York 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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This tributary summary is a living document in draft form and has not gone through a formal peer review process. We are grateful for contributions to the development of these materials from the following individuals: Jeni Keisman, Rebecca Murphy, Olivia Devereux, Jimmy Webber, Qian Zhang, Meghan Petenbrink, Tom Butler, Zhaoying Wei, Jon Harcum, Renee Karrh, Mike Lane, and Elgin Perry.

Contents

1. Purpose and Scope

The York 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 (below pycnocline) 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 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 York River.

2. Location

The York River watershed covers approximately 4% of the Chesapeake Bay watershed drainage basin. Its watershed is approximately 6,537 km^2 (Table 1) and is contained within one state, Virginia (Figure 1).

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 York River watershed stretches across three major physiographic regions, namely, Piedmont, Mesozoic Lowland, and Coastal Plain (Bachman *et al.*, 1998) (Figure 1). The Piedmont physiography covers primarily 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.

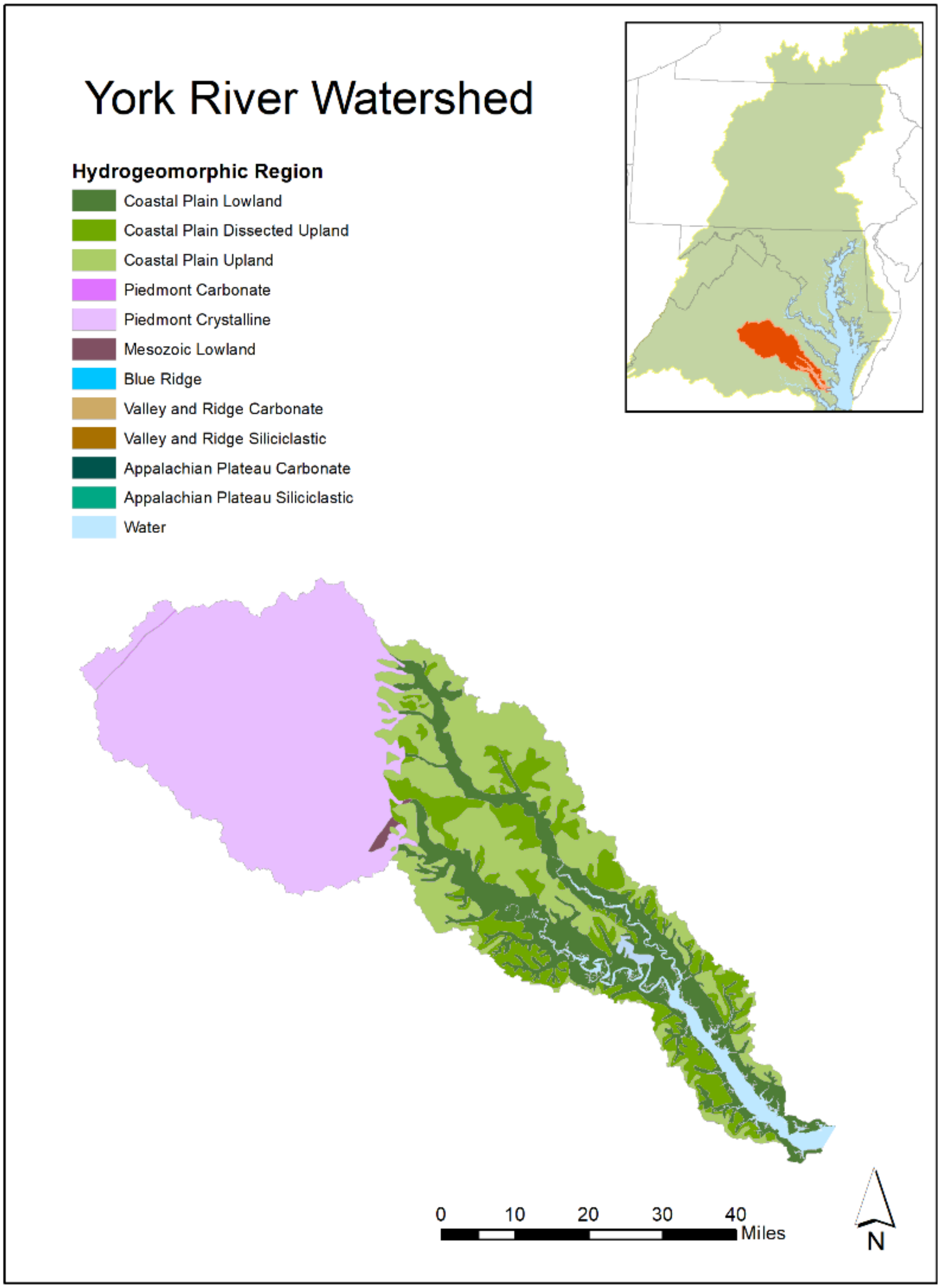

Figure 1. Distribution of physiography in the York River watershed.

2.2 Land Use

Land use in the York watershed is dominated (75%) by natural areas. Urban and suburban land areas have increased by 75,958 acres since 1985, agricultural lands have decreased by 34,246 acres, and natural lands have decreased by 41,081 acres. Correspondingly, the proportion of urban land in this watershed has increased from 5% in 1985 to 10% in 2019 (Figure 2).

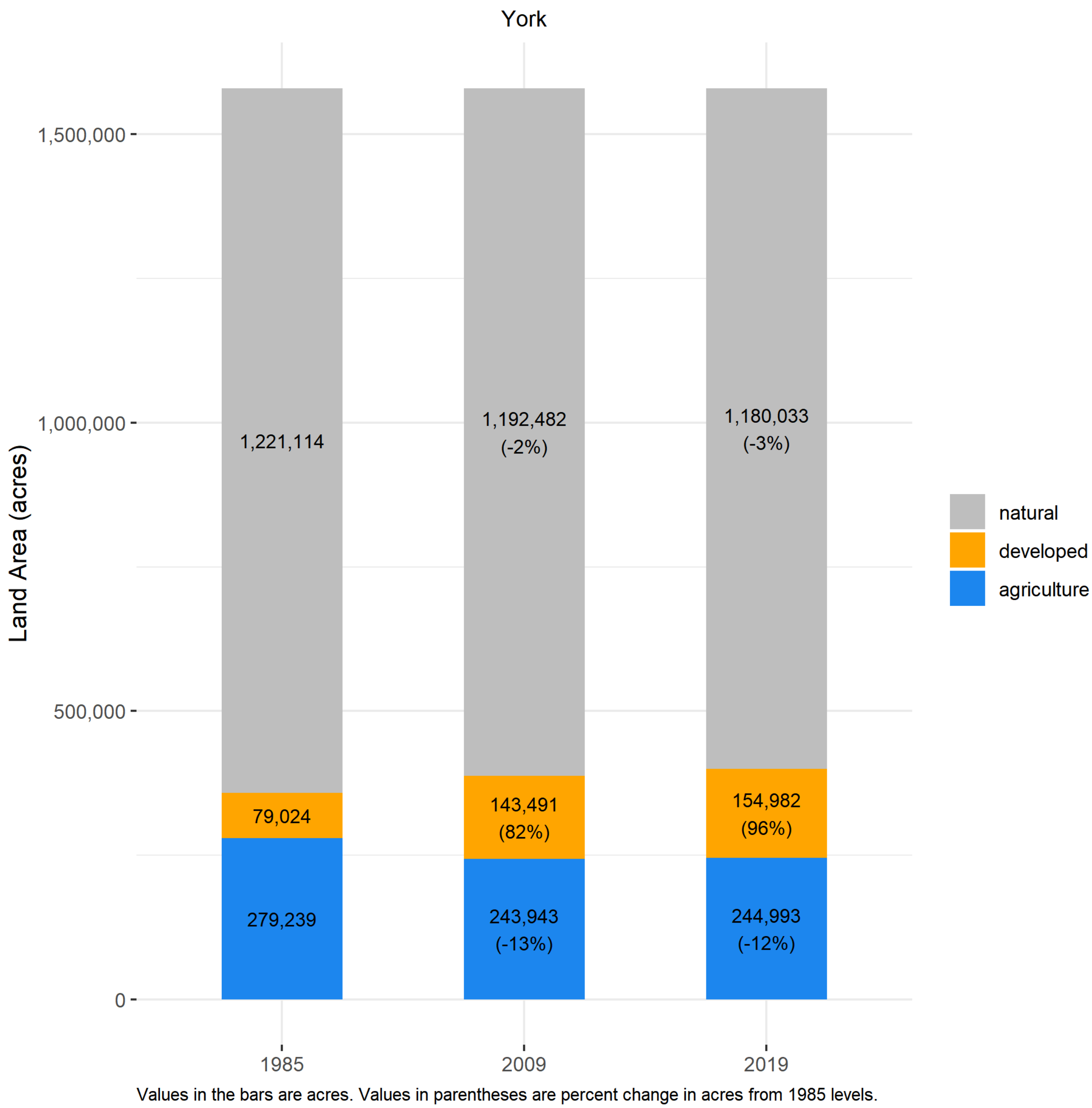

Figure 2. Distribution of land uses in the York watershed. Percentages are the percent change from 1985 for each source sector.

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.

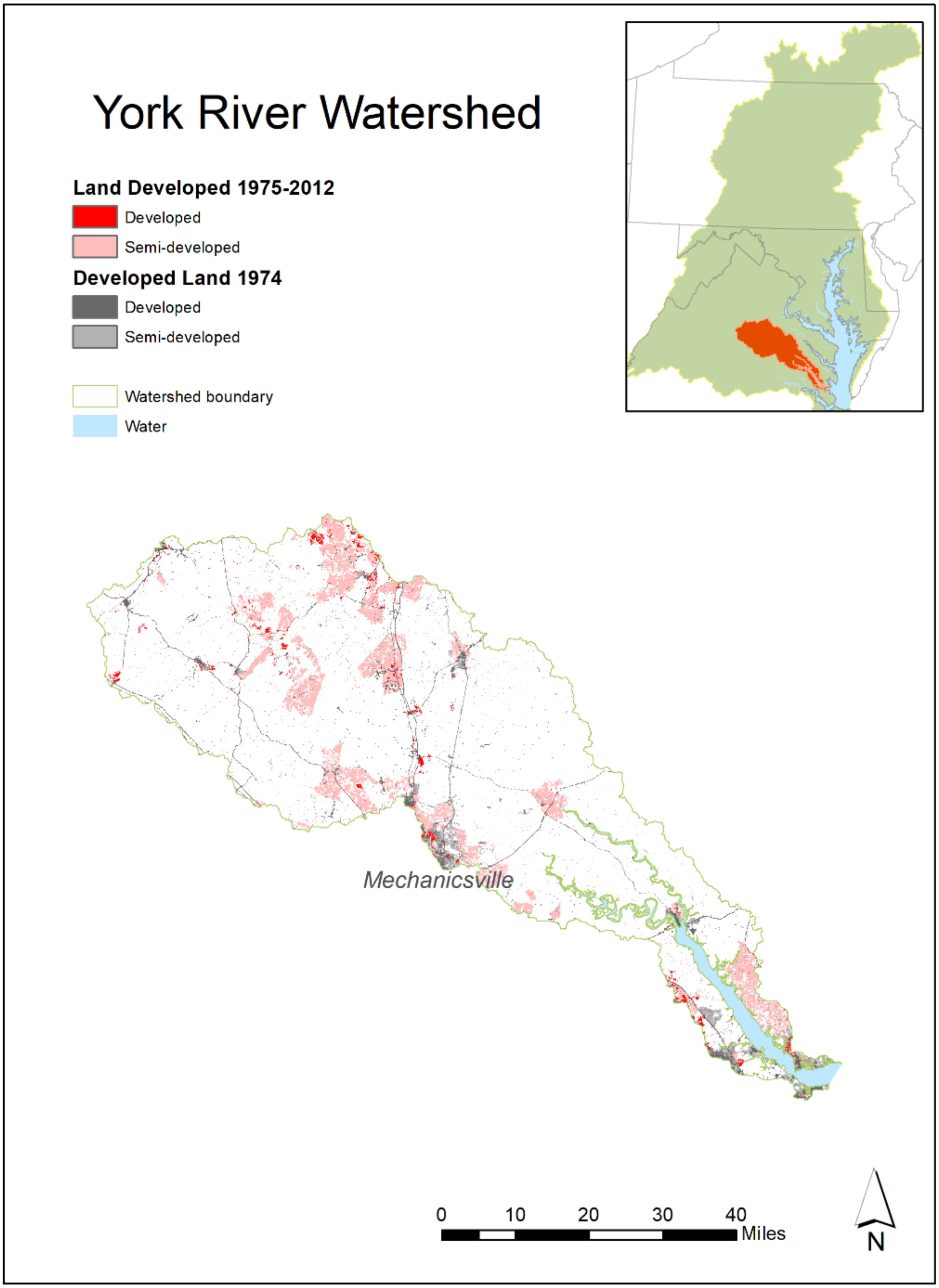

Figure 3. Distribution of developed land in the York River watershed. Derived from Falcone (2015). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

2.3 Tidal Waters and Stations

For the purposes of water quality standards assessment and reporting, the tidal waters associated with the York River are divided into six segments (U.S. Environmental Protection Agency, 2004) (Figure 4). These include two tributaries, the Mattaponi River and the Pamunkey River, that join to form the York River. Segments in the Mattaponi and Pamunkey Rivers include Tidal Fresh and Oligohaline regions (MPNTF, MPNOH, PMKTF, PMKOH). In the York River, the Mesohaline region and Polyhaline region each are a segment (YRKMH, YRKPH).

