DRAFT

Rappahannock Tributary Report:

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

November, 2021

Contents

1. Purpose and Scope

This report summarizes long term changes in a suite of water quality parameters and associated potential drivers of those trends at stations monitored in the tidal portion of the Rappahannock River for the period 1985 through 2018. An attempt is made to connect the observed trends in water quality and potential natural and anthropogenic drivers of change in the Rappahannock River watershed based on our current understanding of the relationships between these drivers and water quality conditions. Water quality parameters described below include surface total nitrogen (TN), surface total phosphorus (TP), spring and summer 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 N, P, 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. Continued monitoring and evaluation of both water quality parameters and the drivers that influence them are essential tools for the long-term environmental management goals for the Rappahannock River.

2. Location

The Rappahannock River is the largest tributary to the Chesapeake Bay in terms of area, and the fourth largest in terms of nutrient loads. Its watershed spans approximately 7,370 km^2, and accounts for seven percent of the area of the state of Virginia. Major tributaries to the Rappahannock River include the Rapidan, Robinson, and Corrotoman rivers. Approximately 56% of the Rappahannock River watershed is located above the fall-line at Fredericksburg, VA.

2.1 Watershed Physiography

The Rappahannock River watershed stretches across four major physiographic regions, namely, Blue Ridge, Mesozoic Lowland, Piedmont Crystalline, and Coastal Plain (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 4.1.

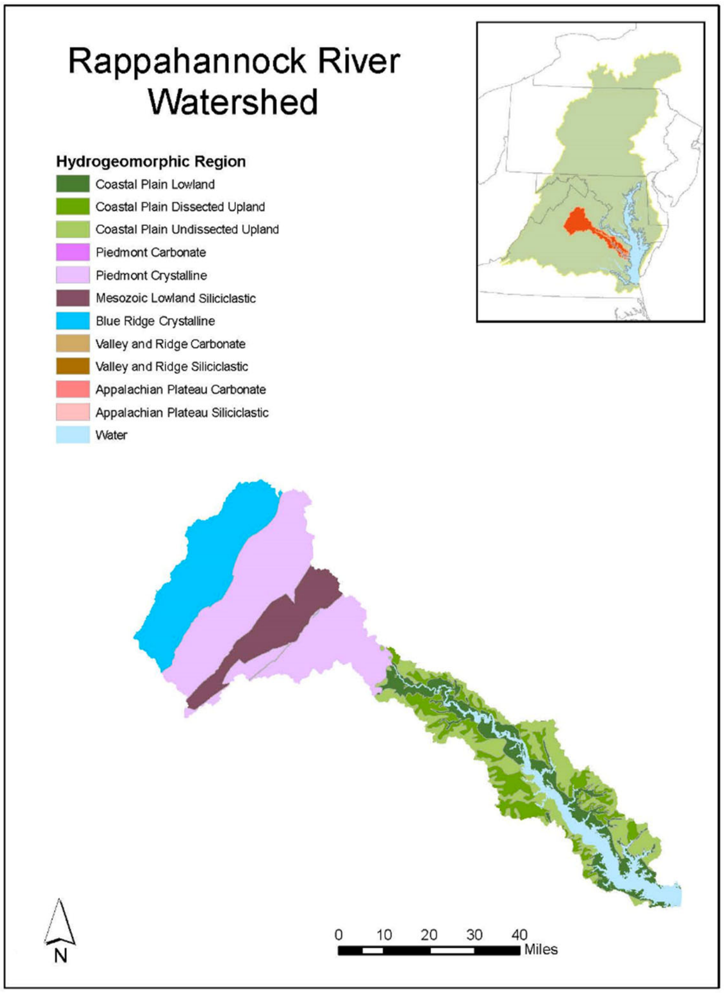


Figure 1. Distribution of physiography in the Rappahannock River watershed. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

2.2 Land Use

Although land use in the Rappahannock watershed is dominated (66%) by natural areas, urban and suburban land areas have increased from just under 89,000 acres in 1985 to just over 166,000 acres by 2019, an increase of 87% (Figure 2). There was a concomitant decrease in the percentages of both natural and agricultural land use types of 2% and 12%, respectively, during the period (Figure 2). In general, developed lands in the 1970s were concentrated in the tidal portion of the watershed and, while expansion of developed lands continued below the fall-line, they have begun to expand in regions above the fall line as well (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 4.1.

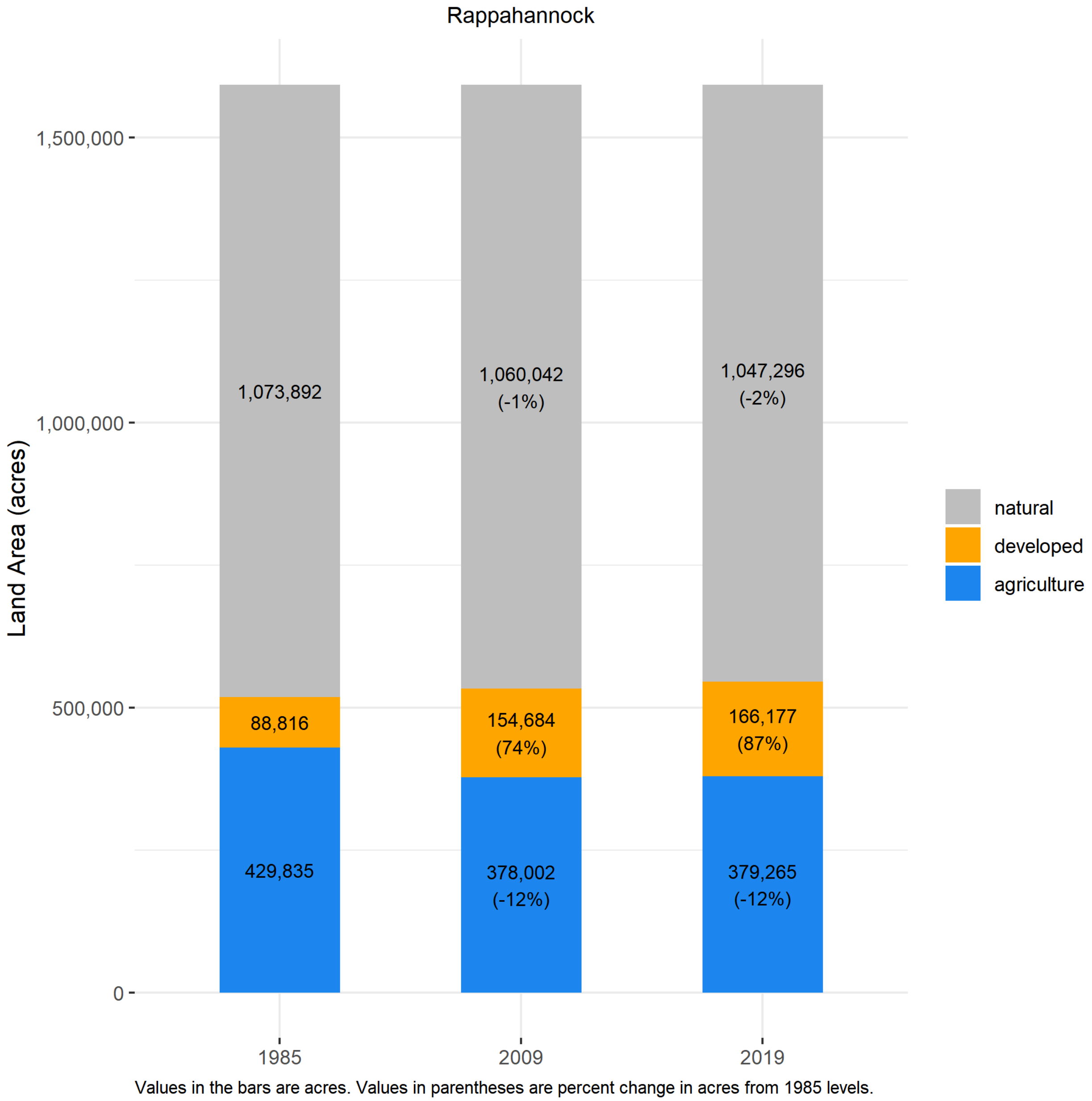


Figure 2. Distribution of land uses in the Rappahannock River watershed.

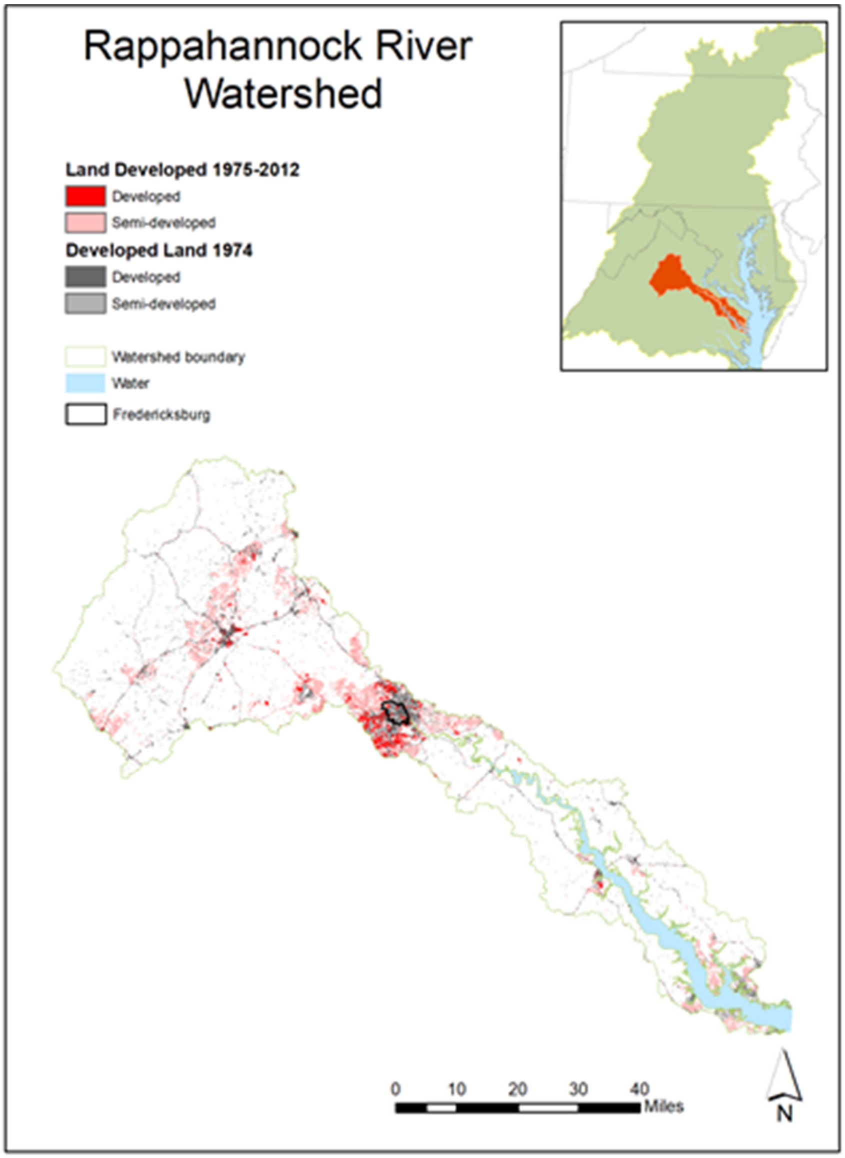


Figure 3. Distribution of developed land in the Rappahannock River watershed. Derived from Falcone (2015). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

2.3 Tidal Waters and Stations

For the purposes of water quality standards assessment and reporting, the tidal waters associated with the Rappahannock River were divided into four segments: The tidal fresh (RPPTF), oligohaline (RPPOH), and mesohaline (RPPMH) and the Corrotoman River (CRRMH), a tributary of the Rappahannock, located on its northern banks about 13 km from the mouth of the river (Figure 4).

