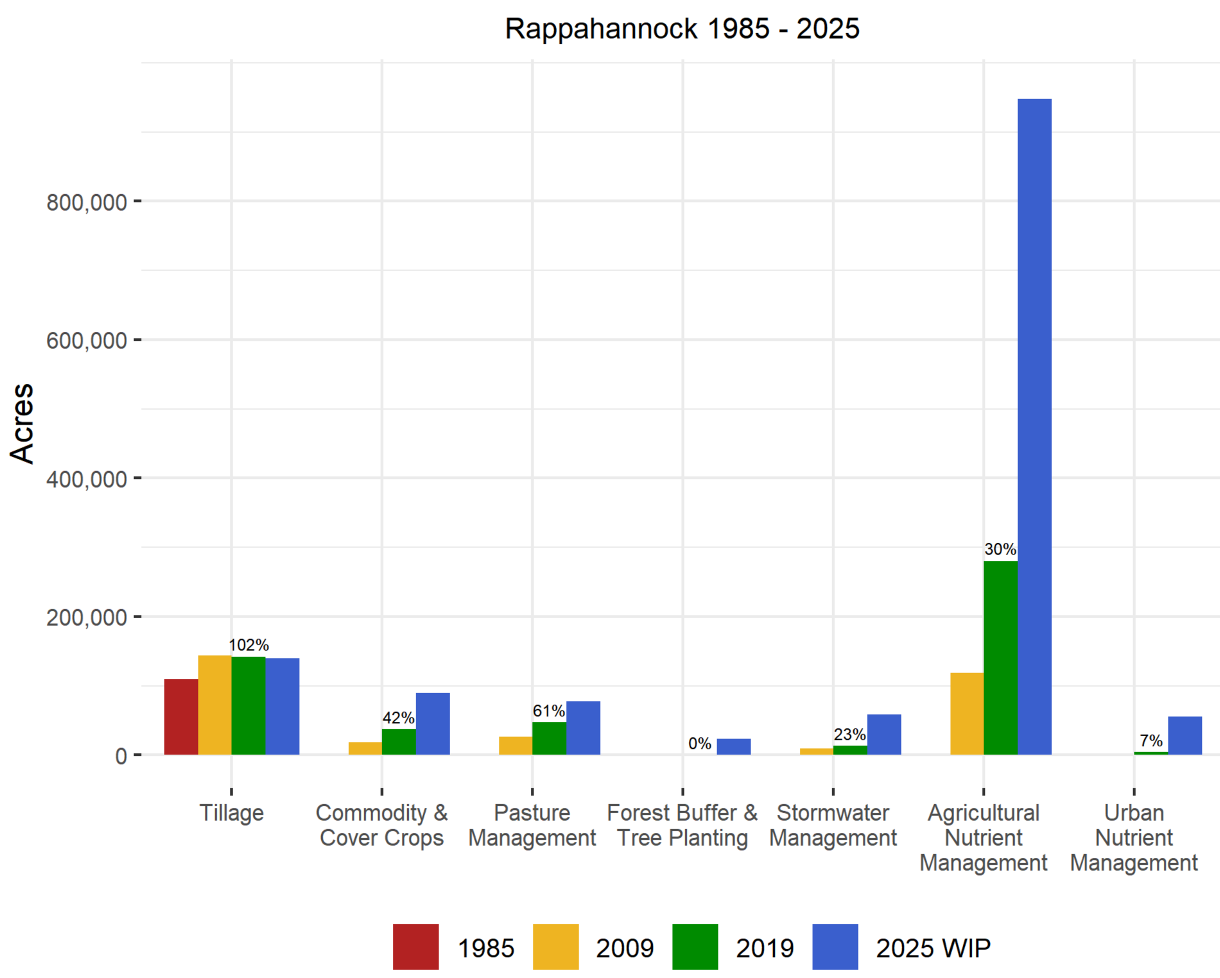


Figure 20. Expected long-term average loads of nitrogen, phosphorus, and sediment from different sources to the tidal Rappahannock, as obtained from the Chesapeake Assessment Scenario Tool (CAST-19). Data shown are time-average delivered loads over the average hydrology of 1991-2000, once the steady state is reached for the conditions on the ground, as obtained from the 1985, 2009, and 2018 progress (management) scenarios.