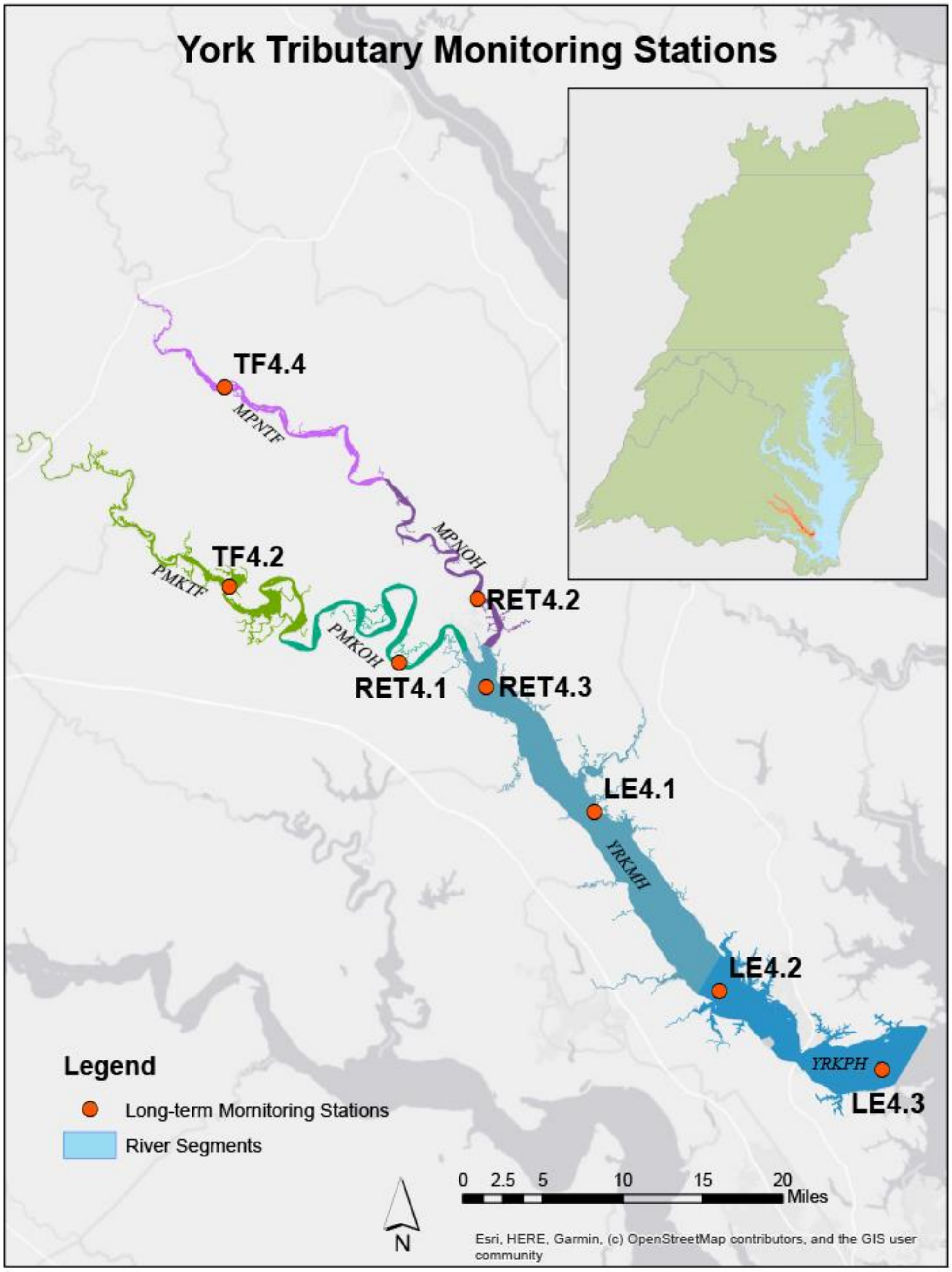

Figure 4. Map of tidal York River segments and long-term monitoring stations. Base map credit Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community, World Geodetic System 1984.

Long-term trends in water quality are analyzed by Virginia Department of Environmental Quality (VADEQ) and Old Dominion University (ODU) at eight stations stretching from the Mattaponi and Pamunkey Rivers to the mouth of the York 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 York River and tributaries 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 each of the tributary segments have met or not met either 30-day or instantaneous Open Water (OW) and Deep Water (DW) 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 tidal fresh Mattaponi and Pamunkey River segments (MPNTF and PMKTF) both met the 30-day mean OW summer DO requirements, but none of the other York segments met the requirements for the criteria shown (Zhang *et al.*, 2018b).

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

time period	MPNTF	MPNOH	PMKTF	PMKOH	YRKMH	YRKPH
1985-1987						
1986-1988						
1987-1989						
1988-1990						
1989-1991						
1990-1992						
1991-1993						
1992-1994						
1993-1995						
1994-1996						
1995-1997						
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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) criteria evaluation results. Green indicates that the criterion was met. White indicates that the criterion was not met.

time period	YRKPH
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 DW summer 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 bottom depths at each of these stations is different due to varying bathymetry, but the bottom DO trends at these stations are expected to represent water in the DW designated use. As mentioned above, only the tidal fresh segments met the OW summer criteria in the 2016-2018 period. In the Mattaponi, the tidal fresh observed DO trend is going down, while in the Pamunkey it is going up. In the other York River segments not meeting the OW criteria, the surface DO is either not trending or improving, suggesting possible progress. For the bottom DO, one station indicate possible degradation while the segment is not meeting the DW 30-day mean summer requirements.

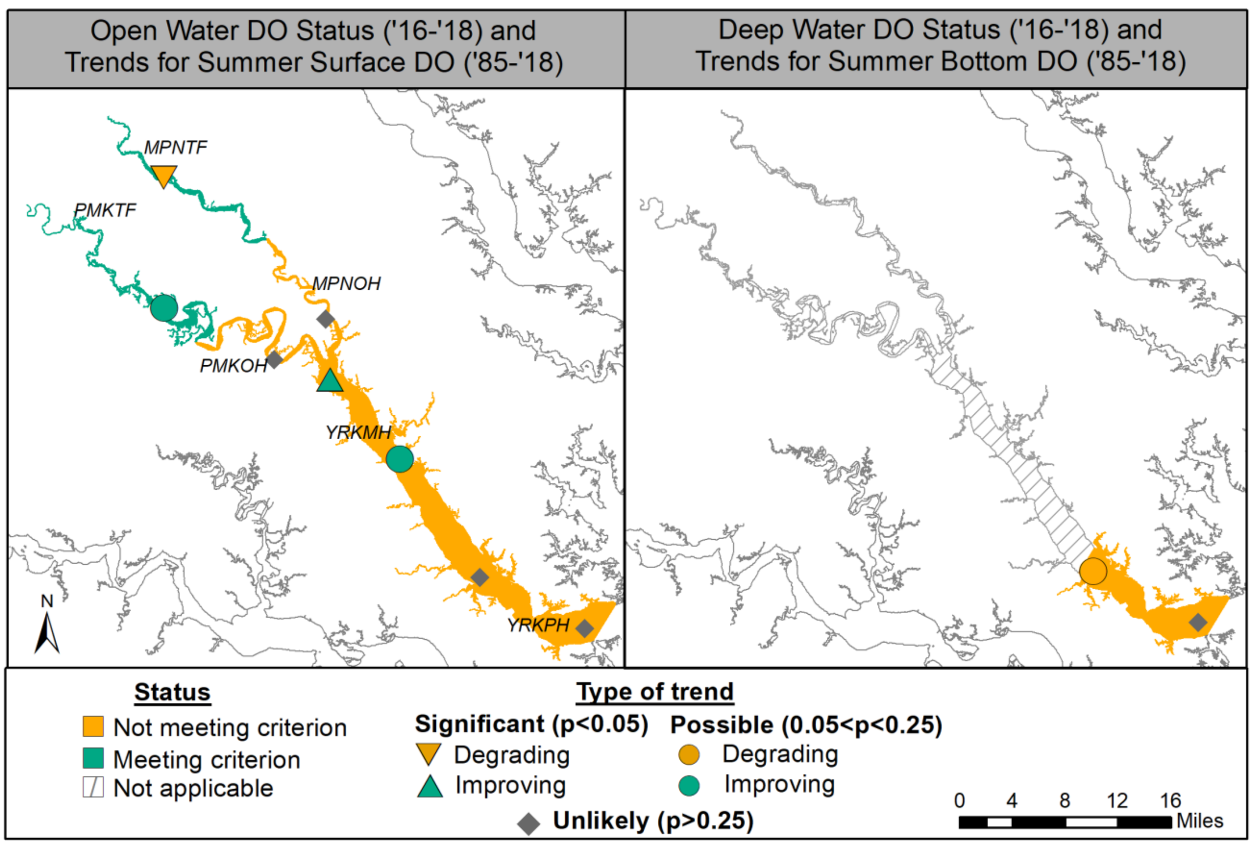

Figure 5. Pass-fail DO criterion status for 30-day OW summer DO and DW summer DO designated uses in York segments along with long-term trends in DO concentrations. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

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 eight York, Mattaponi and Pamunkey River stations labeled in Figure 4. For more details on the GAM implementation that is applied each year by VA Department of Environmental Quality with 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 station and parameter, sometimes gaged river flow is used for this adjustment and sometimes salinity is used, but we refer to all these results as "flow-adjusted" for simplicity.

To determine if there has been a change over time (i.e., a trend) at a particular station for a given parameter, we compute a percent change between the estimates at 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) trends are mixed in the York and its tributaries (Figure 6). The tidal fresh stations of the Mattaponi and Pamunkey Rivers (TF4.4 and TF4.2) are degrading over the long-term, both with and without flow adjustment. The oligohaline and mesohaline stations (RET4.1, RET4.2, RET4.3, LE4.1) have a mixture of improving, degrading, and no trends over the long-term. And the polyhaline York River stations (LE4.2 and LE4.3) have improving TN trends over the long-term, with and without flow adjustment. Over the short-term, several of these trends persist, but there are no trends at the majority of the stations (Figure 6).

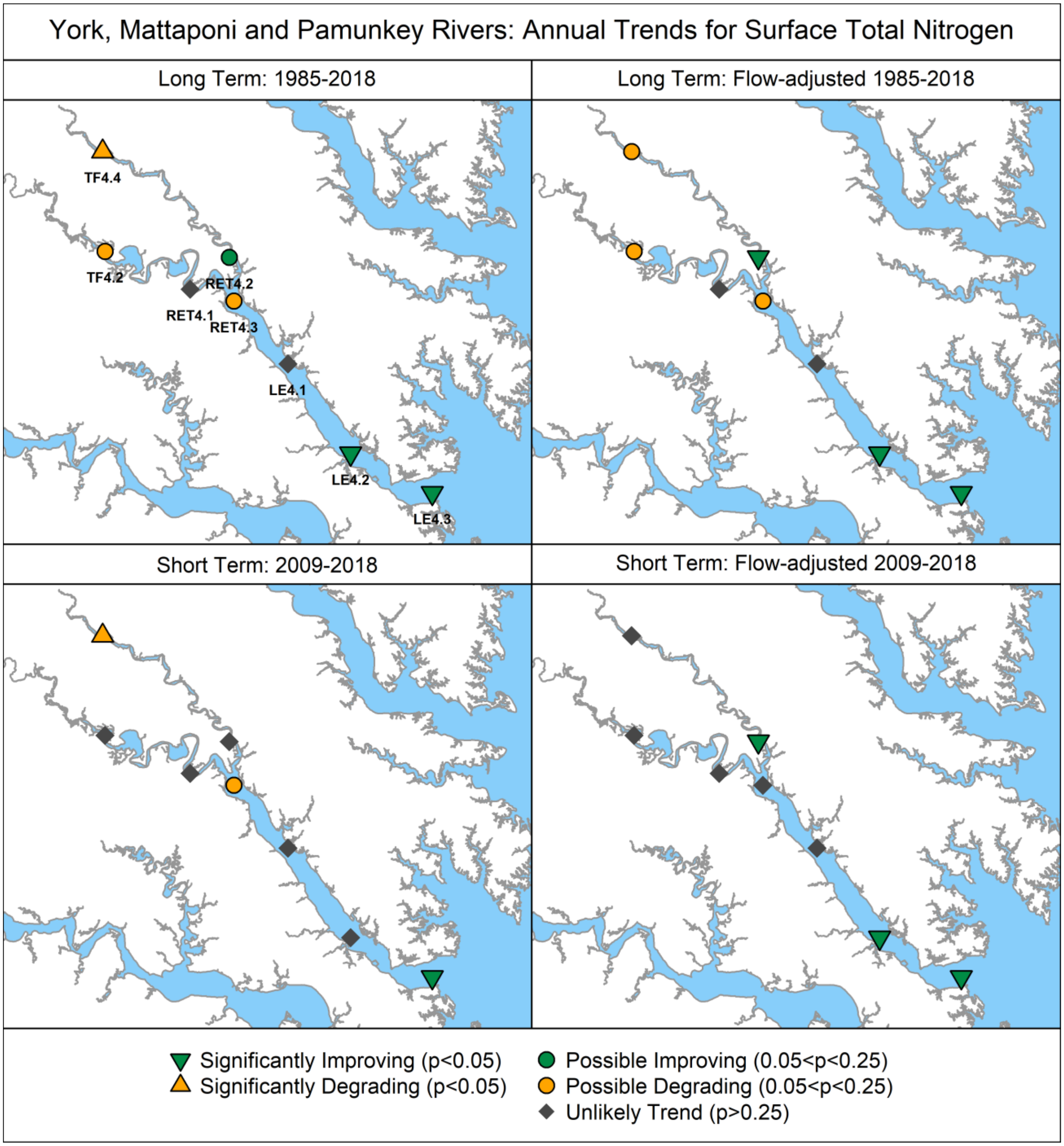

Figure 6. Surface TN Trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

The long-term trends in TN are difficult to discern in the data and non-flow-adjusted mean annual GAM estimates presented in 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, these time series start in 1994. The increases at the tidal fresh stations (TF4.4 and TF4.2) are slight but noticeable compared to the oligohaline stations on the same graphs (Figure 7). The decreases at the polyhaline stations (LE4.2 and LE4.3) are evident mostly as downward slopes in the second half of the record.