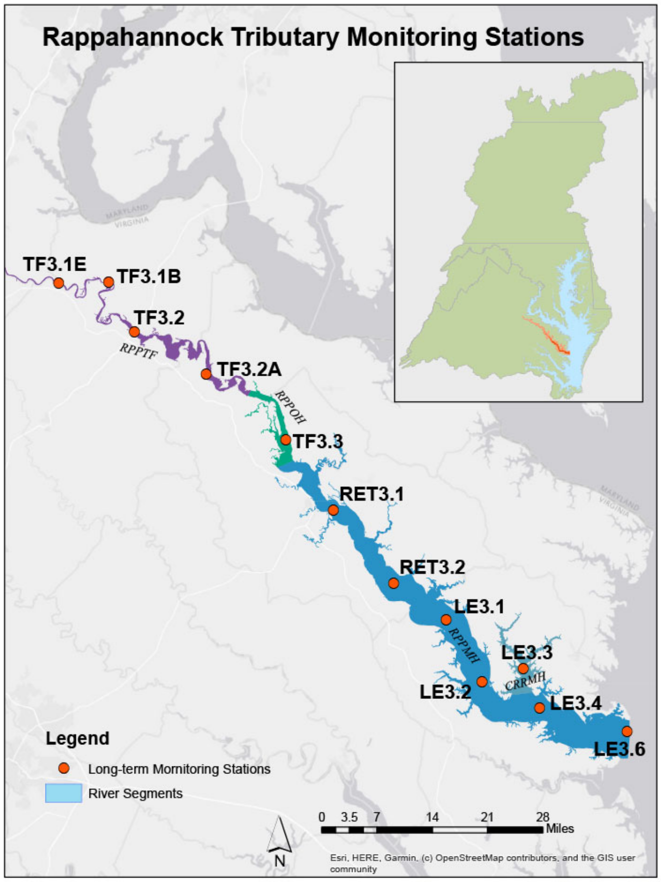


Figure 4. Map of tidal Rappahannock River segments and long-term monitoring stations. Base map credit Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community, World Geodetic System 1984.

Water quality data used to evaluate long term trends were collected by the Virginia Department of Environmental Quality (VADEQ) and Old Dominion University (ODU) at 12 stations stretching from the tidal freshwater portion of the estuary (station TF3.1E) located near the fall line at Fredericksburg to station LE3.6 at the mouth of the Rappahannock where it empties into Chesapeake Bay (Figure 4). Water quality data collected at these stations along with those collected by the VADEQ shallow-water monitoring program (not shown in Figure 4) were used to assess attainment of dissolved oxygen (DO) water quality criteria.

3. Water Quality Trends and Management Goals

The Rappahannock River provides a direct example of the relevance of long-term water quality monitoring and the evaluation long term trends relative to environmental management goals. Multiple water quality standards were developed for the tidal Rappahannock and Chesapeake Bay in general 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 report, a record of the evaluation results indicating whether different Rappahannock segments have met or not met a subset of Open Water (OW), Deep Water (DW), and Deep Channel (DC) DO criteria over time (Zhang et al., 2018a; Hernandez Cordero et al., 2020) is shown below (Figure 5). While analysis of water quality standards attainment was not the focus of this report, the results over time from the evaluation of these three DO criteria the applicable Rappahannock River monitoring segment are included here to provide context for the importance of understanding water quality trends and the underlying drivers that control them. More specifically, trends in the water quality parameters summarized in this report directly affect environmental management goals implemented by interested stakeholders within the watershed. For more information on water quality standards, criteria, and standards attainment, visit the CBP's "Chesapeake Progress" website at www.chesapeakeprogress.com. 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).

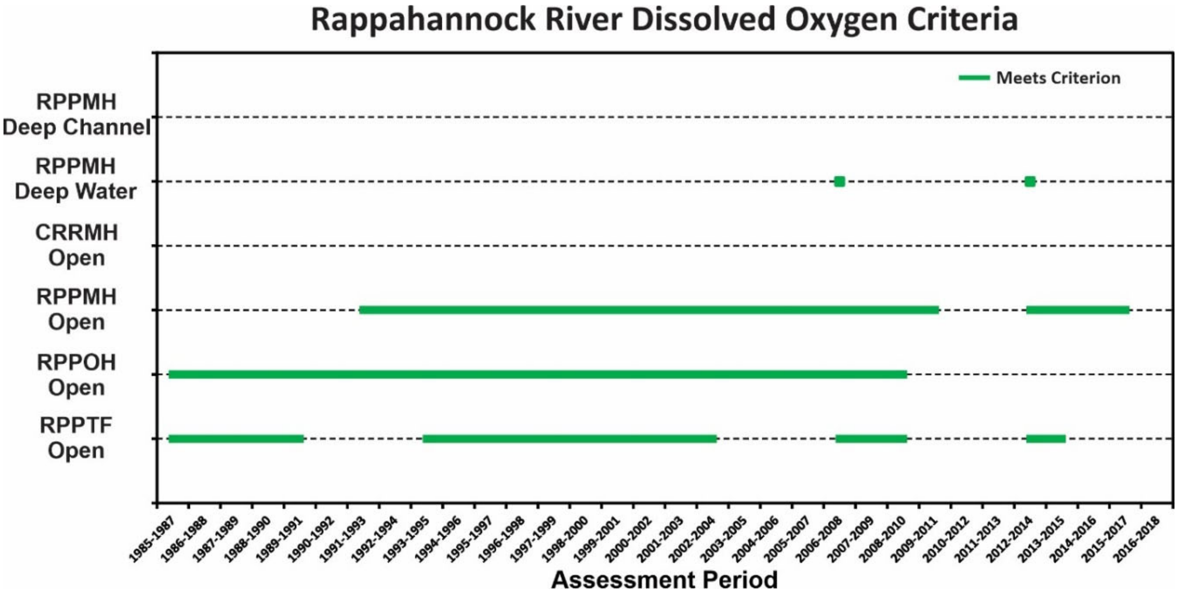


Figure 5. D), Deep Water summer DO (30-day mean), Deep Channel (Instantaneous) and Open Water summer DO (30-day mean June-September assessment period) criteria evaluation results. Green lines indicates the criterion was met. All gaps indicate a violation of the criterion listed.

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 Open Water (OW) summer and Deep Channel (DC) instantaneous DO criteria shown in Figure 5 are overlain with the 1985-2018 change in summer surface DO concentration and the 1985-2018 change in bottom summer DO concentrations, respectively (Figure 6). 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 the 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. This example, clearly shows the importance not only of

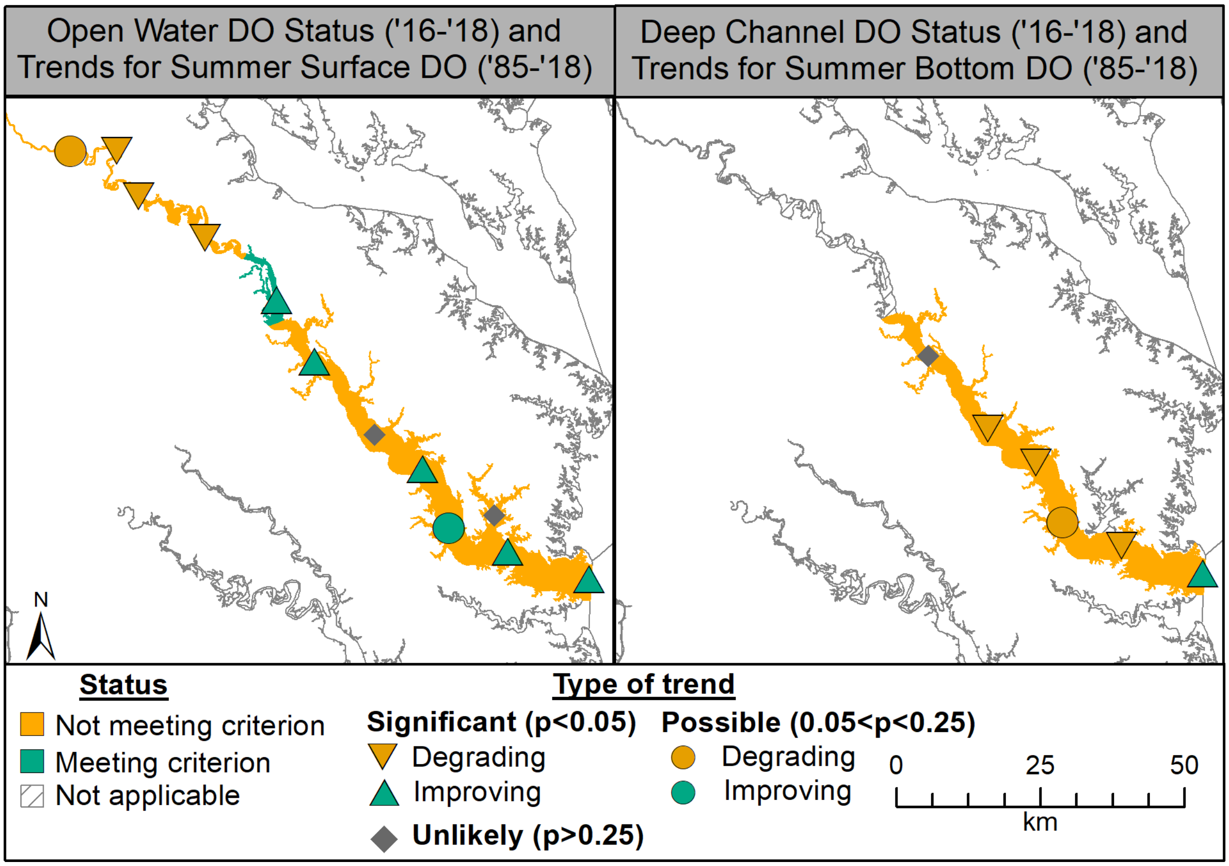


Figure 6. Pass-fail DO criterion status for 30-day OW summer DO and DC instantaneous DO designated uses in Rappahannock segments along with long-term trends in DO concentrations. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

4. Tidal Water Quality Trends

Trend analysis was conducted on water quality observations collected at the 12 tidal stations (Figure 4) by VADEQ and ODU. For more details on the GAM implementation that is applied each year for these stations in collaboration with the Chesapeake Bay Program and Maryland analysts, see Murphy *et al.* (2019). are computed by fitting generalized additive models (GAMs)

Results shown below in each set of maps (e.g., Figure 6) include those generated using two different GAM models applied to each station-parameter combination. The first approach involves fitting a GAM to the raw observations to generate a mean estimate of change over time, as observed in the estuary. The second approach involves including monitored river flow or *in situ* salinity (as an aggregated measure of multiple river flows) in the GAM to explain some of the variation in the water quality parameter. From the results of this second approach, it is possible to estimate the “flow-adjusted” change over time, which gives a mean estimate of what the water quality parameter trend would have been if river flow had been averaged over the period of record. Results of the flow or salinity adjusted results are typically used to help investigators determine if variability in these potential natural stressors rather than changes in anthropogenic stressors such as point and non-point loads are responsible for change in water quality concentrations. Note that depending on the location in the Rappahannock River, adjustment for these effects may be carried out using either gaged river flow at the fall-line or salinity at the station, but for the purposes of simplicity and clarity all such results are referred to as “flow-adjusted”.

Long term trends in predicted values generated by both GAM models are evaluated using methods described in Murphy et al., 2019. Parameter specific maps of statistically significant ($p \leq 0.05$) and potential trends ($0.05 > p \leq 0.25$) were created to allow a comprehensive evaluation of long-term changes in the river for each parameter and identify locations where potential trends may be developing (Murphy et al., 2019). Plots of observed and mean annual or seasonal annual predictions from the first set (no flow adjustment) of GAM model were plotted to examine the overall shape of the trend and general validity of the fit (e.g., Figure 7).

4.1 Surface Total Nitrogen

Although tidal monitoring program in the Rappahannock River began in 1985, changes in methodology used to estimate TN resulted in step trends in the data that make clear evaluations using data prior to 1994 for most but not all stations difficult. As a result, trends presented in the map for TN (Figure 7) may be listed as being from 1985 through 2018 but is in fact from 1994 through 2018. To confirm the period of record for each station evaluated, see Figure 8.

Annual total nitrogen concentrations have decreased (improved) at nearly all the mesohaline Rappahannock tidal stations over both the long-term and short-term, using both non-flow-adjusted results and adjusted protocols (Figure 7). Improving trends were also observed at the uppermost tidal fresh station, but in general the tidal freshwater and oligohaline portions of the estuary showed no change in this parameter.