5.1.4 Best Management Practices (BMPs) Implementation

Data on reported BMP implementation are available for download from CAST (https://cast.chesapeakebay.net, version CAST-2019). Reported BMP implementations on the ground as of 1985, 2009, and 2019 are compared to planned 2025 implementation levels in Figure 21 for a subset of major BMP groups measured in acres. As of 2019, tillage, cover crops, pasture management, forest buffer and tree planting, stormwater management, agricultural nutrient management, and urban nutrient management were credited for 142, 37, 47, 0.1, 13, 280, and 4.1 thousand acres, respectively. Implementation levels for some practices are already close to achieving their planned 2025 levels: for example, 102% of planned acres for tillage had been achieved as of 2019. In contrast, about 42% of planned commodity & cover crops implementation had been achieved as of 2019.



Values above the 2019 bars are the percent of the 2025 goal achieved.

Figure 21. BMP implementation in the Rappahannock watershed

Stream restoration and animal waste management system 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 feet in 1985 to 14,666 feet in 2019. Over the same period, animal waste management systems treated 0 animal units in 1985 and 1,887 animal units in 2019 (one animal unit represents 1,000 pounds of live animal). These implementation levels represent 25% and 6% 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. Flow-normalized nitrogen, phosphorus, and sediment trends have been reported for the long term (1985-2019) and short term (2009-2018) at nontidal network stations throughout the watershed (Moyer and Langland, 2020) (Table 5). 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 5. Long-term (1985 - 2018) and short-term trends (2009 - 2018) 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 https://cbrim.er.usgs.gov/summary.html.

USGS Station ID	USGS Station Name	Trend start water year	Percent change in FN load, through water year 2018		
			TN	TP	SS
01664000	RAPPAHANNOCK RIVER AT REMINGTON, VA	1985	**24.4**	-	-
		2009	**15.4**	-	-
01665500	RAPIDAN RIVER NEAR RUCKERSVILLE, VA	2009	**-5.1**	-	-
01666500	ROBINSON RIVER NEAR LOCUST DALE, VA	1985	2.5	-	-
		2009	3.5	-	-
01667500	RAPIDAN RIVER NEAR CULPEPER, VA	2009	**-8.9**	**-6.8**	-7.1
01668000	RAPPAHANNOCK RIVER NEAR FREDERICKSBURG, VA	1985	**-12.7**	**52.5**	**79.9**
		2009	**6.3**	**27.9**	**28.3**

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 (Kemp *et al.*, 2005; Testa *et al.*, 2017) (Figure 22). 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 Bay tend to be more transparent than tidal-fresh regions, and waters adjacent to nutrient input points are more affected by these inputs than more distant regions (Keisman *et al.*, 2019; Testa *et al.*, 2019). Dissolved oxygen concentrations are affected by salinity- and temperature-driven stratification of the water column, and conversely by wind-driven mixing, in addition to phytoplankton respiration and decomposition (Scully, 2010; Murphy *et al.*, 2011). When anoxia occurs at the water-sediment interface, nitrogen and phosphorus stored in the sediments can be released through anaerobic chemical reactions (Testa and Kemp, 2012). When low-oxygen water and sediment burial suffocate benthic plant and animal communities, their nutrient consumption and water filtration services are lost. Conversely, when conditions improve enough to support abundant SAV and benthic communities, their functions can sustain and even advance progress towards a healthier ecosystem (Cloern, 1982; Phelps, 1994; Ruhl and Rybicki, 2010; Gurbisz and Kemp, 2014).