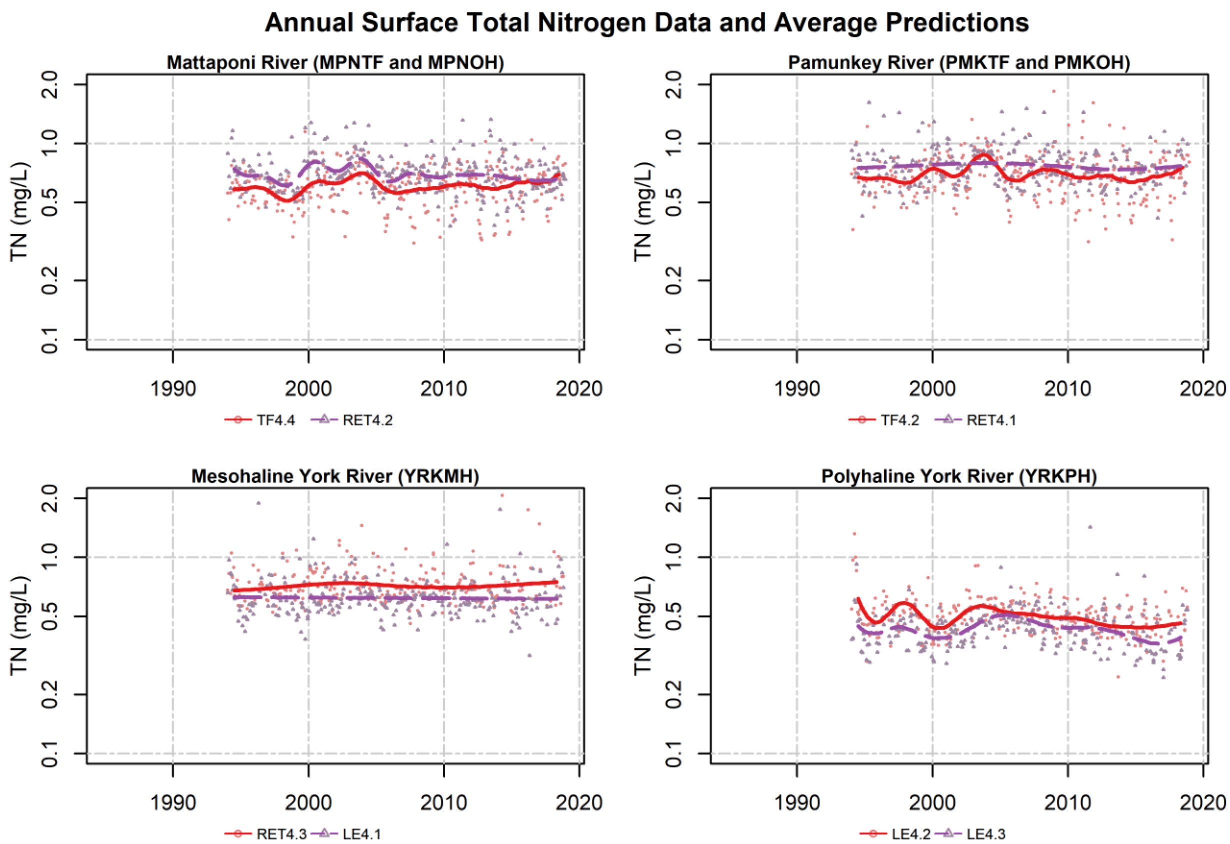

Figure 7. Surface TN data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

4.2 Surface Total Phosphorus

Surface total phosphorus (TP) trends are degrading at the oligohaline and mesohaline stations over the long-term, with and without flow-adjustment (Figure 8). There is only one possible improving long-term trend at LE4.3, otherwise no long term trends. In the short-term, TF4.2, LE4.2 and LE4.3 have improving trends both with and without flow-adjustment and RET4.3 without flow-adjustment.

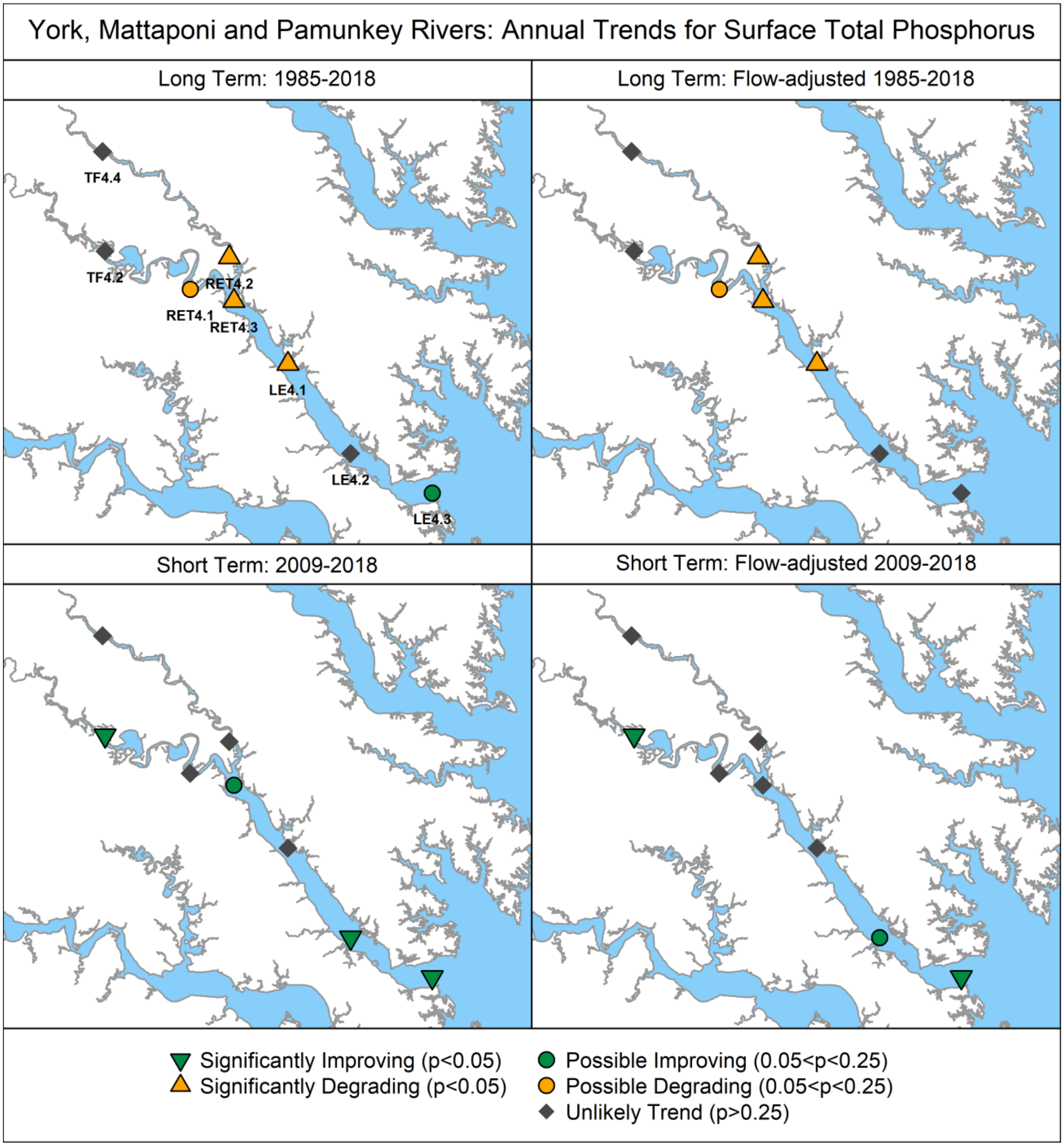

Figure 8. Surface TP trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

TP concentrations and mean annual GAM estimates increased slightly at the beginning of the record at each of the stations (Figure 9), leading in some cases to the long-term degrading trends presented in Figure 8. The TP increases clearly do not persist throughout the record at any of the stations, and in some cases there has been decreases since the mid-1990s that continued through the last 10-years (Figure 9), resulting in short-term improving trends.

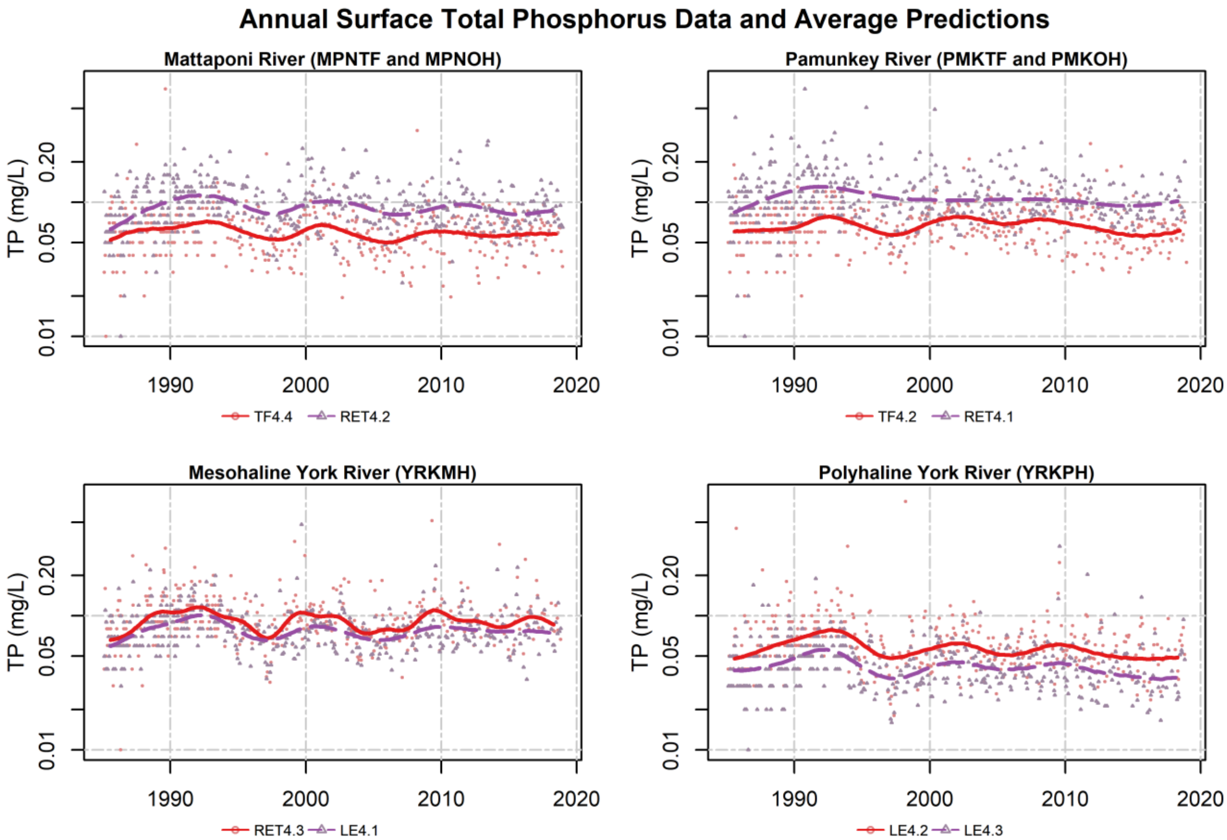

Figure 9. Surface TP data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

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 are improving at TF4.4, LE4.2 and LE4.3 over the long-term, with and without flow-adjustment (Figure 10). One additional station, RET4.3 shows a long-term degradation with flow-adjustment. All other stations have no trend over the long-term. Over the short-term, LE4.3 still has a possible improving trend, the tidal fresh stations have possible degrading trends after flow adjustment, and the oligohaline Mattaponi and Pamunkey stations have possible improvements (Figure 10).