Slight decreases are apparent over the long-term at many stations in both the data and the non-flow-adjusted mean annual GAM estimates (Figure 8). Most stations seem to exhibit a roughly decadal cycle of increasing and decreasing concentration as indicated by the plots of predicted values that appear to be similar within a given salinity regime (Figure 8). An upswing in 2018 is clear in many of these graphs as well, which are likely due higher river flows in that year (Figure 8).

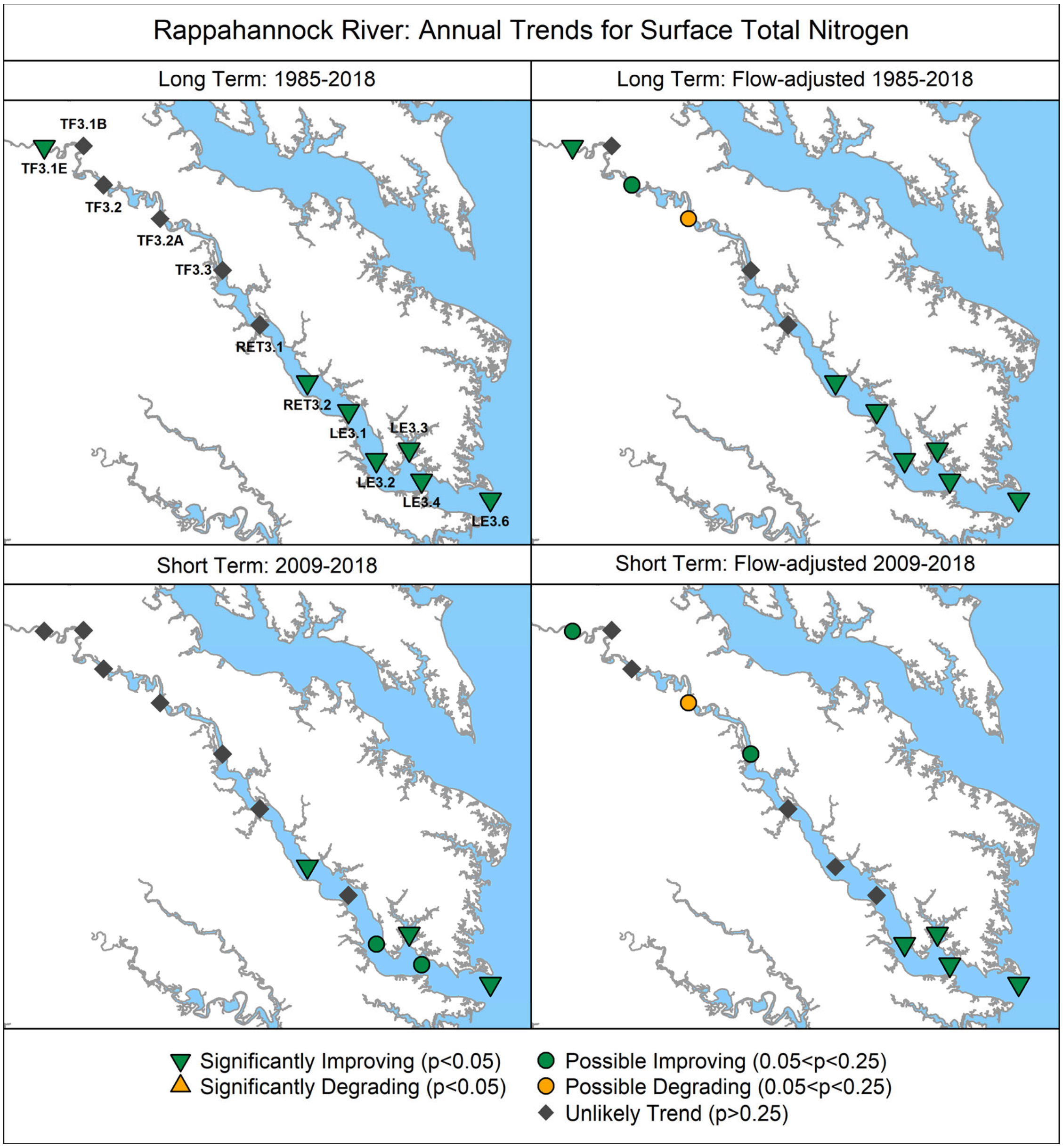


Figure 7. Surface trends in total nitrogen concentrations. Note that for the Rappahannock most of these trends begin in 1994 due to data availability. Basse map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

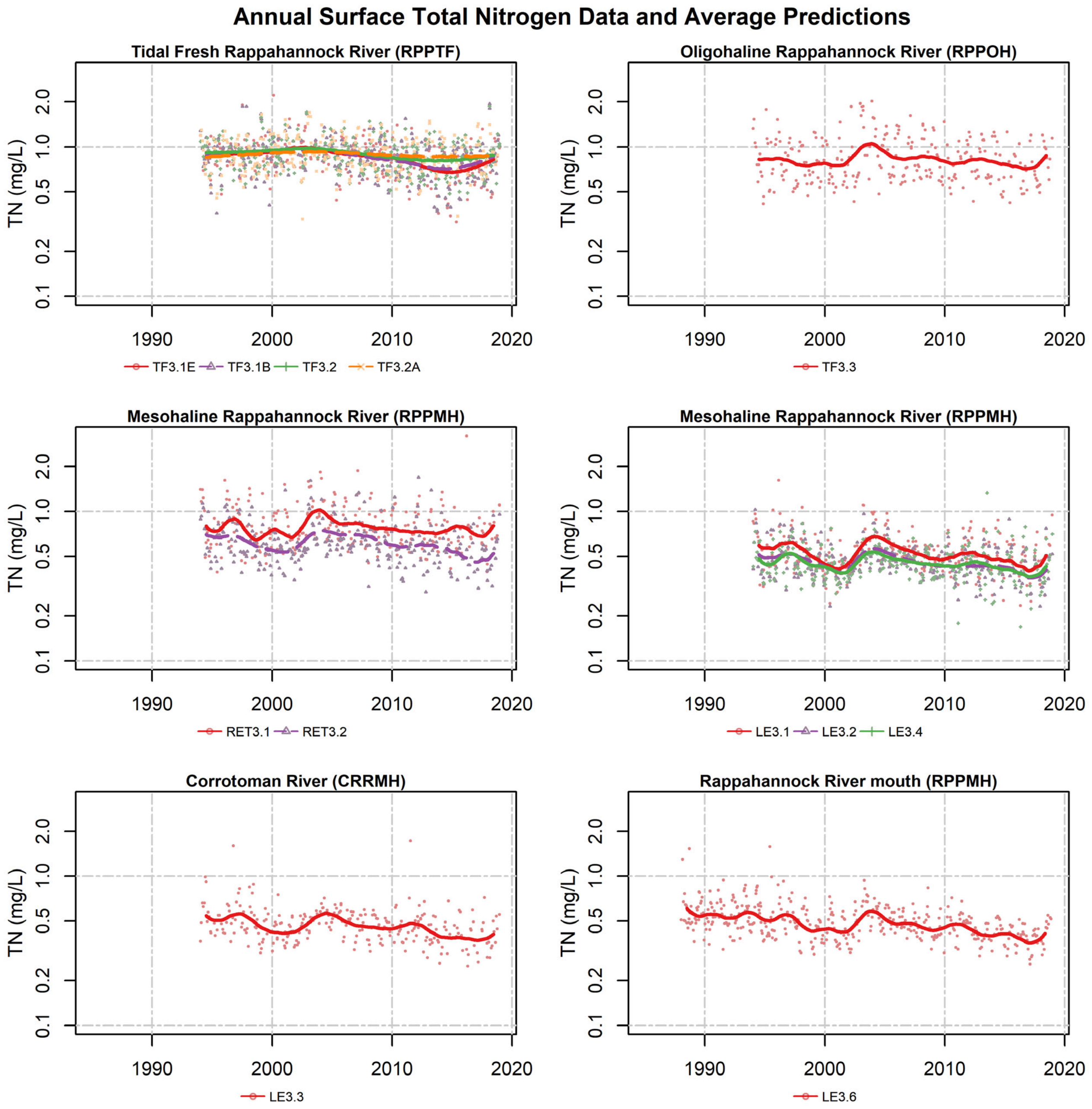


Figure 8. Surface TN data (dots) and the average long-term pattern generated from non-flow adjusted GAM. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

4.2 Surface Total Phosphorus

Surface total phosphorus trends decreased (improved) consistently over the long term at most stations in of the tidal fresh portion of Rappahannock River before and after accounting for the effects of flow (Figure 9). Short term trends in upper portion of the tributary were also improving but at fewer stations (Figure 9). The middle and lower portions of the tributary show little in the way of significant long term or short trends regardless of the effect of flow (Figure 9). GAM Predictions of total phosphorus shows little to no appreciable in with concentrations fluctuating roughly between 0.05 to 0.15 mg/L at most stations. The only exceptions were stations TF3.1E and TF3.1B where predicted concentrations showed evidence of an appreciable decline (Figure 10) consistent with the observed trends (Figure 9).