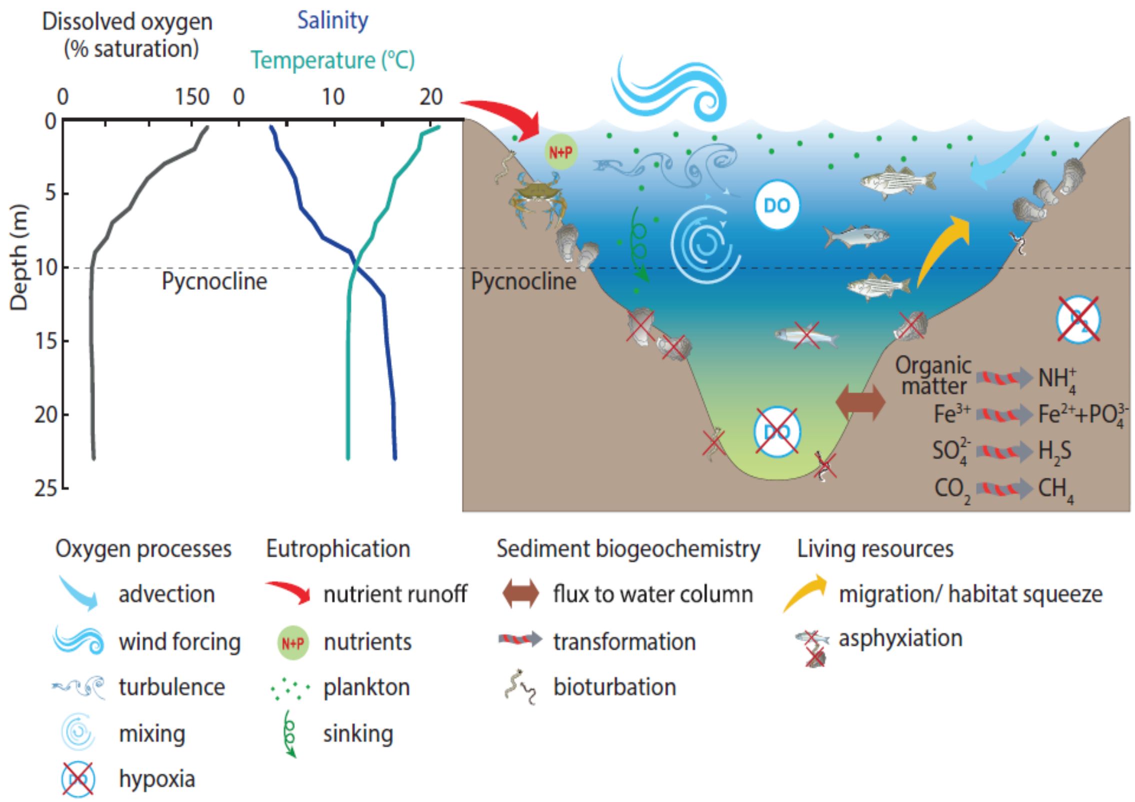


Figure 22. Conceptual diagram illustrating how hypoxia is driven by eutrophication and physical forcing, while affecting sediment biogeochemistry and living resources. From Testa *et al.* (2017).

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 23 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 24 and 25 are comparisons of estimated annual average nitrogen and phosphorus loads, respectively, for the 2018 progress scenario in CAST versus the estuarine volume for the same set of estuaries and sub-estuaries.

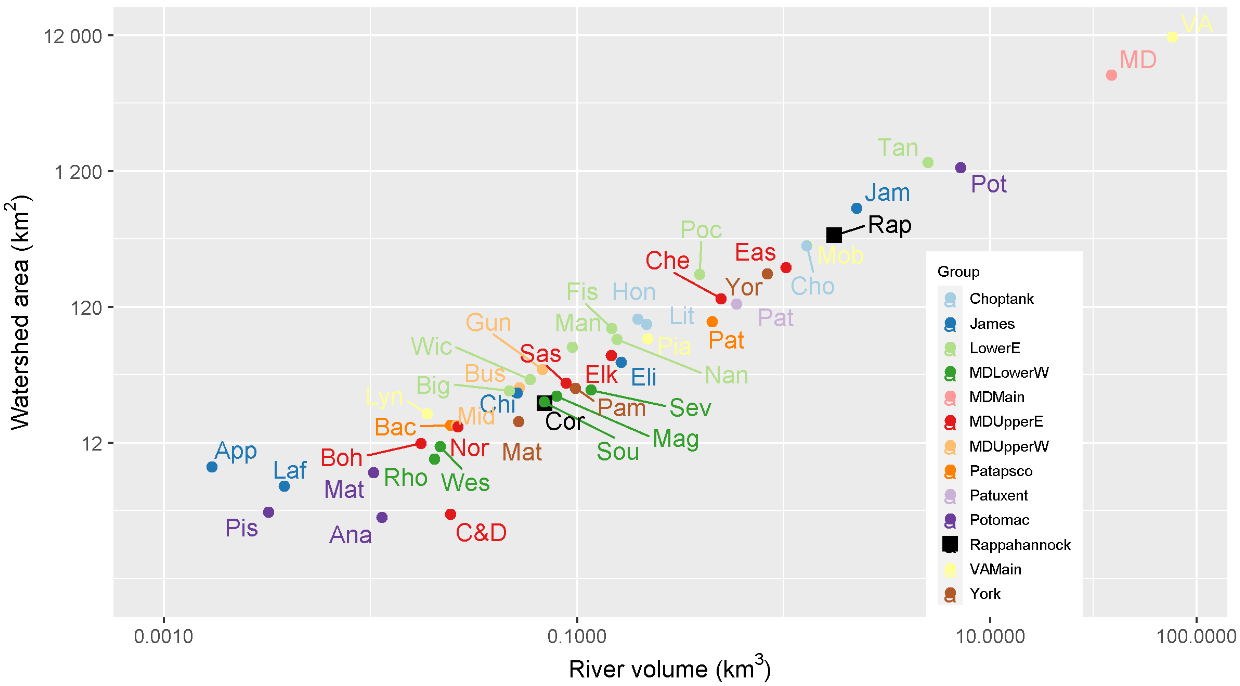


Figure 23. Watershed area vs estuarine volume.