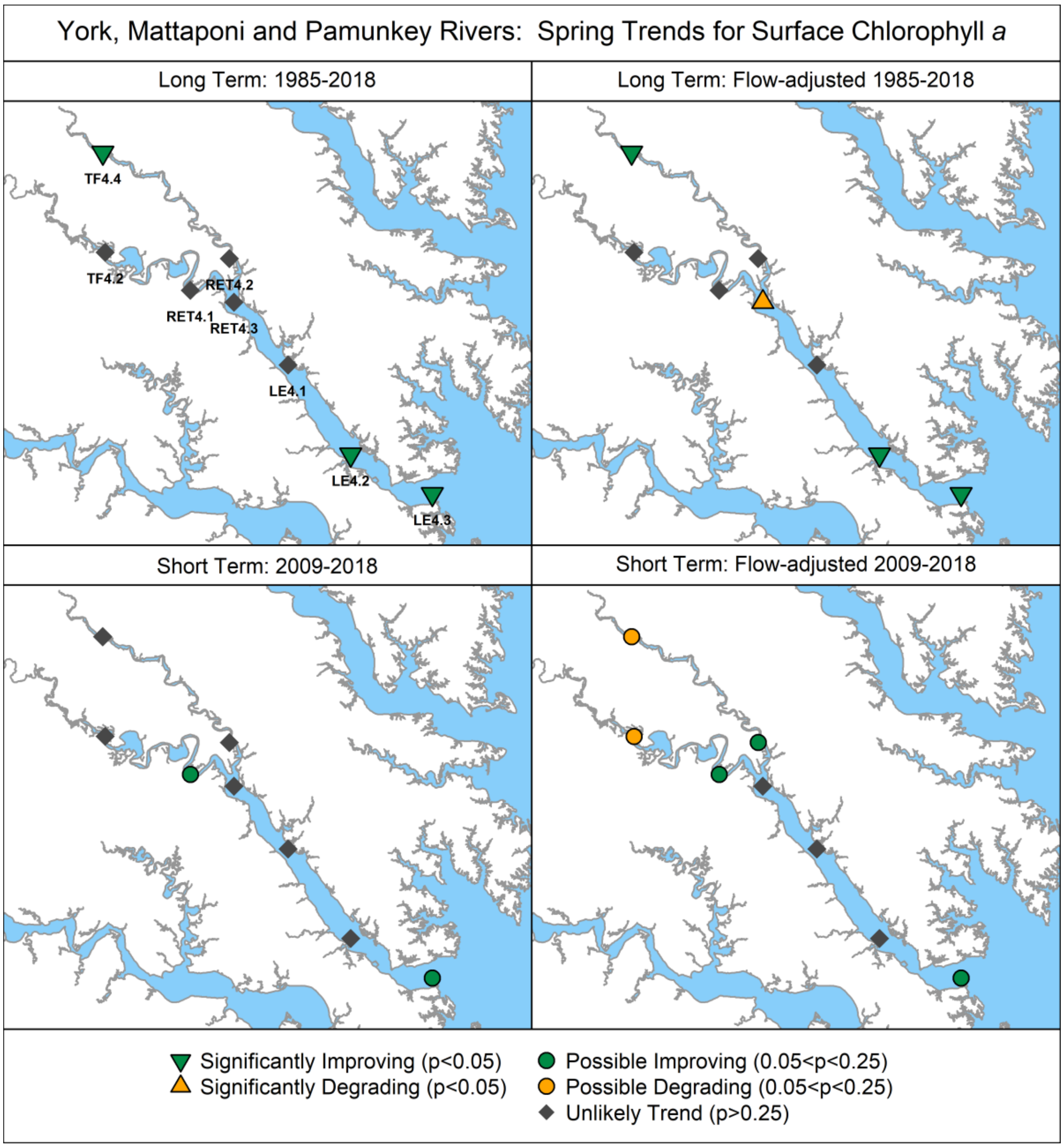

Figure 10. Surface spring (March-May) chlorophyll *a* trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

A high amount of variability in the long-term patterns can be seen in some of the spring chlorophyll *a* data sets and mean spring GAM estimates (Figure 11). The trends presented in Figure 10 are apparent in the GAM estimates. Spring chlorophyll *a* at TF4.4 is decreasing, especially compared to the more constant RET4.2. In the mesohaline York, RET4.3 is increasing over time, and the polyhaline stations (LE4.2 and LE4.3) are clearly decreasing with some of the extreme high chlorophyll *a* values not observed in the last decade (Figure 11).

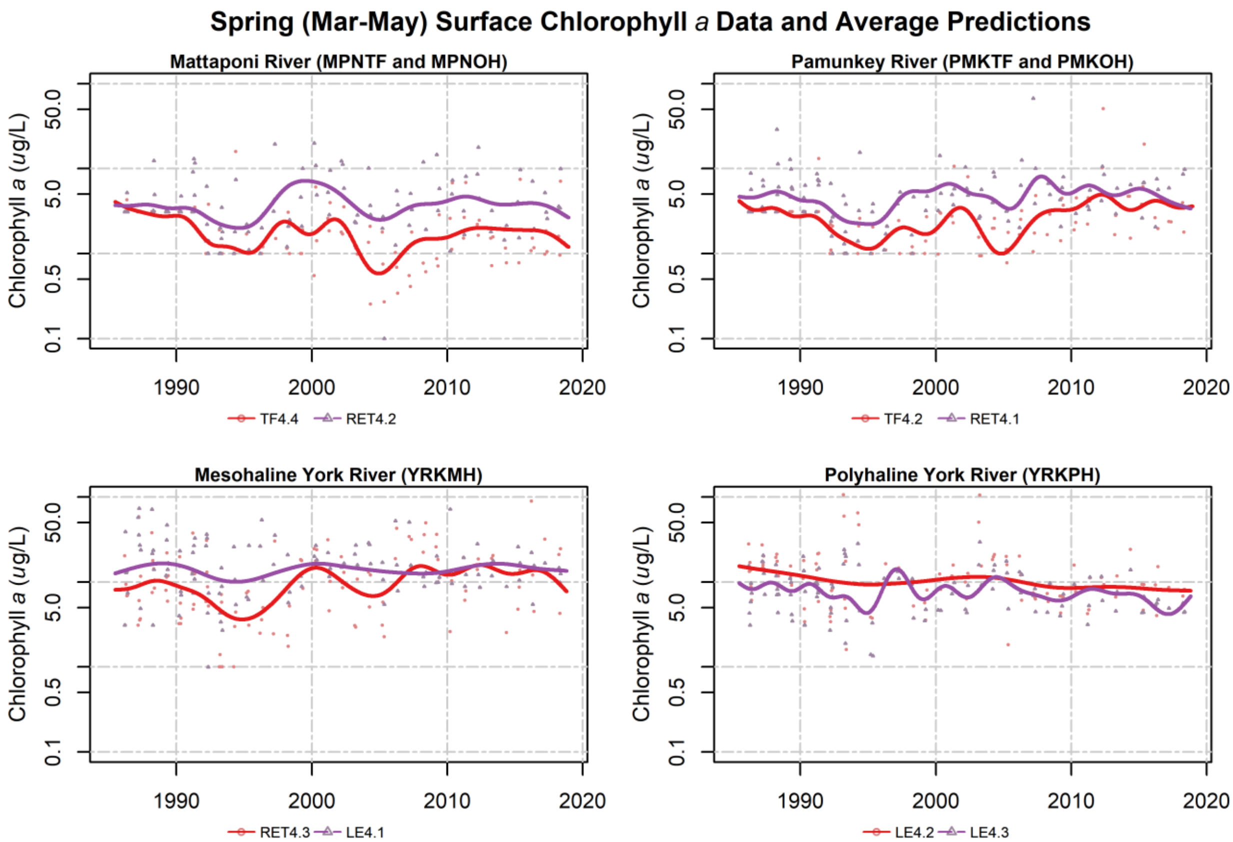

Figure 11. Surface spring chlorophyll *a* data (dots) and average long-term pattern generated from non-flow adjusted GAM. Colored dots represent March-May data corresponding to the monitoring station indicated in the legend; colored lines represent mean spring GAM estimates for the noted monitoring stations.

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

There are fewer summer chlorophyll *a* trends than spring, with some notable differences in direction as well. Summer TF4.4 has a long-term improving trend both with and without flow-adjustment, which is the only station with a significant trend in the summer results (Figure 12). With flow-adjustment, there are cluster of possible degrading trends for the RET stations. The polyhaline stations (LE4.2 and LE4.3) are possibly degrading over the summer long-term without flow adjustment (Figure 12), which is the opposite to the trend reported in spring (Figure 10). There are no summer short-term non-adjusted trends, but several possible degradations in the Mattaponi and Pamunkey Rivers and a possible improvement at LE4.3 (Figure 12).

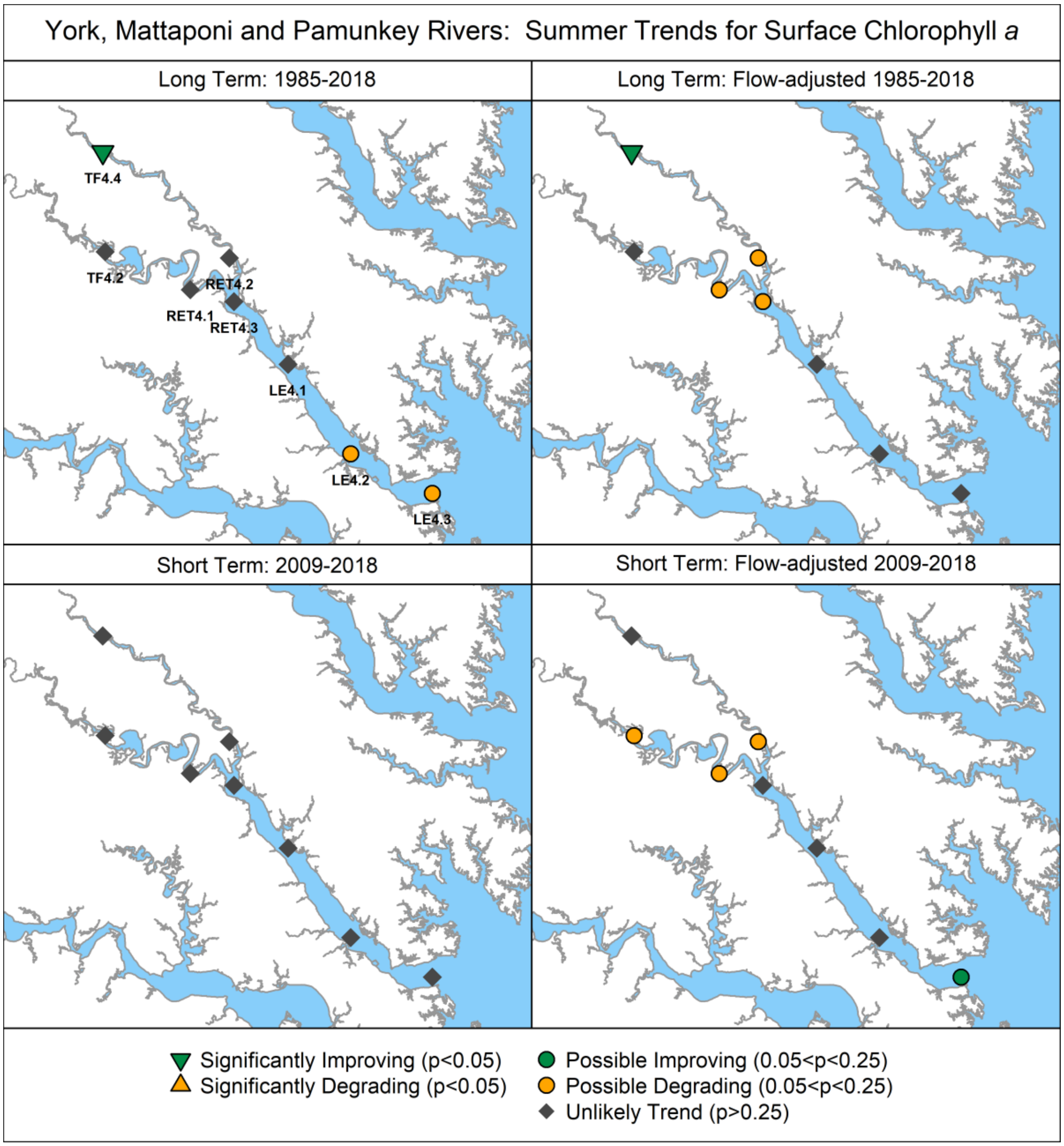

Figure 12. Surface summer (July-September) chlorophyll *a* trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

The magnitude of the summer chlorophyll *a* concentrations are slightly higher than the spring concentrations in the tidal fresh and oligohaline regions (Figure 13 compared to Figure 11). The summer mean GAM estimates also look fairly level over time at most stations, following from the relative lack of trends (Figure 12). The tidal fresh Mattaponi (TF4.4) GAM estimates decrease from the beginning to end of the record, and the polyhaline stations (LE4.2 and LE4.3) have a clear increase (Figure 13).