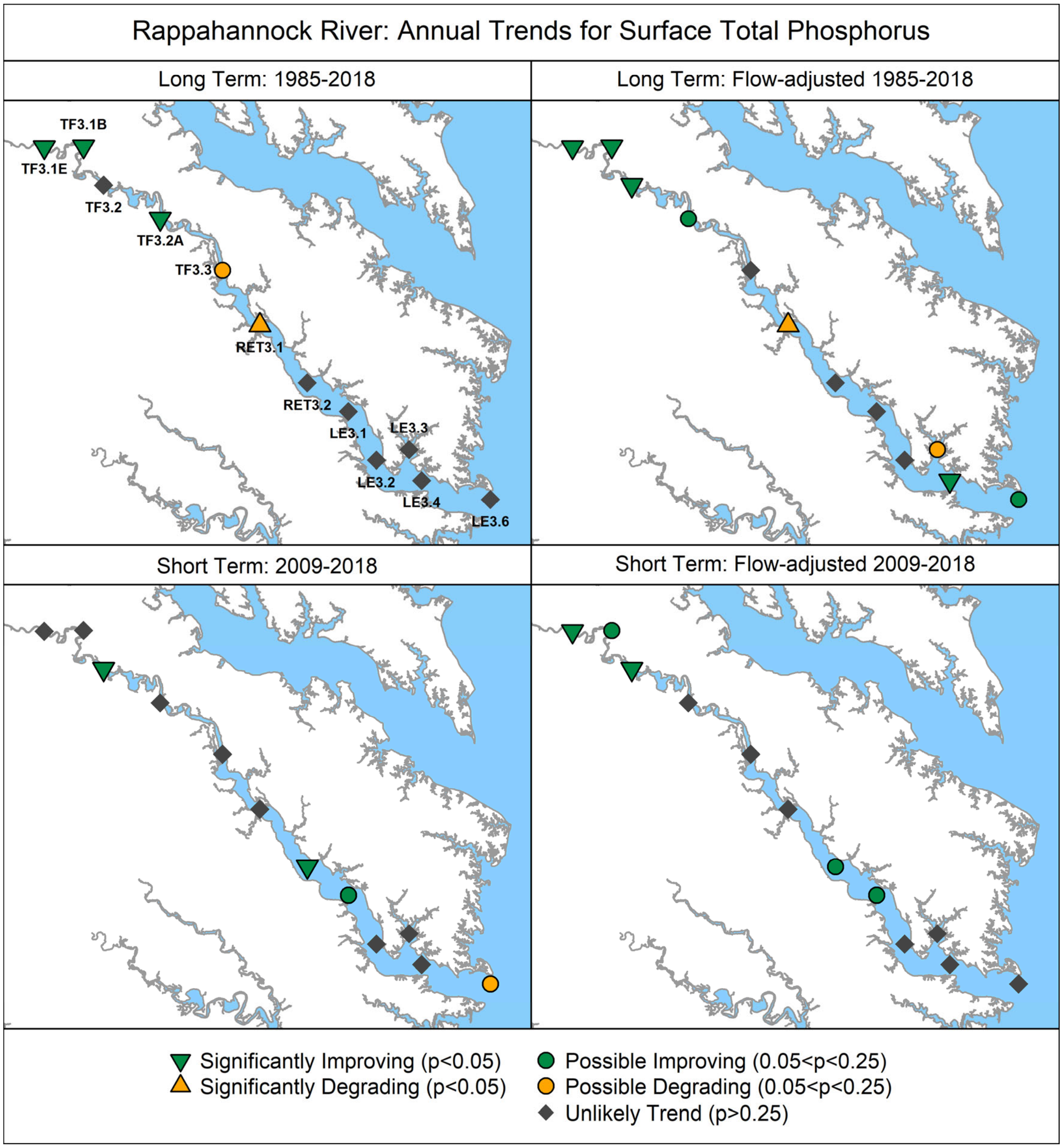


Figure 9. Surface TP trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

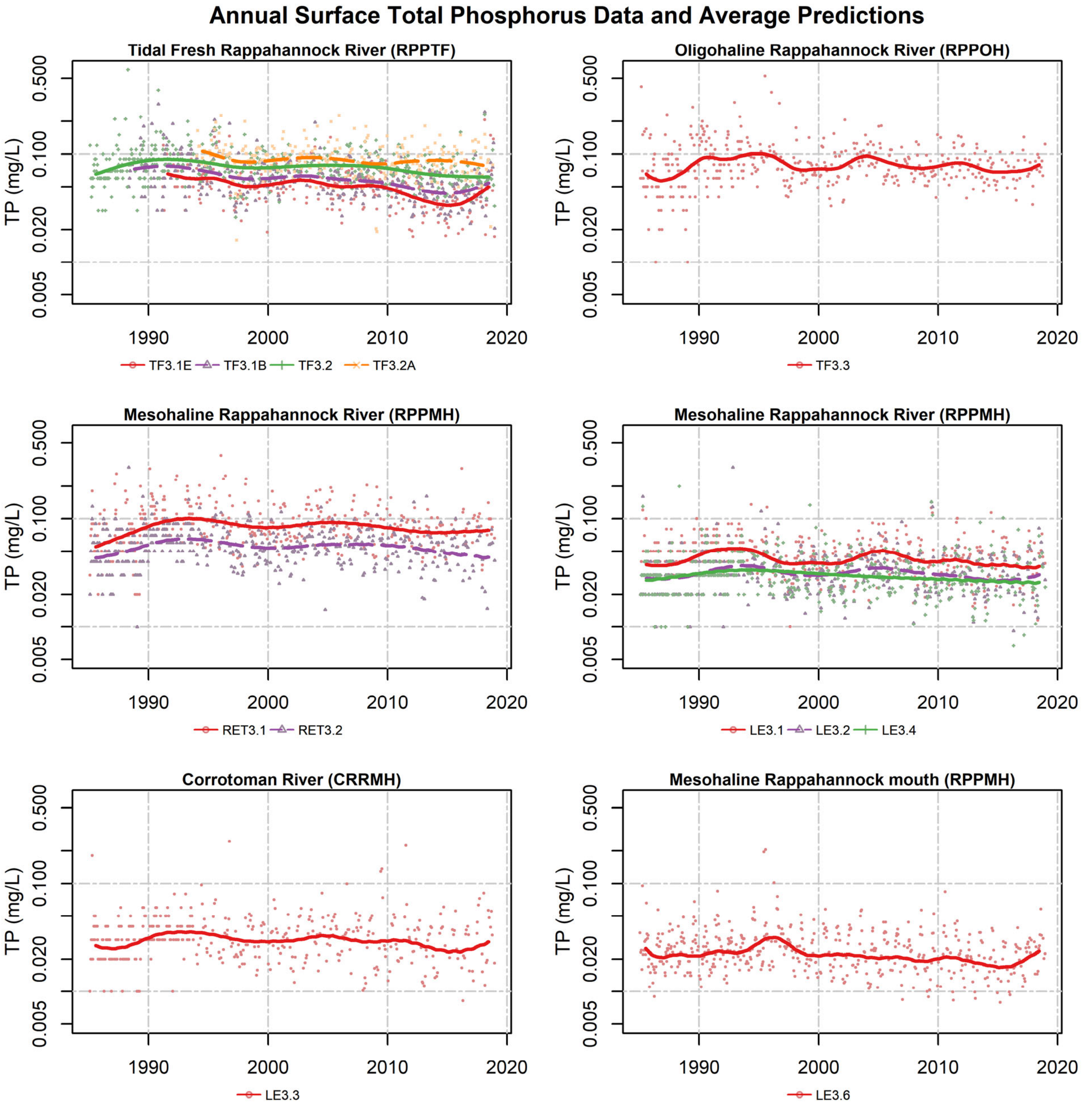


Figure 10. Surface TP data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

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 11) are mixed, with some significant degradations in the middle tributary stations over the long-term, and improvements in the tidal fresh and mesohaline. Possible improvements in the tidal fresh spring chlorophyll *a* persisted in the short-term while possible degrading or no trends were found at other stations. Spring observed and predicted mean values showed high variability over the long-term patterns for many stations is likely reflective of the dynamics of local phytoplankton populations (Figure 12). Plots of the predicted mean spring chlorophyll show clear increases at stations TF3.3 and RET3.1 (Figure 12).

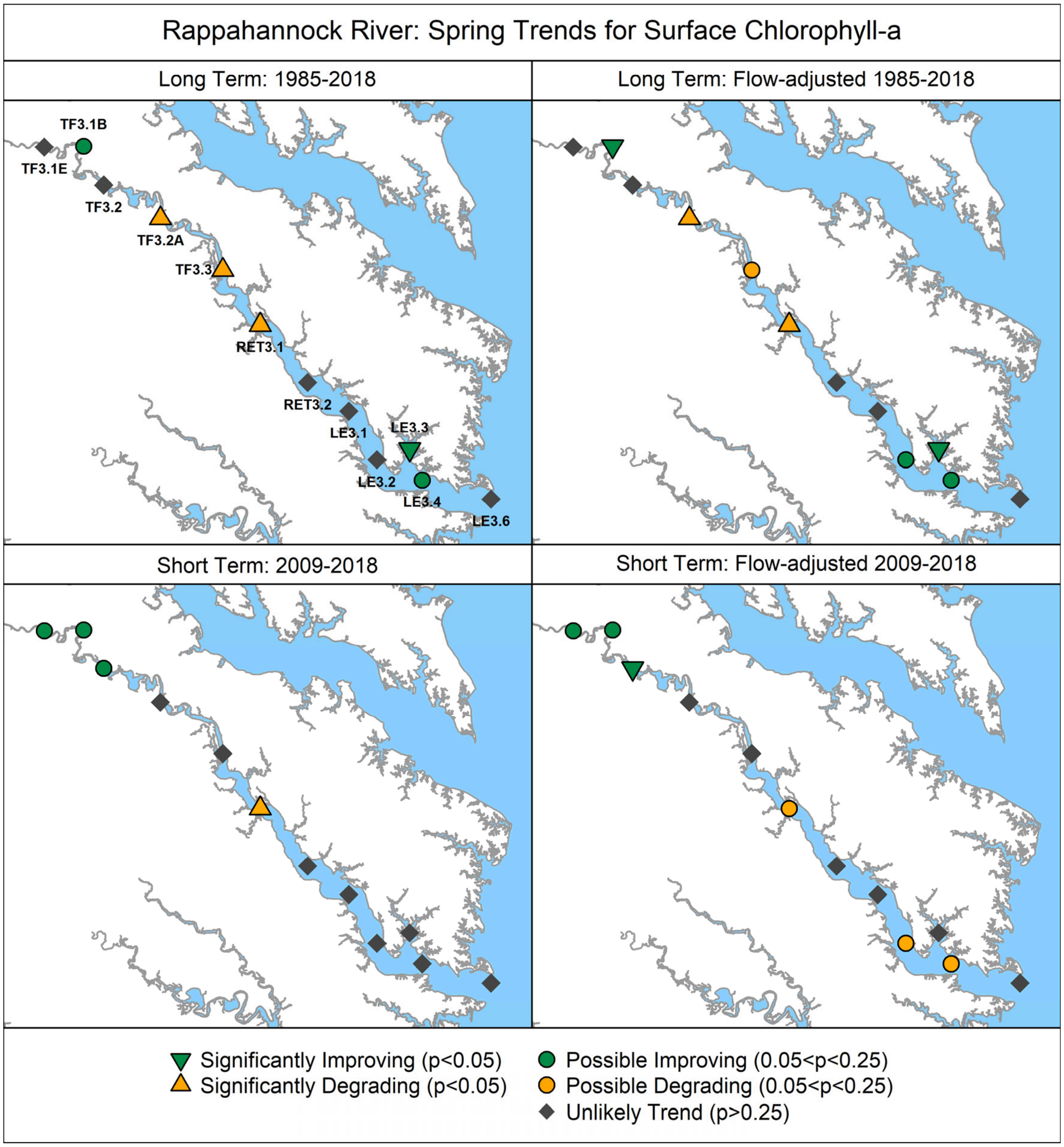
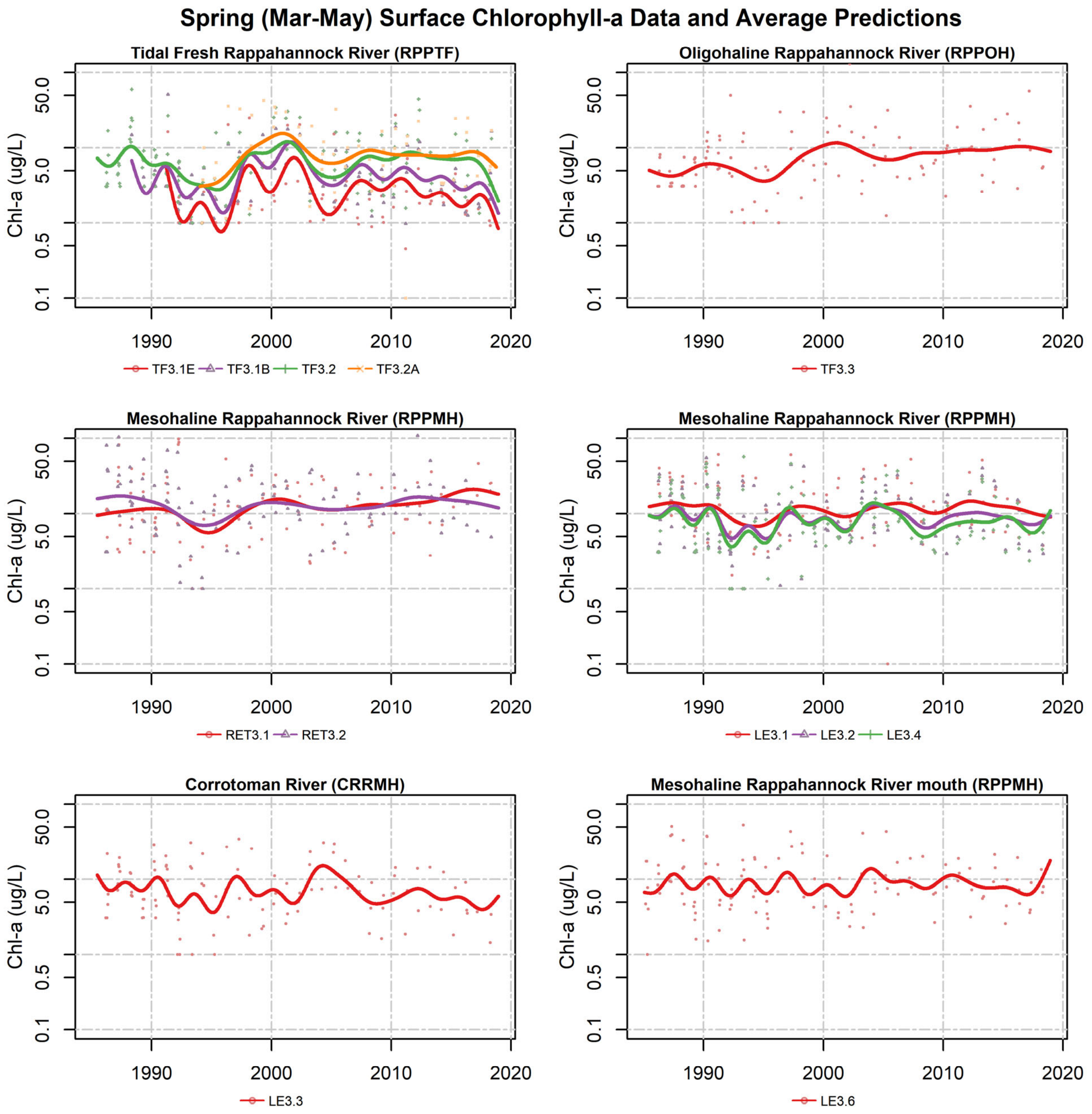


Figure 11. Surface spring (March-May) chlorophyll *a* trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.