Abbreviated tributary name	Full tributary name	Abbreviated tributary name	Full tributary name
Ana	Anacostia River	Mat	Mattaponi River
App	Appomattox River	MD	MD MAINSTEM
Bac	Back River	Mid	Middle River
Big	Big Annemessex River	Mob	Mobjack Bay
Boh	Bohemia River	Nan	Nanticoke River
Bus	Bush River	Nor	Northeast River
C&D	C&D Canal	Pam	Pamunkey River
Che	Chester River	Pat	Patapsco River
Chi	Chickahominy River	Pat	Patuxent River
Cho	Choptank River	Pia	Piankatank River
Cor	Corrotoman River	Pis	Piscataway Creek
Eas	Eastern Bay	Poc	Pocomoke River
Eli	Elizabeth River	Pot	Potomac River
Elk	Elk River	Rap	Rappahannock River
Fis	Fishing Bay	Rho	Rhode River
Gun	Gunpowder River	Sas	Sassafras River
Hon	Honga River	Sev	Severn River
Jam	James River	Sou	South River
Laf	Lafayette River	Tan	Tangier Sound
Lit	Little Choptank River	VA	VA MAINSTEM
Lyn	Lynnhaven River	Wes	West River
Mag	Magothy River	Wes	Western Branch (Patuxent River)
Man	Manokin River	Wic	Wicomico River

Mat	Mattawoman Creek	Yor	York River

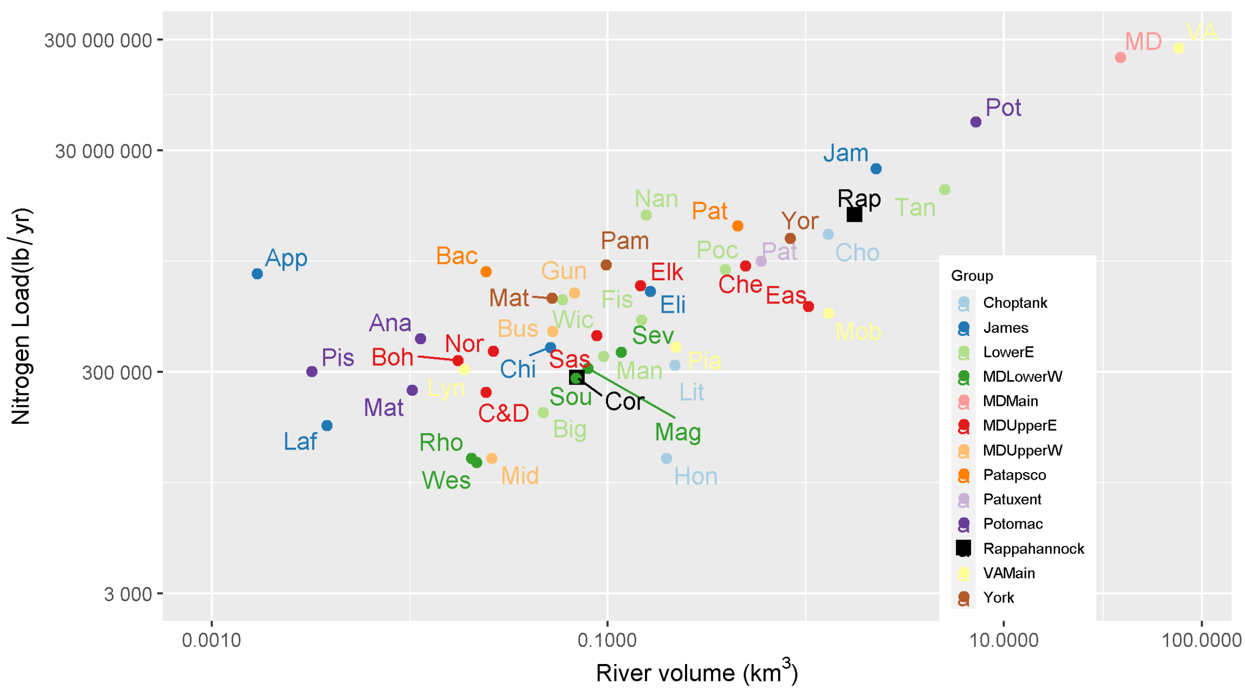


Figure 24. Annual average expected nitrogen loads versus estuarine volume. Nitrogen loads are from the 2018 progress scenarios in CAST (Chesapeake Bay Program, 2020), which is an estimate of nitrogen loads under long-term average hydrology given land use and reported management as of 2018.