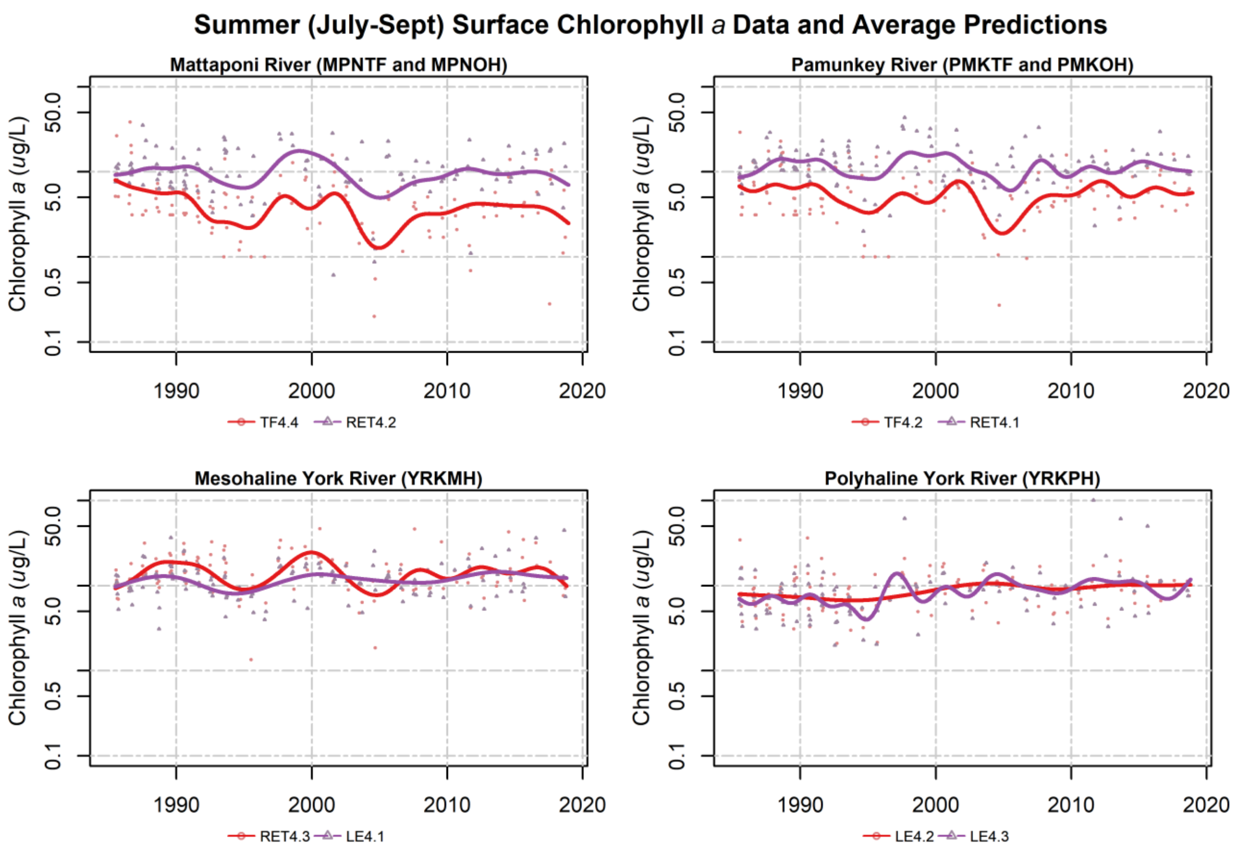

Figure 13. Surface summer chlorophyll *a* data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent July-September data corresponding to the monitoring station indicated in the legend; colored lines represent mean summer GAM estimates for the noted monitoring stations.

4.5 Secchi Disk Depth

Trends in Secchi disk depth, a measure of visibility through the water column, have degraded over the long-term at three of the four Mattaponi and Pamunkey River stations, with and without flow-adjustment (Figure 14). The short-term trends are also degrading at the two tidal fresh stations. No trends or mixed possible trends are occurring over the long-term at the other York River stations. Over the short-term, there is possible improvement in the lower part of the York River (Figure 14).

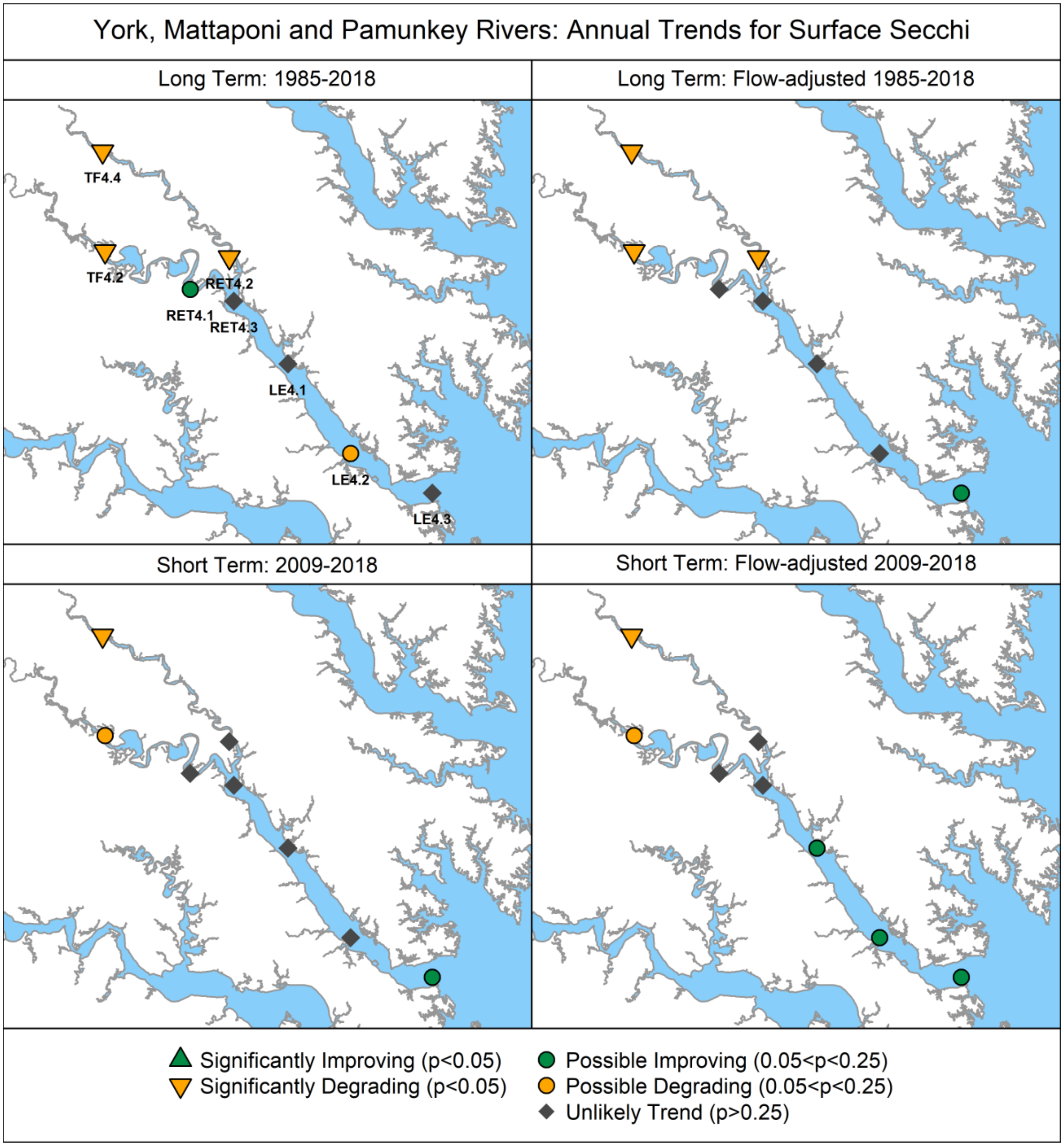

Figure 14. Annual Secchi depth trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Secchi depth values were higher at the two tidal fresh stations (TF4.4 and TF4.2), but have decreased over the record so that their mean annual GAM estimates are similar to the downstream oligohaline mean values by the end of the record (Figure 15). Patterns seem fairly constant at the other stations with the exception of LE4.3 which does appear to be increasing over the last 10 years (Figure 15), consistent with its short-term improving trend (Figure 14).

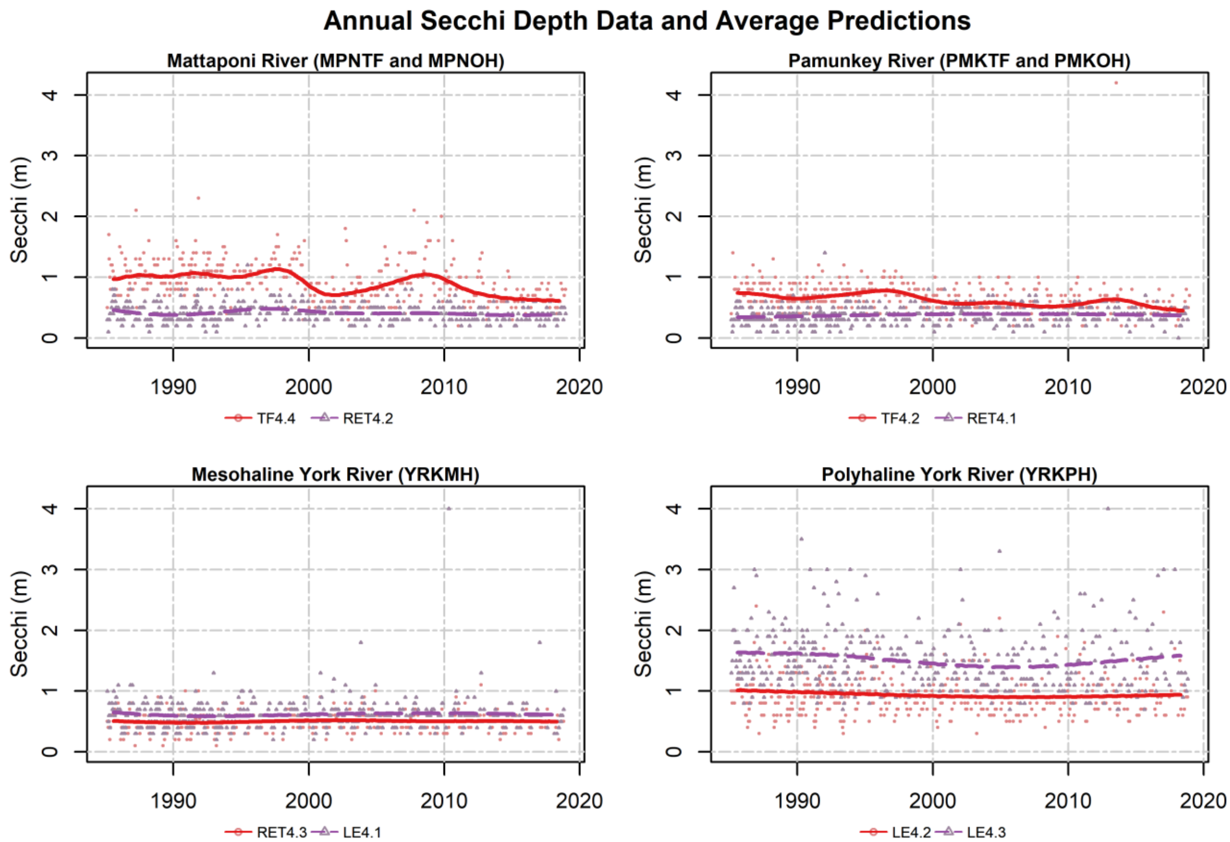

Figure 15. Annual Secchi depth data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

4.6 Summer Bottom Dissolved Oxygen (June-September)

Trends in York River summer bottom DO have decreased consistently at TF4.4 and LE4.1 over the long- and short-term, with and without flow-adjustment (Figure 16). Degrading trends have also been observed at LE4.2 consistently across methods. Improving trends over the long-term have occurred at TF4.2, both with and without flow-adjustment.