Spring (Mar-May) Surface Chlorophyll-a Data and Average Predictions

Tidal Fresh Rappahannock River (RPPTF)

Oligohaline Rappahannock River (RPPOH)

Mesohaline Rappahannock River (RPPMH)

Mesohaline Rappahannock River (RPPMH)

Corrotoman River (CRRMH)

Mesohaline Rappahannock River mouth (RPPMH)

Figure 12. 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 13), with more degrading or potentially 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. Stations in the lower tidal fresh to upper mesohaline portion (stations TF3.2A, TF3.3, and RET3.1) exhibited degrading trends over the long-term but most of these trends were not observed in the short-term regardless of flow adjustment (Figure 13). The remaining stations in the lower mesohaline Rappahannock River and Corrotoman River exhibit degrading or potentially degrading long-term and short-term trends with a higher number of potentially degrading trends found in the flow-adjusted results. This indicates that freshwater inputs may have mediated increasing summer chlorophyll *a* concentrations in the lower portions of the tributary.

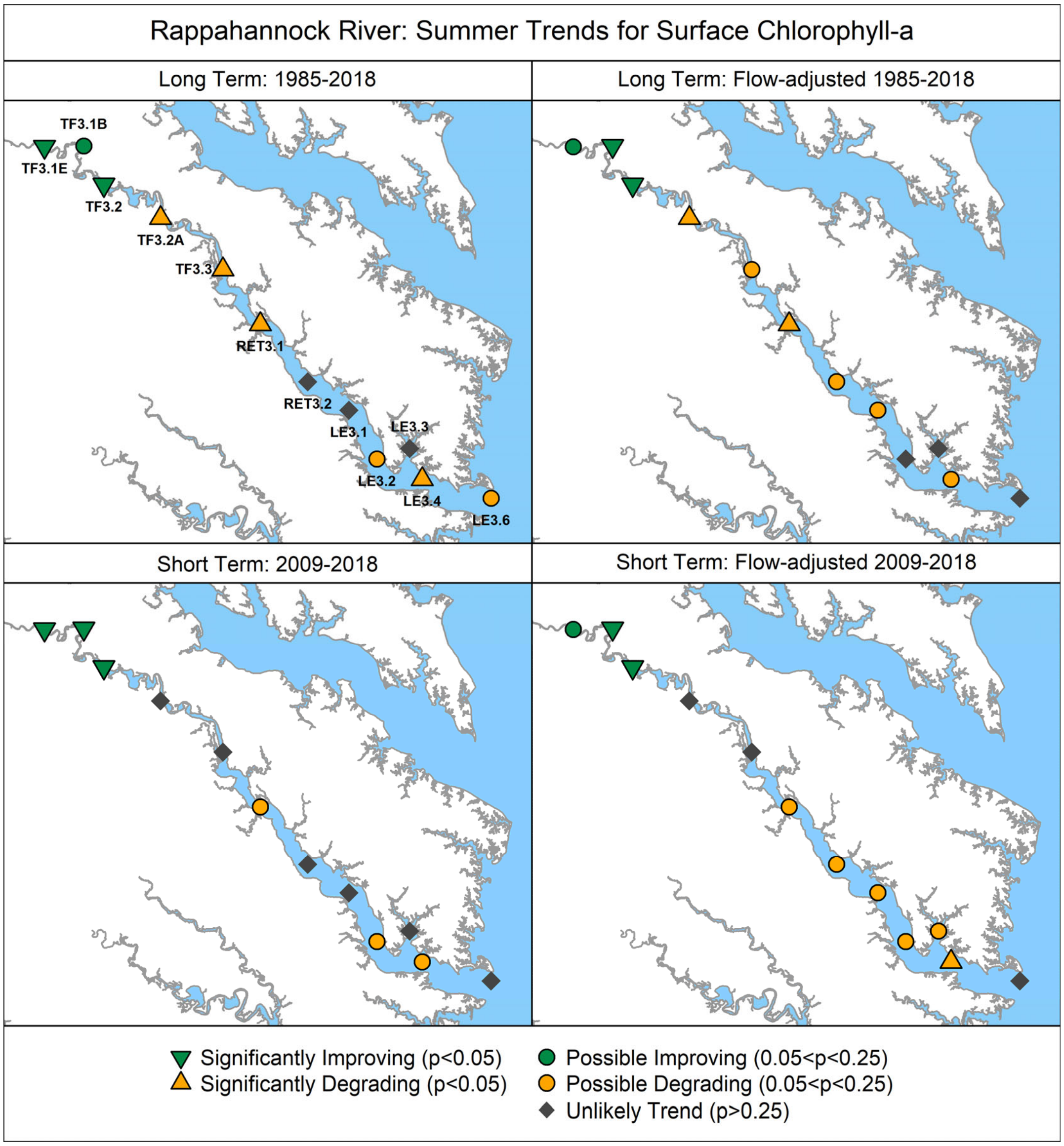


Figure 13. Surface summer (July-September) chlorophyll *a* trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

The magnitude of the summer tidal fresh chlorophyll *a* concentrations is much higher than it is in spring (compare Figures 12 and 14). The decreases at the tidal fresh stations are also clear, despite the large fluctuations. The increases at the more downstream stations were more readily apparent, especially at TF3.3 and RET3.1 which rose from approximately 10.0 µg/L to roughly 20 µg/L from the start of monitoring to 2018 (Figure 14).

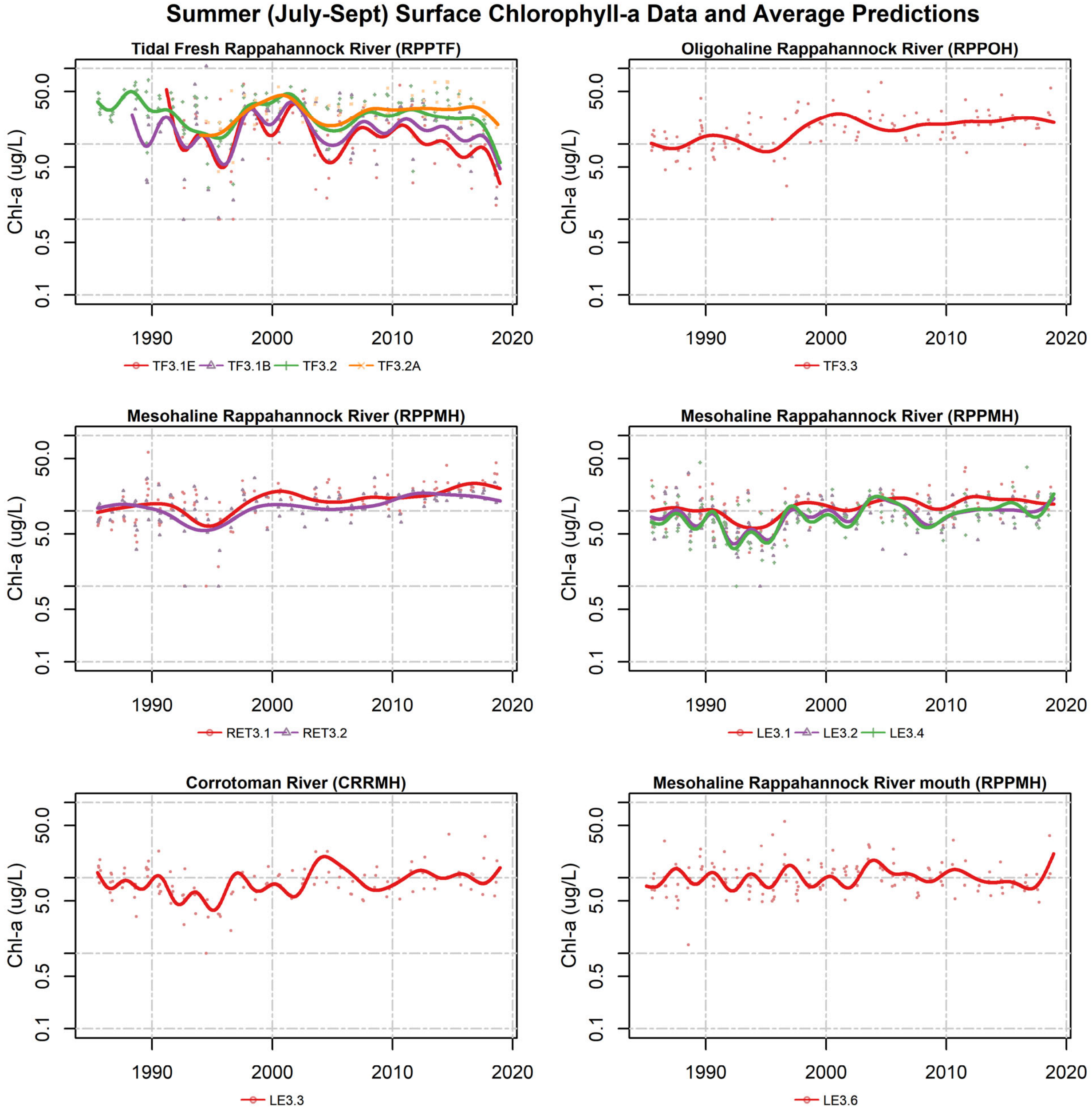


Figure 14. Surface summer chlorophyll *a* data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent July-September data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean summer GAM estimates for the noted monitoring stations.

4.5 Secchi Disk Depth

As with chlorophyll *a*, trends in Secchi depth exhibit clear spatial patterns. Improving or potentially trends in the tidal freshwater stations were generally consistent over the long- and short-term independent of flow adjustment (Figure 15). At the oligohaline and upper mesohaline stations TF3.3 and RET3.1 degrading trends were observed in long term with and without flow adjustment but only station TF3.3 exhibited this trend in the short-term (Figure 15). Degrading trends in Secchi at stations TF3.3 and RET3.1 generally paralleled those of summer chlorophyll a regardless of time period assess and flow adjustment suggesting excess phytoplankton production may be a root cause of lower water clarity. Degrading or potentially degrading trends in Secchi depth were observed at nearly all the stations in the mesohaline portion of the Rappahannock River over the long-term which appear to have been related in part to flow effects (Figure 15). None of these trends were observed in the short-term (Figure 15).