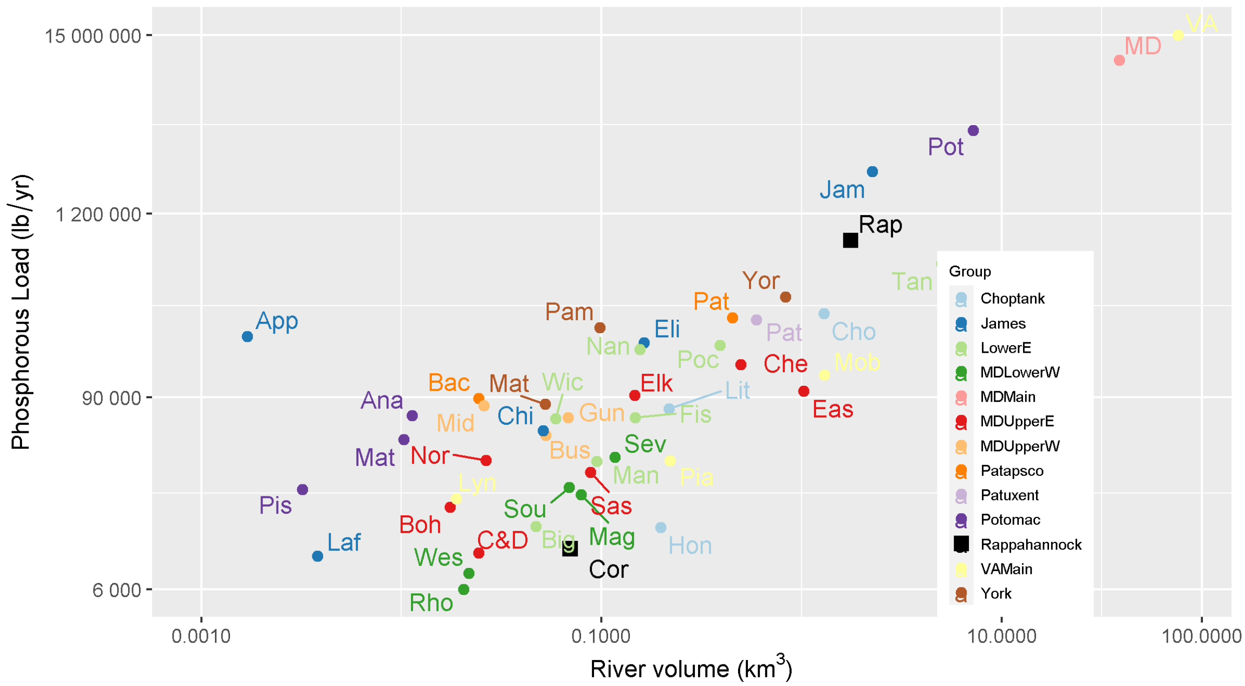


Figure 25. Annual average expected phosphorus loads versus estuarine volume. Phosphorus loads are from the 2018 progress scenarios in CAST (Chesapeake Bay Program, 2020), which is an estimate of phosphorus loads under long-term average hydrology given land use and reported management as of 2018.

The Rappahannock river estuary volume and watershed contain approximately 2 and 4% of the total volume and watershed of the Chesapeake Bay. This ranks the Rappahannock as the 7th largest volume and 5th largest watershed area aggregated tributary in this summary (Figures 23, 24, and 25). The ratios of watershed area, nitrogen loading, and phosphorus loading to estuarine volume are consistent with other estuaries in the Chesapeake system, indicating a moderate level of susceptibility to eutrophication. The smaller tributary within the Rappahannock system, the Corrotoman river has a slightly lower load of phosphorus relative to its estuarine volume.

5.3 Insights on Change in the Rappahannock

Completion of Section 5.3 is contingent upon stakeholder interest and availability of resources. It requires:

- *Synthesis of the information provided in previous sections and of the recent literature on explaining trends in general and any work conducted on this tributary in particular;*
- *Discussion with local technical experts to clarify insights and vet hypotheses and preliminary findings.*

Drafting of this section for the Rappahannock Tributary Summary is currently in progress.

6. Summary

Completion of Section 6 is contingent upon completion of Section 5.3. Drafting of this section is expected by end-of-year 2021.

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Appendix

Additional tidal trend maps and plots are in a separate Appendix document for:

- Bottom Total Nitrogen
- Bottom Total Phosphorus
- Surface Dissolved Inorganic Nitrogen
- Surface Orthophosphate
- Surface Total Suspended Solids
- Summer Surface Dissolved Oxygen
- Surface Water Temperature