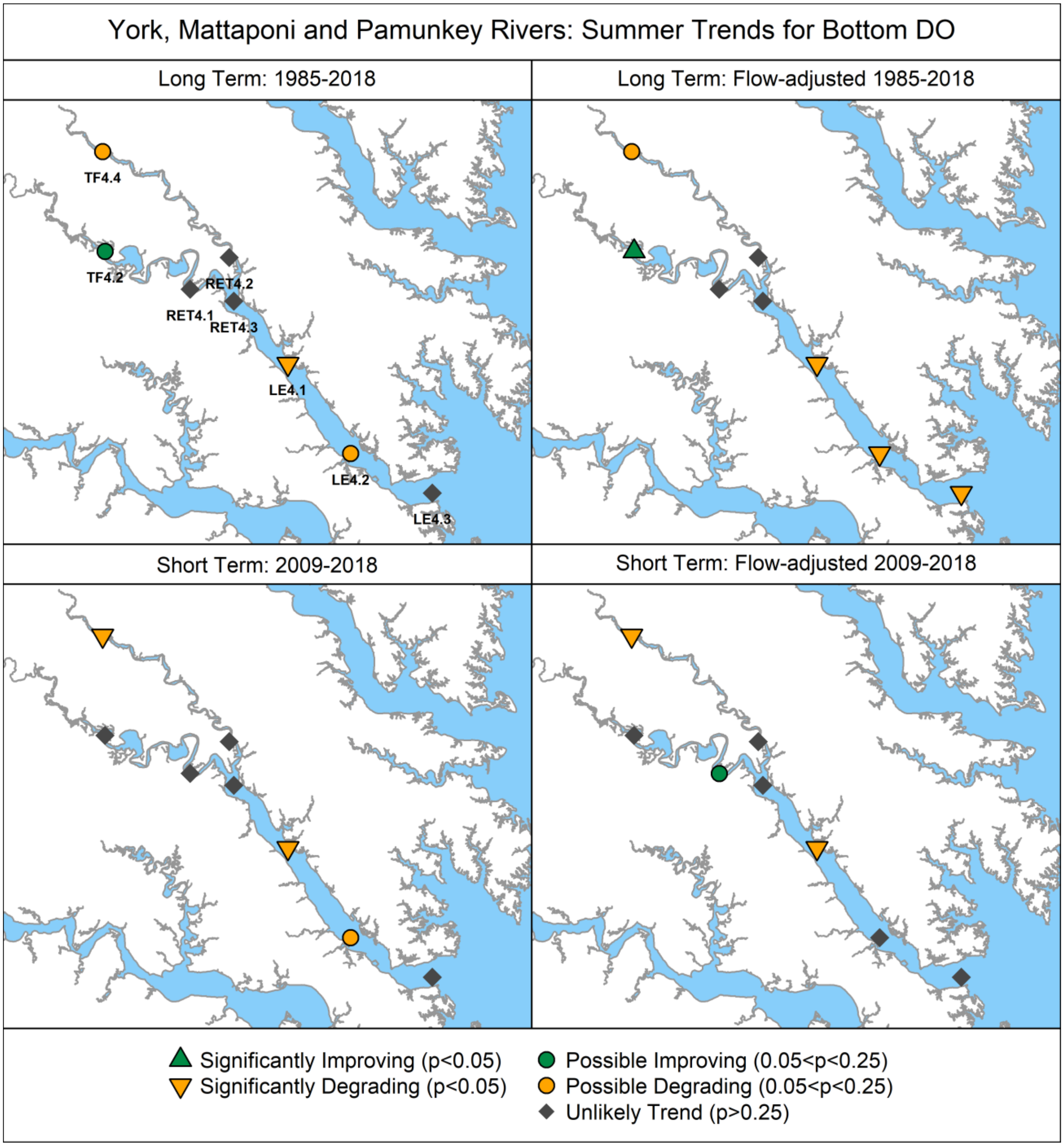

Figure 16. Summer (June-September) bottom DO trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Mean bottom summer oxygen GAM estimates are not too different across the stations in the York, Mattaponi and Pamunkey Rivers, although lower observations are more frequent at the mesohaline and polyhaline stations (Figure 17). The long-term decrease at LE4.1 in the mesohaline is clear, with more very low oxygen concentrations occurring recently. Other patterns over time appear to be variable (Figure 17), consistent with the bottom DO trends in Figure 16.

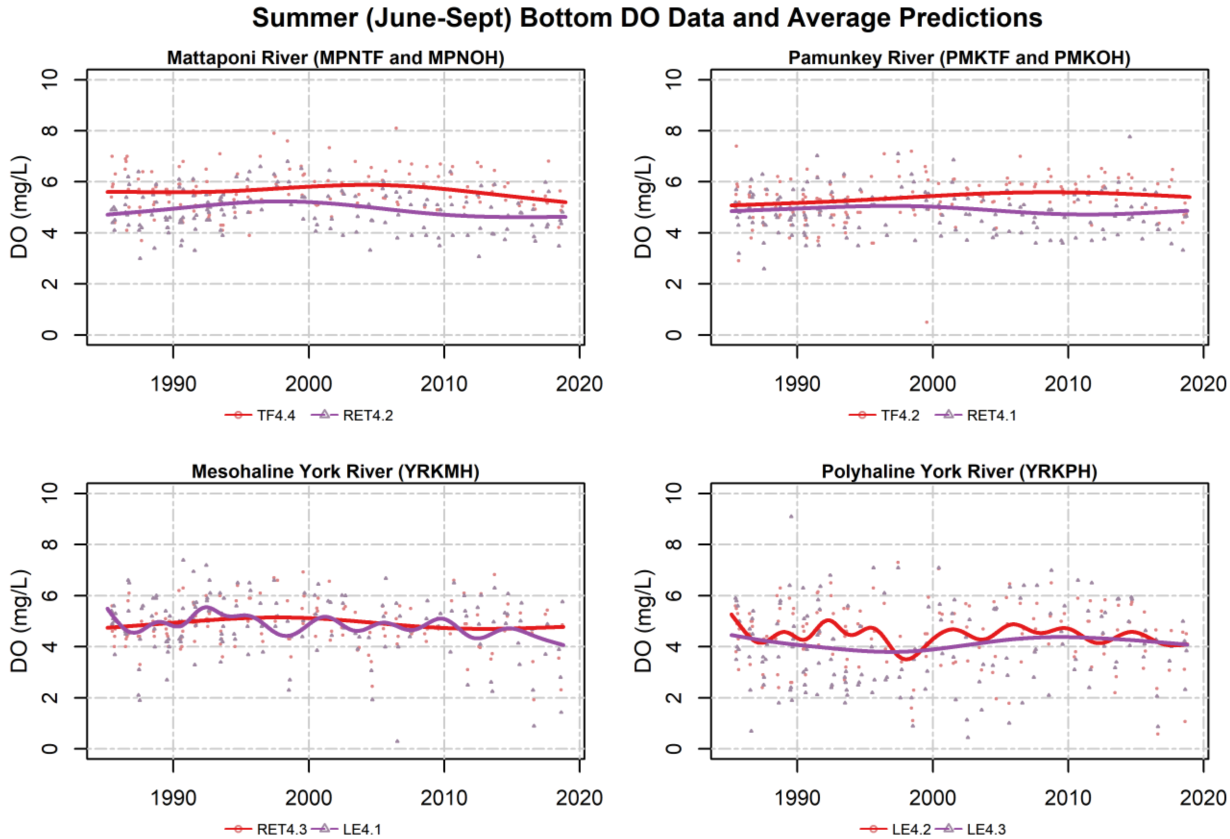

Figure 17. Summer (June-September) bottom DO data (dots) and mean summer long-term pattern generated from non-flow adjusted GAM. Colored dots represent June-September data corresponding to the monitoring station indicated in the legend; colored lines represent mean summer GAM estimates for the noted monitoring stations.

5. Factors Affecting Trends

5.1 Watershed Factors

5.1.1 Effects of Physical Setting

The geology of the York 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).

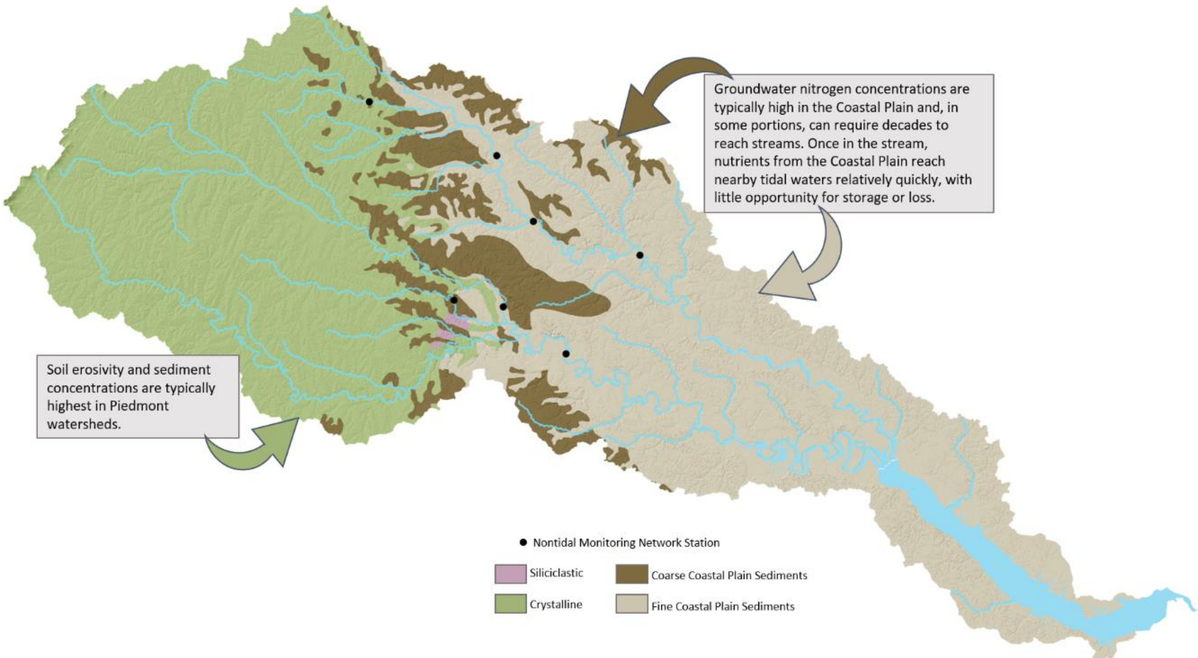

Figure 18. Effects of watershed hydrogeomorphology on nutrient transport to freshwater streams and tidal waters. Base map modified from King *et al.* (1974) and Ator *et al.* (2005), North American Datum 1983.

Nitrogen

Groundwater is an important delivery pathway of nitrogen, as nitrate to most streams in the Chesapeake Bay watershed (Ator and Denver, 2012; Lizarraga, 1997). Groundwater nitrate concentrations in the York River watershed are highest in streams above the fall line that drain Piedmont soils (Greene and others, 2005; Terziotti and others, 2017). Crystalline rocks in the above fall line portion of the York river watershed 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 York 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 York River watershed, but in-stream concentrations are typically highest in streams above the fall line that drain Piedmont geology (Brakebill *et al.*, 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 Noe, 2013; Gellis *et al.*, 2015; Gillespie *et al.*, 2018; Hopkins *et al.*, 2018), 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

The delivery of nitrogen, phosphorus, and sediment in non-tidal streams to tidal waters in the York River watershed shore 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 portions of in the York 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 York River are 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 (Noe and Hupp, 2009; Ensign *et al.*, 2014). 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 York were primarily from the below-RIM areas, whereas phosphorus loads were equally contributed by the RIM and below-RIM areas (Figure 19). Over the period of 1985-2018, 0.089, 0.0068, and 6.5 million tons of nitrogen, phosphorus, and suspended sediment loads were exported through the York River watershed, with 65%, 50%, and 75% of those loads from the below-RIM areas, respectively.

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

Nitrogen

Estimated TN loads showed an overall decline of -9.6 ton/yr in the period between 1985 and 2018, which is statistically significant ($p < 0.68$). This reduction was largely driven by a long-term decline in the below-RIM loads (-10 ton/yr; $p < 0.31$). Within the below-RIM loads, statistically significant reductions were observed with the point sources (-3.2 ton/yr, $p < 0.01$) and the atmospheric deposition to the tidal waters (-0.79 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).

Phosphorus

Estimated TP loads showed an overall decline of 0.40 ton/yr in the period between 1985 and 2018, although it is not statistically significant ($p = 0.66$). This decline was largely driven by the below-RIM loads (-0.84 ton/yr; $p < 0.05$). Within the below-RIM load, point sources showed a statistically significant decline in this period (-0.76 ton/yr; $p < 0.01$), whereas nonpoint sources showed a long-term increase (0.17 ton/yr, $p = 0.48$). 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 558 ton/yr in the period between 1985 and 2018, although it is not statistically significant ($p = 0.34$). Both the RIM and below-RIM loads showed long-term 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 (-3.0 ton/yr; $p < 0.01$).