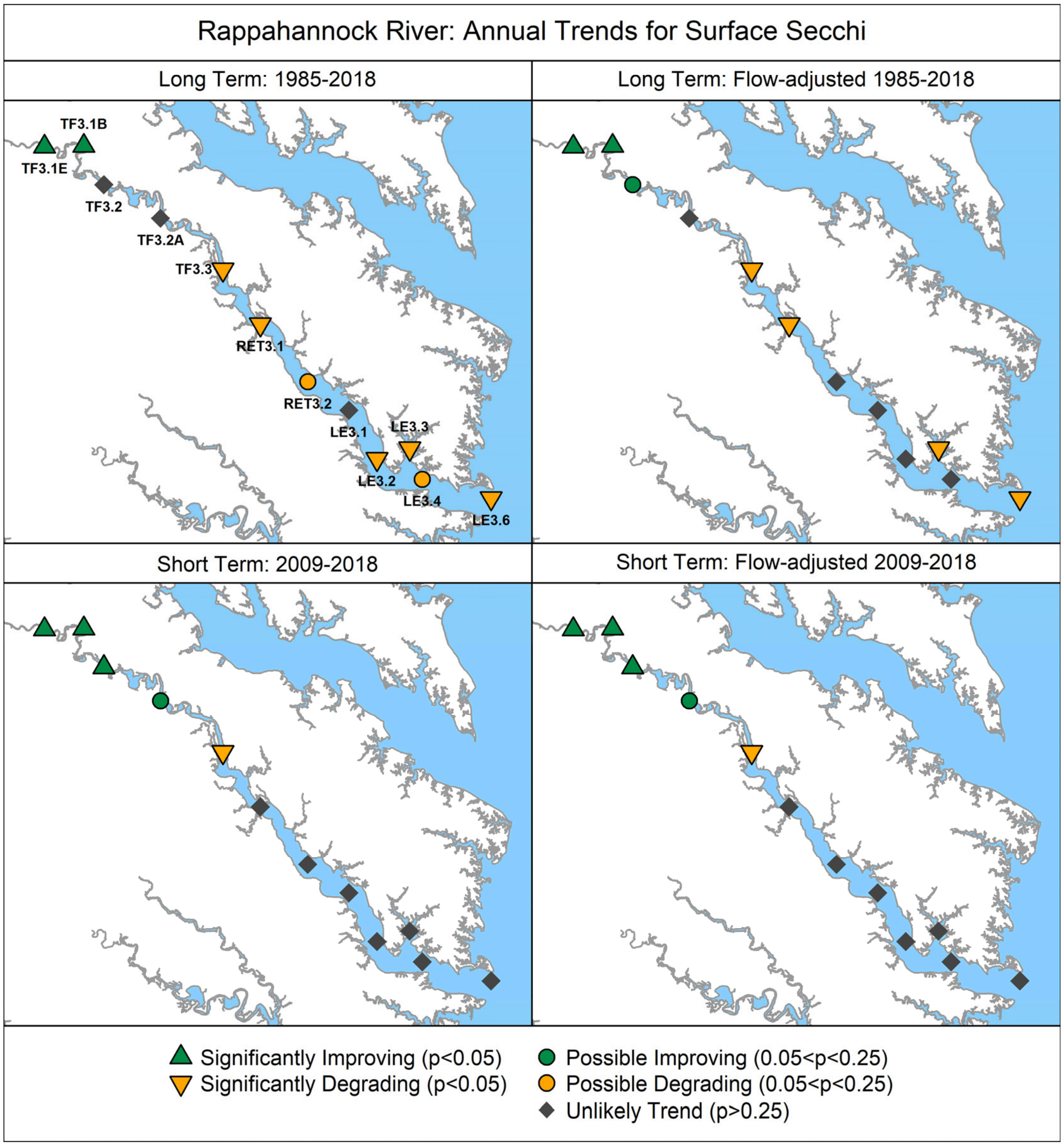


Figure 15. Annual Secchi depth trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Secchi depth is consistently higher at the mesohaline stations than at the tidal fresh or oligohaline stations in the Rappahannock River (Figure 16). Plots of the observed and GAM predicted values clearly reflect the observed long-term trends with increasing depths indicating improvements in the tidal freshwater and decreasing depths at the oligohaline and mesohaline stations reflecting the observed degrading trends (Figure 16). Many of the mesohaline stations show variability in Secchi depth that seems similar to that shown by chlorophyll *a* concentrations. This provides additional albeit indirect evidence for a potential connection between long-term patterns in Secchi and chlorophyll *a* concentrations in the Rappahannock River.

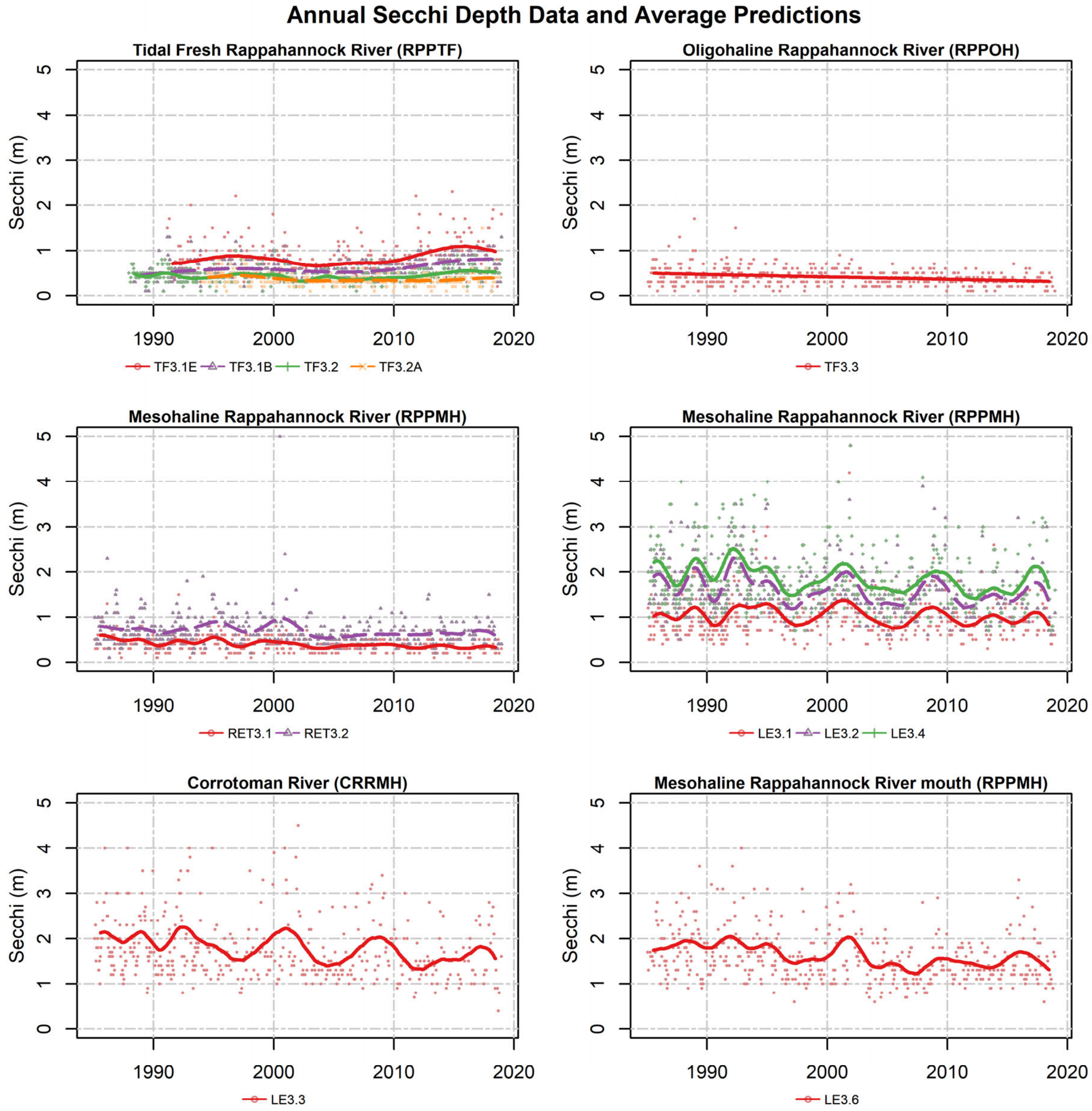


Figure 16. Annual Secchi depth data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

4.6 Summer Bottom Dissolved Oxygen

Degrading or potentially degrading long-term trends in summer dissolved oxygen concentrations were observed at most stations in the Rappahannock River and do not appear to be related to flow effects (Figure 16). An improving long-term trend was observed at station LE3.6 in the mouth of the Rappahannock which does appear to be tied to freshwater flow effects (Figure 17). In the short-term, only degrading and potentially degrading trends at the lower mesohaline stations many of which appear due to flow effects (Figure 17).

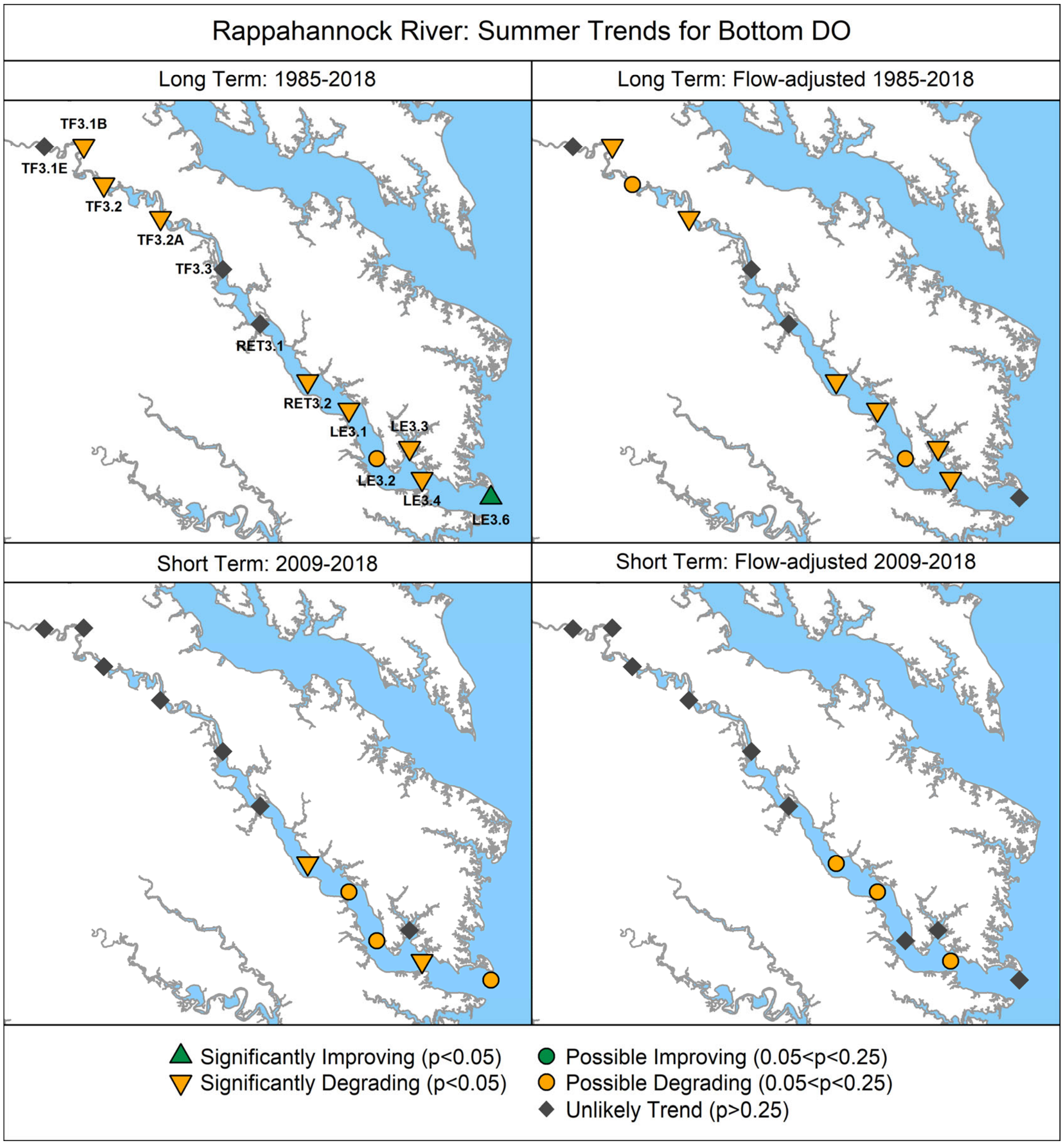


Figure 17. Summer (June-September) bottom DO trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Summer data and average summer GAM predicted values reflect the spatial variability in concentrations and the long-term trends observed (Figure 17). Concentrations in the tidal fresh and middle Rappahannock were higher than the lower estuary, but the tidal fresh concentrations are declining and periodically go below the 5 mg/L summer Open Water mean criterion. Concentrations at some mesohaline stations go below the Deep Channel criterion of 1 mg/L during the summer and trends at many of these stations are degrading (Figures 17-18).

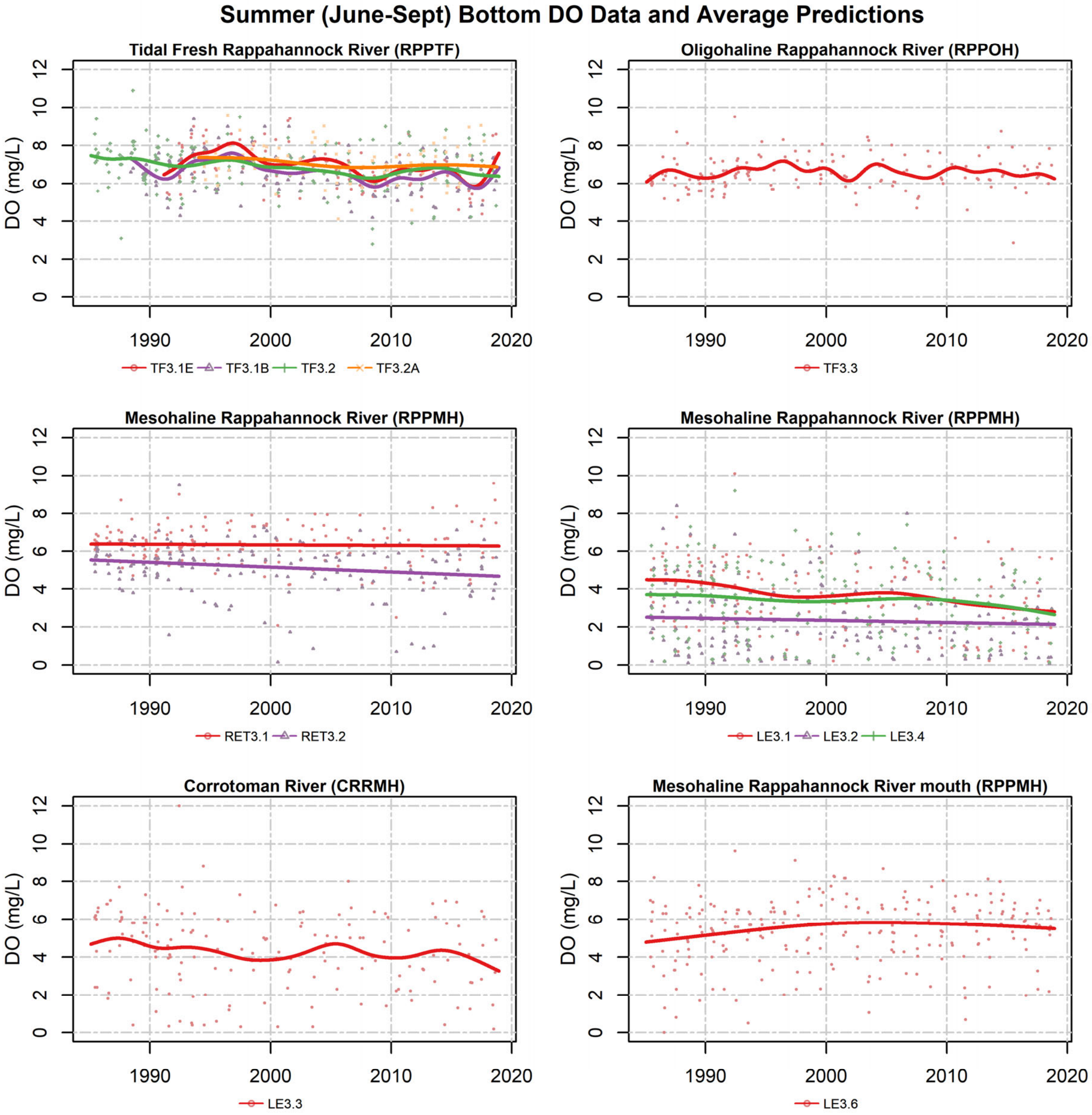


Figure 18. Summer (June-September) bottom DO data (dots) and average long-term seasonal pattern generated from non-flow adjusted GAMs. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean summer GAM estimates for the noted monitoring stations.

5. Factors Affecting Water Quality 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 transmissivity of nitrogen, phosphorus, and sediment delivered to non-tidal and tidal streams. Flow-adjusted or flow normalized nitrogen, phosphorus, and/or sediment trends in load have been measured between 2007 – 2018 at four stations throughout the watershed and show a mixture of improving and degrading conditions (Moyer et al., 2019; Table 2). These trends resulted from variability in nutrient applications, the delivery from the landscape to streams, and from processes that affect in-stream loss or retention of nutrients and sediment.

Table 2. Trends (2009 – 2018) in flow normalized total nitrogen (TN), total phosphorus (TP), and suspended sediment (SS) for nontidal network monitoring locations in the Rappahannock River watershed.

USGS Station ID	USGS Station Location	**TN**	**TP**	**SS**
1668000	Rappahannock River near Fredericksburg	**6.3**	**27.9**	**28.3**
1664000	Rappahannock River at Remington	**15.4**	**-**	**-**
1667500	Rapidan River near Culpeper	**-8.9**	**-6.8**	**-7.1**
1665500	Rapidan River near Ruckersville	**-5.1**	**-**	**-**

Decreasing trends are listed in green, increasing trends in orange, results reported as no trend listed in black. TN=Total nitrogen, TP= Total phosphorus, SS=Suspended sediment.

Nitrogen

Groundwater is the primary 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 (Figure 19). Groundwater nitrate concentrations in the Rappahannock River watershed are highest in streams above the fall line that drain Piedmont soils (Greene et al., 2005; Terziotti et al., 2017). Crystalline rocks in the above fall line portion of the Rappahannock river watershed contain large amounts of oxic groundwater, which promotes nitrate transport (Tesoriero et al., 2015), but their low porosity limits the amount of surface water infiltration (Lindsey et al., 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 et al., 2003). A similar range of water ages (0–33 years) has been measured from Piedmont crystalline springs (Phillips et al., 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).

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 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 others, 2015; Gellis and Noe, 2013; Gillespie and others, 2018; Hopkins and others, 2018), bank sediment density (Wynn and Mostaghimi, 2006), vegetation (Wynn and Mostaghimi, 2006), stream valley geomorphology (Hopkins et al., 2018), and developed land uses (Brakebill et al., 2010).

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).

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 Kim, 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 (Ensign et al., 2014; Noe and Hupp, 2009). The average age of sediment stored in-channel is typically assumed to be less than a year (Gellis et a., 2017), but delivery to tidal waters can be exponentially longer as sediment moves in and out of different storage zones during downstream transport.

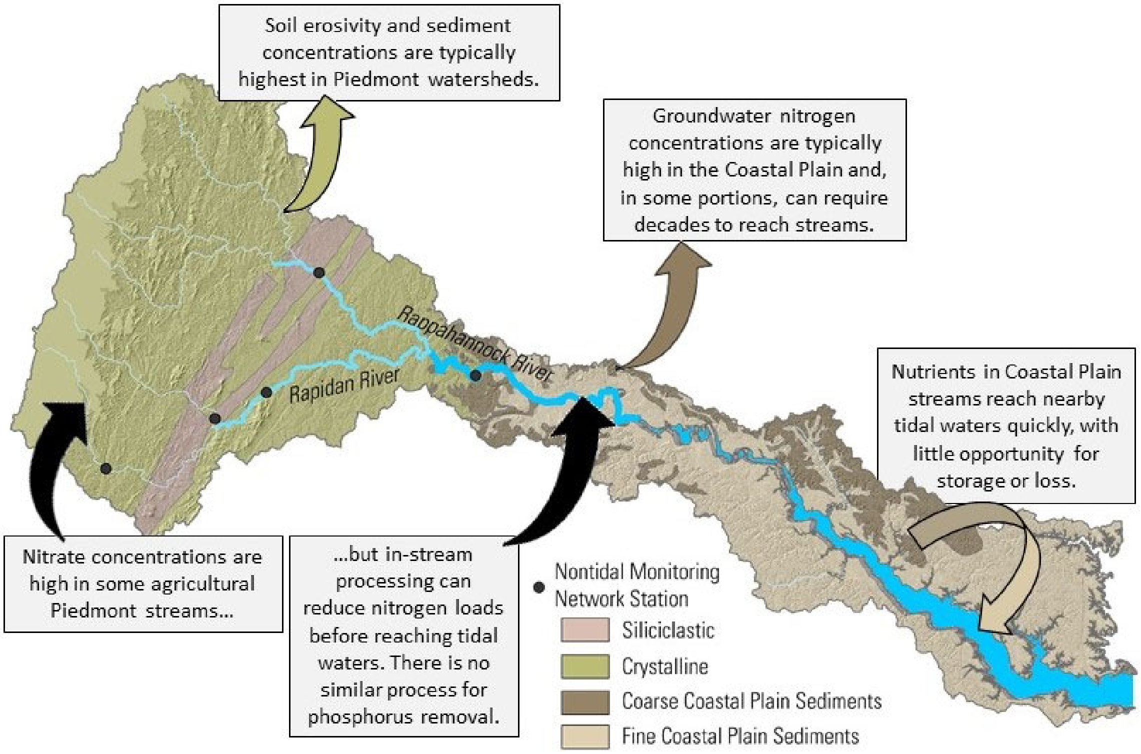


Figure 19: Effects of watershed hydrogeomorphology on nutrient transport to freshwater streams and tidal waters. Base map modified from King and Biekman, 1974 and Ator et al., others, 2005, North American Datum 1983

5.1.2. Estimated Nutrient and Sediment Loads

Estimated loads to tidal portions of Chesapeake Bay tributaries are a combination of monitored fluxes from USGS River Input Monitoring (RIM) stations located at the nontidal-tidal interface and below-RIM simulated loads from the Chesapeake Bay Program Watershed Model (CBWM). Nitrogen, phosphorus, and sediment loads to the tidal Rappahannock originated from both above and below the fall line (Figure 19). On average, areas above and below the fall line contributed equally to TN loads from 1985-2014, while most of the phosphorus loads were contributed from above the fall line. Over the concurrent period of 1985-2014, 0.12, 0.014, and 18.4 million tons of nitrogen, phosphorus, and sediment loads were exported through Rappahannock, with 51%, 67%, and 40% of those loads coming from the RIM area, respectively.

Overall, estimated nitrogen loads were about 25% higher in 2014 than in 1985, phosphorus loads were about 61% higher, and sediment loads were about 36% higher in 2014 than in 1985 (Table 3). In general, the long-term patterns exhibited by all three estimated loads both above and below the fall-line was similar. There is an initial increase from 1985 through the mid to late 1990s followed by a steep decline until 2003 when loads of all three parameters reached maximum levels for the period of record (Figure 21). Loads of all parameters were relatively stable thereafter except for two peak years in 2011 and 2014 for all three parameters after which loads below the fall line were not estimated. In 2018, above fall-line loads in all three parameters peaked again (Figure 20). There were no statistically significant ($p<0.05$) trends in loadings for any of the three parameters; however, total nitrogen and suspended solids below the fall-line exhibited trends that were close to statistical significance at *p*-values of 0.06, and 0.08, respectively (Table 3).

Table 3. 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	**Change in 1985-2014**		**MK Trend in 1985-2014**	
	Rate, kg/year	Percent, %	Slope, kg/year/year	p-value
TN				
Total	862,259	25%	20,680	0.318
AFL	543,082	26%	10,829	0.643
BFL	319,177	23%	18,737	0.064
TP				
Total	255,276	61%	5,088	0.134
AFL	281,529	110%	4,836	0.125
BFL	-26,253	-16%	-145	0.695
SS				
Total	201,051,937	36%	4,205,218	0.175
AFL	199,548,574	97%	3,615,993	0.212
BFL	1,503,363	0%	279,280	0.080

A similar Mann-Kendall analysis conducted on the edge-of-stream EPA Model Progress load estimates produced at the segment spatial scale for the Rappahannock River (https://cast.chesapeakebay.net/) revealed substantially different results from those above (Table 4; Figures 21A-C). Note that the Progress model run loads serve as estimates of change in management actions or BMPs functioning in a given year and do not account for change in loads due to natural stressors or the potential effect of weather conditions on anthropogenic loads. As such, they may under or overestimate the loads that directly enter the tidal portions of river.