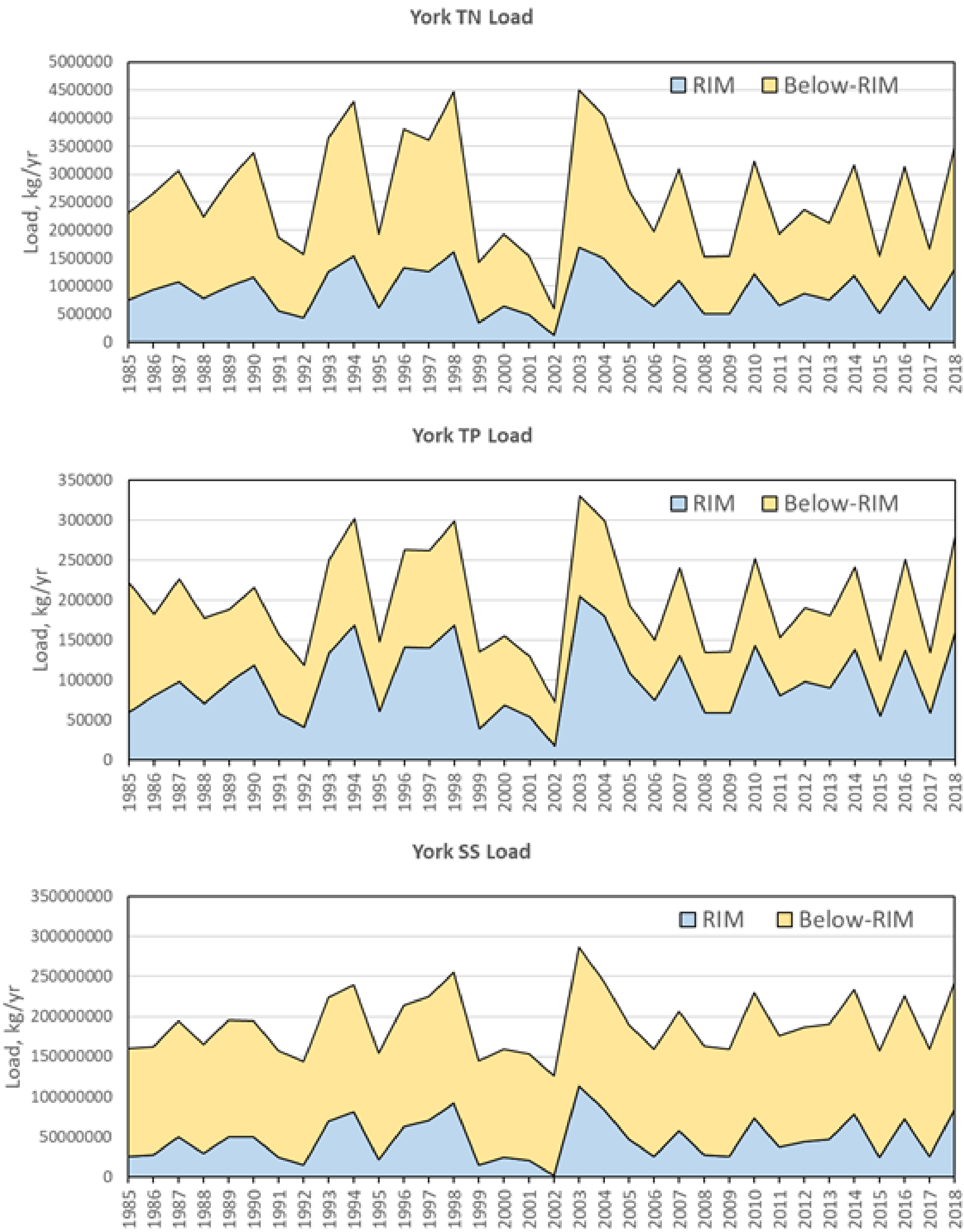

Figure 19. Estimated total loads of nitrogen (TN), phosphorus (TP), and suspended sediment (SS) from the RIM and below-RIM areas of the York River. RIM refers to the USGS River Input Monitoring sites located just above the head of tide of the two tributaries (i.e., Mattaponi and Pamunkey), which includes 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 York River watershed.

Variable	Trend, metric ton/yr	Trend p-value
TN		
Total watershed	-9.6	0.68
RIM watershed [1]	0.14	0.98
Below-RIM watershed [2]	-10	0.31
Below-RIM point source	-3.2	< 0.01
Below-RIM nonpoint source [3]	-2.8	0.72
Below-RIM tidal deposition	-0.79	< 0.05
TP		
Total watershed	-0.40	0.66
RIM watershed	0.61	0.55
Below-RIM watershed	-0.84	< 0.05
Below-RIM point source	-0.76	< 0.01
Below-RIM nonpoint source	0.17	0.48
SS		
Total watershed	558	0.34
RIM watershed	424	0.33
Below-RIM watershed	146	0.46
Below-RIM point source	-3.0	< 0.01
Below-RIM nonpoint source	141	0.44

[1] Loads for the RIM watershed were estimated loads at the USGS RIM stations 01673000 (Pamunkey River near Hanover, Va.) and 01674500 (Mattaponi River near Beulahville, 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 York River by -7%, -38%, and -9%, 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 (-20%), natural (-7%), stream bed and bank (-2%), and wastewater (-26%) sources were partially counteracted by increases from developed (84%) and septic (83%) sources.

The two largest sources of phosphorus loads as of 2019 were the stream bed and bank and wastewater sectors. Overall, expected declines from agriculture (-55%), natural (-7%), stream bed and bank (-13%), and wastewater (-74%) sources were partially counteracted by increases from developed (101%) sources.

For sediment, the largest sources are shoreline and stream bed and bank areas: these two sources changed by -1% and -24%, respectively between 1985 and 2019. Sediment loads from the agriculture sector changed by -53%, whereas sediment load from developed areas changed by 43%.

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.

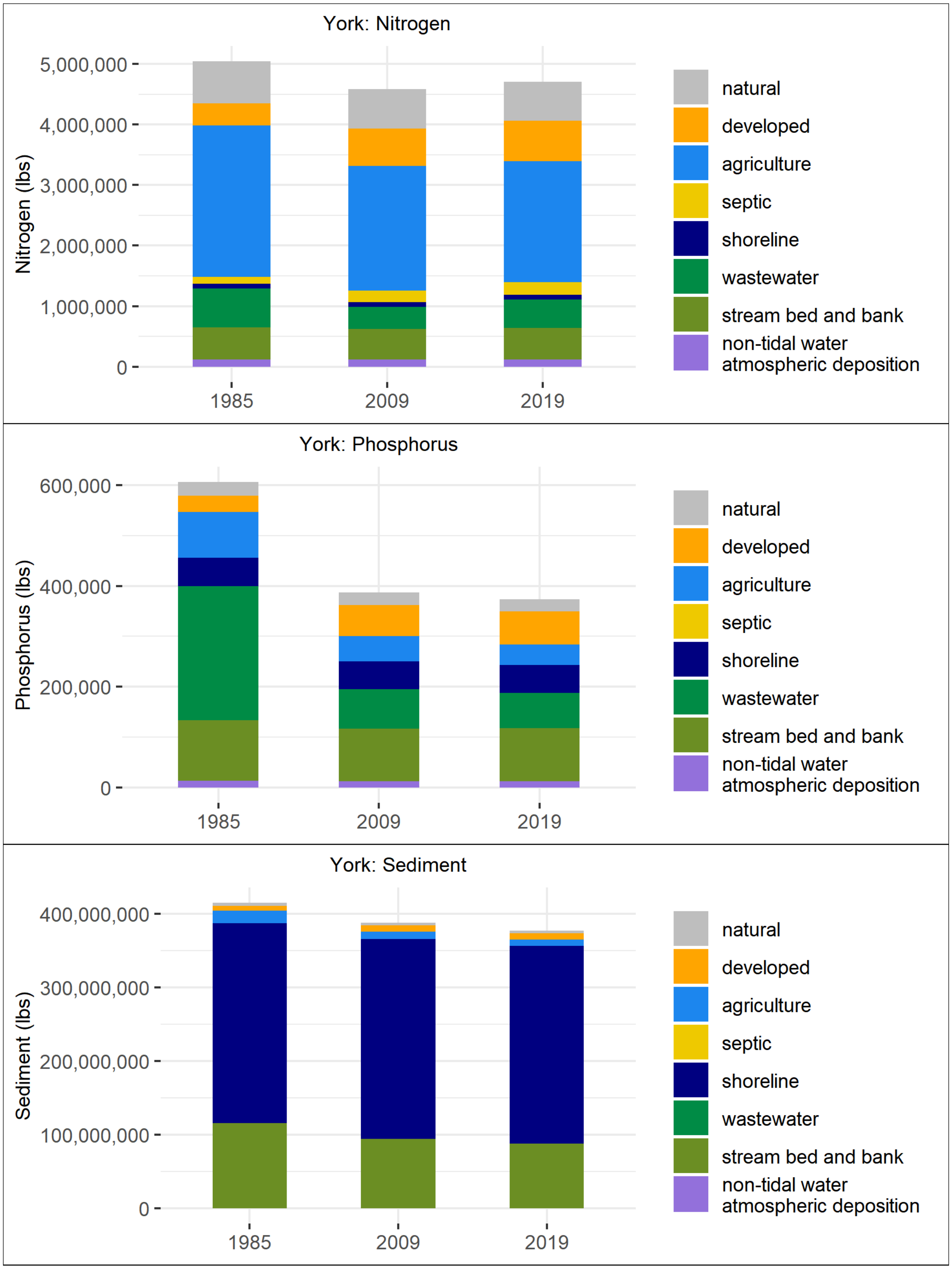

Figure 20. Expected long-term average loads of nitrogen, phosphorus, and sediment from different sources to the tidal York, as obtained from the Chesapeake Assessment Scenario Tool (CAST-19). Data shown are time-average delivered loads over the average hydrology of 1991-2000, once the steady state is reached for the conditions on the ground, as obtained from the 1985, 2009, and 2019 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 116, 32, 38, 0.0, 12, 170, and 3.1 thousand acres, respectively. Implementation levels for some practices are already close to achieving their planned 2025 levels: for example, 98% of planned acres for pasture management had been achieved as of 2019. In contrast, about 5% of planned urban nutrient management implementation had been achieved as of 2019.

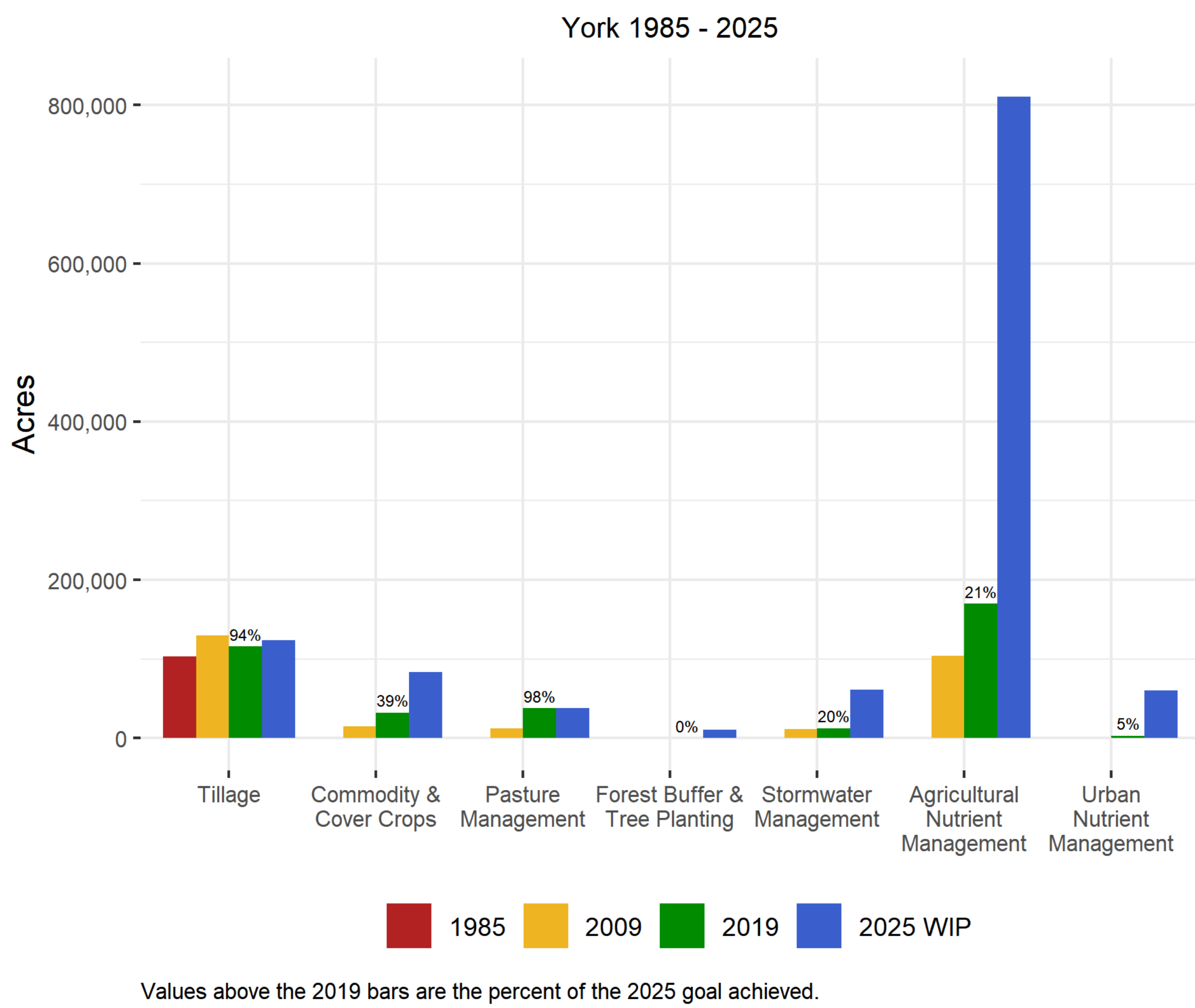

Figure 21. BMP implementation in the York watershed

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 17,432 feet in 2019. Over the same period, animal waste management systems treated 0 animal units in 1985 and 3,856 animal units in 2019 (one animal unit represents 1,000 pounds of live animal). These implementation levels represent 14% and 12% 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 York 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
01671020	NORTH ANNA RIVER AT HART CORNER NEAR DOSWELL, VA	1985	**31.2**	-	-
		2009	**10.9**	15.6	**29.1**
01671100	LITTLE RIVER NEAR DOSWELL, VA	2009	**-18.9**	-	-
01673000	PAMUNKEY RIVER NEAR HANOVER, VA	1985	**12.4**	**78.2**	**82.7**
		2009	**15.5**	**10.2**	**20.7**
01673800	PO RIVER NEAR SPOTSYLVANIA, VA	1987	**18.0**	-	-
		2009	**4.4**	-	-
01674000	MATTAPONI RIVER NEAR BOWLING GREEN, VA	1985	**20.4**	-	-
		2009	**17.0**	-	-
01674500	MATTAPONI RIVER NEAR BEULAHVILLE, VA	1985	**-2.7**	**7.0**	**11.8**
		2009	**13.4**	**15.2**	**35.8**

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).

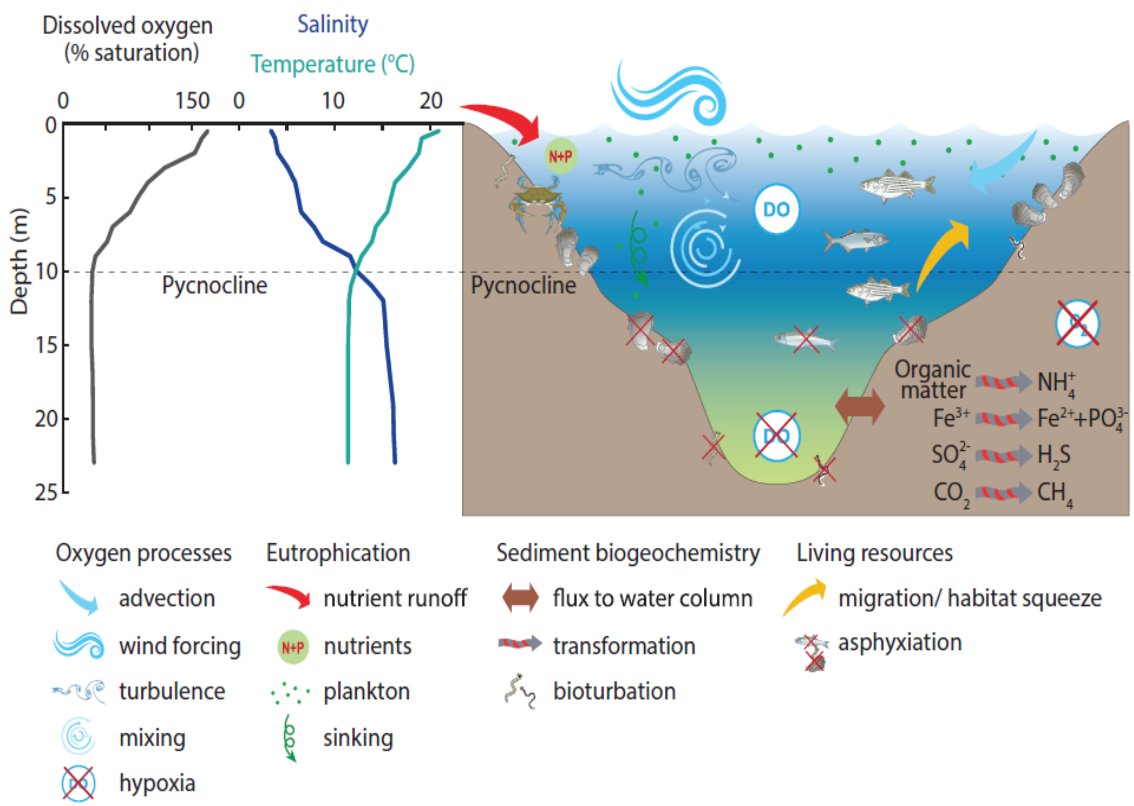

Figure 22. Conceptual diagram illustrating how hypoxia is driven by eutrophication and physical forcing, while affecting sediment biogeochemistry and living resources. From Testa *et al.* (2017).

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.

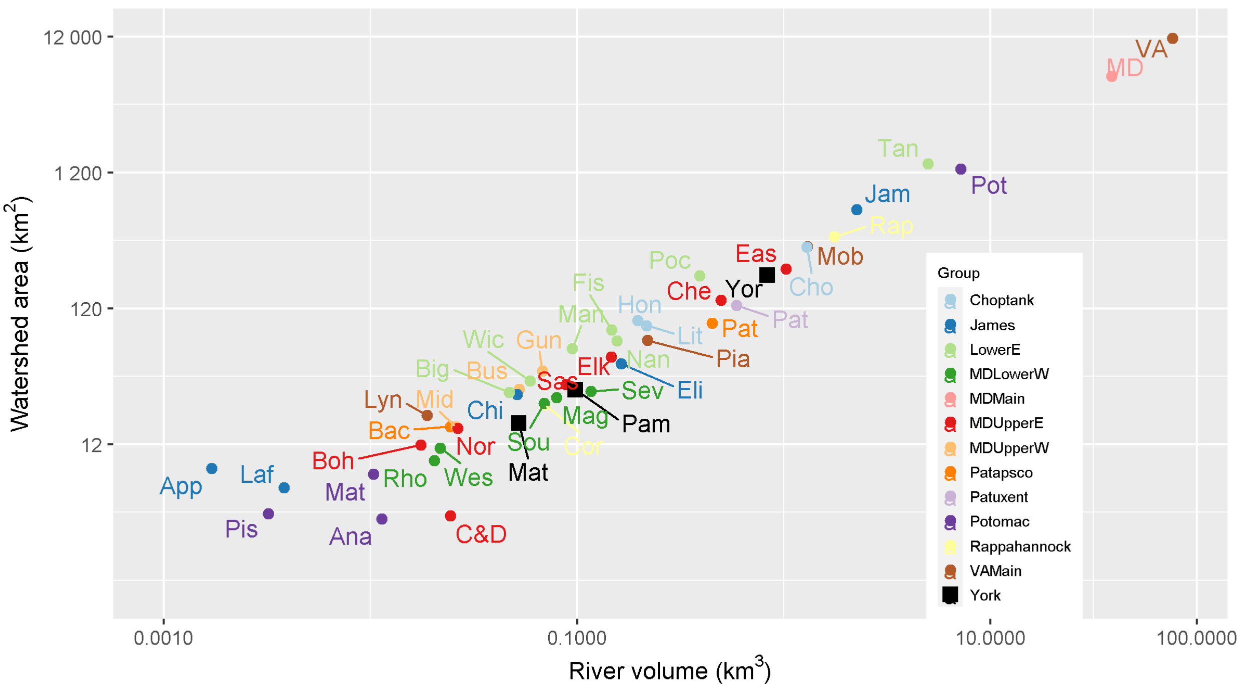

Figure 23. Watershed area vs estuarine volume.

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

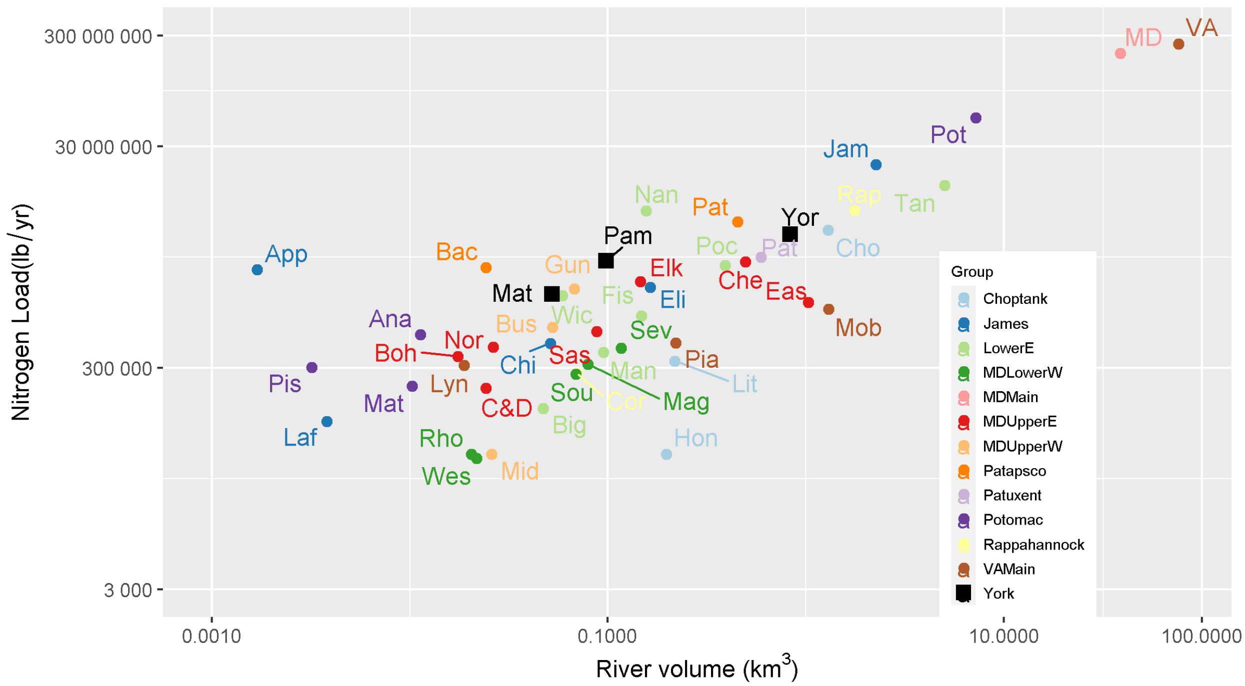

Figure 24. Annual average expected nitrogen loads versus estuarine volume. Nitrogen loads are from the 2018 progress scenarios in CAST (Chesapeake Bay Program, 2020), which is an estimate of nitrogen loads under long-term average hydrology given land use and reported management as of 2018.

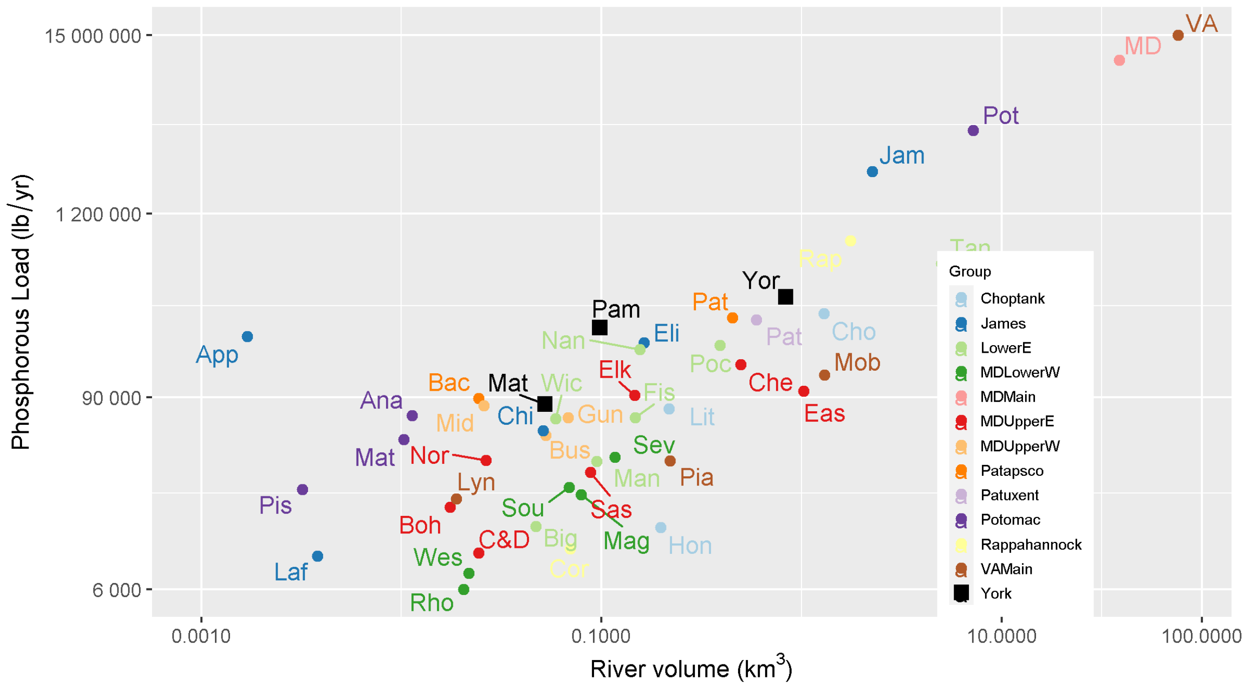

Figure 25. Annual average expected phosphorus loads versus estuarine volume. Phosphorus loads are from the 2018 progress scenarios in CAST (Chesapeake Bay Program, 2020), which is an estimate of phosphorus loads under long-term average hydrology given land use and reported management as of 2018.

The York river estuary volume and watershed contain approximately 1 and 4% of the total volume and watershed of the Chesapeake Bay. This ranks the York as the 9th largest volume and 4th 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 tributaries within the York system, the Mattaponi and Pamunkey rivers both have slightly elevated loads of phosphorus relative to their estuarine volume. These tributaries have elevated nitrogen loads relative to estuarine volume.

5.3 Insights on Changes in the York

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.*

6. Summary

Completion of Section 6 is contingent upon completion of Section 5.3.

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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