Loads in total nitrogen declined significantly from 5.6% to 14.1% in all segments of the Rappahannock River except the oligohaline portion of the river (RPPOH) where no significant trend was detected. Most segments show an initial decline in total nitrogen loads followed by a steady rise until around the year 2000 when loadings again begin to steadily decline (Figure 21A). Segment RPPTF was the only exception where total nitrogen loads were generally stable at around 8,000,000 lbs. per year until 2000 when they began to decline (Figure 21A). Significant declines in total phosphorus loads were observed in all segments of the river ranging from 12% in the Corrotoman River (CRRMH) to 55% in oligohaline Rappahannock River (RPPOH). Plots of loads in all segments showed declines from the start of monitoring through 2018 (Figure 21B). Suspended sediment loads showed significant declines in all segments from 17% in the tidal fresh Rappahannock River (RPPTF) to nearly 37% in the Corrotoman River (CRRMH). These declines appear to have occurred after a period of relative stability in suspended sediment loads that for most segments extended from 1985 through the mid-1990s or early 2000s with the exception of the oligohaline

Rappahannock River (RPPOH) where suspended sediments showed a steadily decline from 1985 through 2018 (Figure 21C).

In terms of both absolute and percent change the tidal fresh Rappahannock River saw the largest reductions overall in total nitrogen loads with a decline of nearly 1.2 million lbs. from 1985 through 2018 (Table 4). Nearly all segments in the Rappahannock River showed absolute reductions in total phosphorus that were amounted to nearly a third of the initial estimate inputs. In an absolute sense, the tidal fresh portion of the river saw the largest change in suspended sediment loads with a reduction of nearly 176 million lbs. from 1985 through 2018; however, percent changes were higher in the lower segments of the Rappahannock River where reductions in suspended sediment loads amounted to nearly a third of the initial estimated inputs (Table 4).

These results suggest a potential connection between improving trends in water quality concentrations of nutrient parameters and the trends in water clarity with changes in BMPs for the tidal freshwater portion of the Rappahannock River. Declining trends in this segment may be linked to reductions in loads

Table 4. Summary of Mann-Kendall segment specific trends for loads in nutrients and suspended sediment below the fall for the period of 1985-2018 loads from the Rappahannock River watershed. Provided are the test statistic and associated p value, Sen Slope estimate, and change in load over time expressed as the total change (number of years * Sen slope) and percent change from initial conditions.

Total Nitrogen							
	Mann-Kendall Trend Analysis			Change in load			
CBPSEG	Test Statistic	p-value	Sen Slope	1985	2018	Change in Load	% Change
RPPTF	-387	<0.001	-33,950	8,193,213	7,373,294	-1,154,294	-14.1
RPPOH	-	1.0000	-	467,403	461,175	No estimate	
RPPMH	-157	0.0207	-3,991	2,426,268	2,273,593	-135,700	-5.6
CRRMH	-254	<0.001	-1,110	348,785	315,862	-37,748	-10.8
Total Phosphorus							
	Mann-Kendall Trend Analysis			Change in Load			
CBPSEG	Test Statistic	p-value	Sen Slope	1985	2018	Change in Load	% Change
RPPTF	-501	<0.001	-12578	1,127,474	738,777	-427,654	-37.9
RPPOH	-495	<0.001	-431	26,314	13,418	-14,640	-55.6
RPPMH	-497	<0.001	-1514	160,951	98,111	-51,461	-32.0
CRRMH	-354	<0.001	-72	20,343	17,361	-2,442	-12.0
Suspended Sediments							
	Mann-Kendall Trend Analysis			Change in Load			
CBPSEG	Test Statistic	p-value	Sen Slope	1985	2018	Change in Load	% Change
RPPTF	-433	<0.001	-5,166,552	1,022,095,000	865,987,900	-175,662,768	-17.2
RPPOH	-453	<0.001	-439,226	48,241,636	35,660,716	-14,933,684	-31.0
RPPMH	-467	<0.001	-1,877,432	224,305,648	168,526,400	-63,832,688	-28.5
CRRMH	-354	<0.001	-368,612	36,266,120	25,346,858	-12,532,818	-34.6

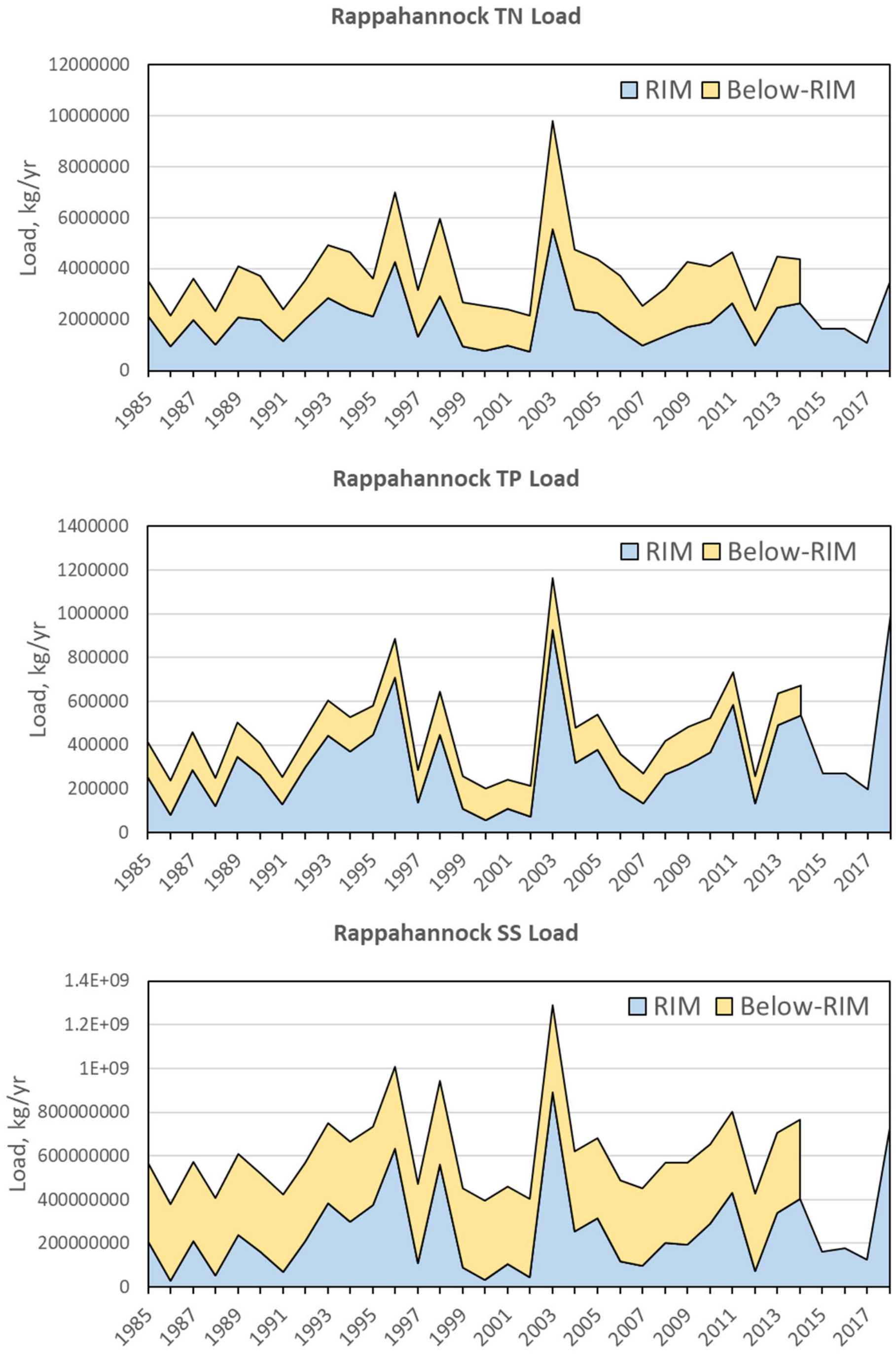


Figure 20. Estimated total loads of nitrogen (TN), phosphorus (TP), and suspended sediment (SS) from the RIM and below-RIM areas of the Rappahannock River. RIM refers to the USGS River Input Monitoring site located at the fall-line of this tributary and will include upstream point source loads. Below-RIM estimates are a combination of simulated non-point and reported point-source loads. Below-RIM loads end in in 2014 because non-point source loads are not available after that date.

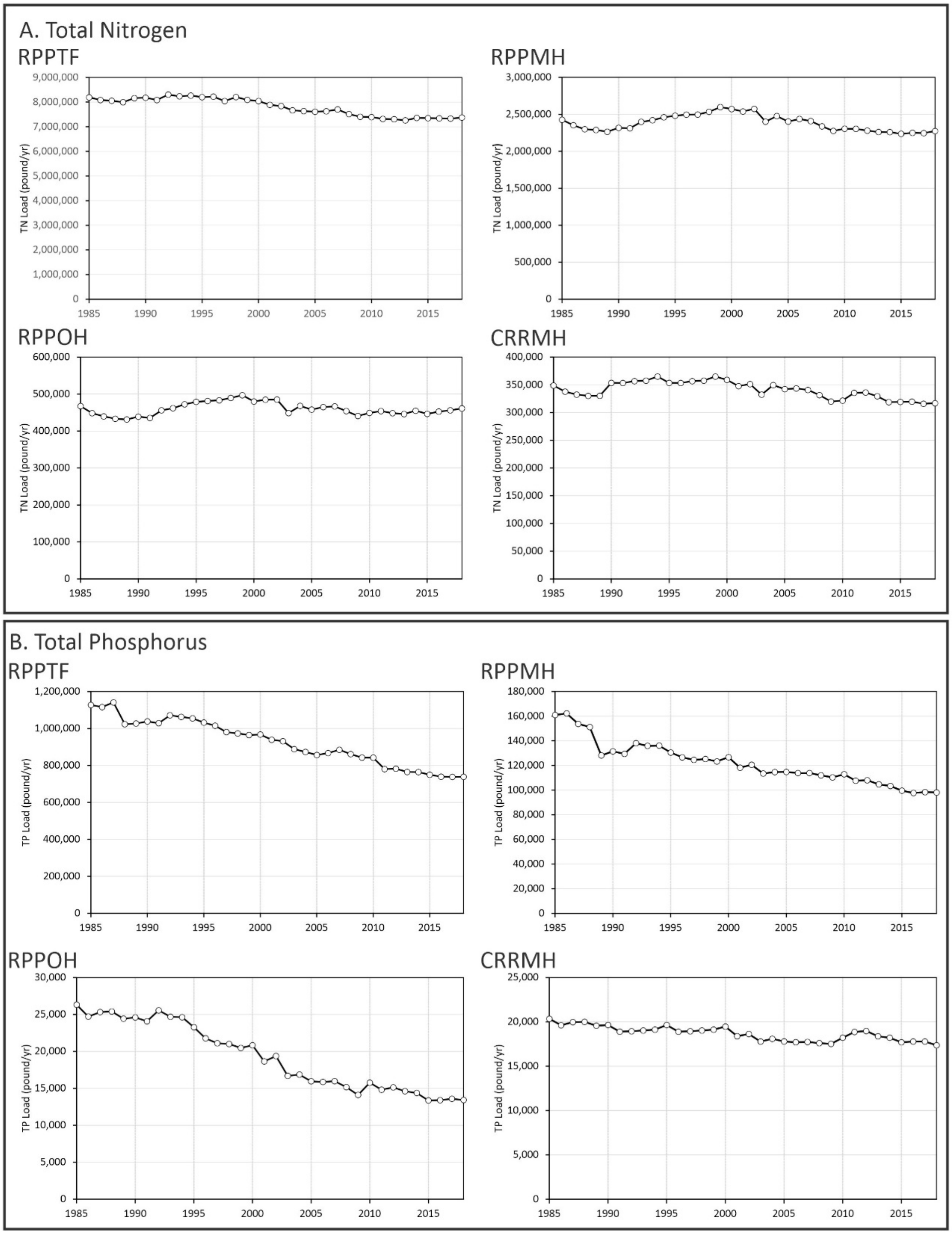


Figure 21. Estimated loads of A. Total Nitrogen (TN), B. Total Phosphorus (TP), and C. Suspended Sediment (SS) by CBP segment estimated by CAST (https://cast.chesapeakebay.net/). Shown are the USEPA 1985 through 2018 Progress load estimates for all agencies delivered at the edge of stream for each segment in the Rappahannock River for the period of 1985 through 2018. Estimates include all reported point source loads from all agencies combined with simulated non-point source loads.

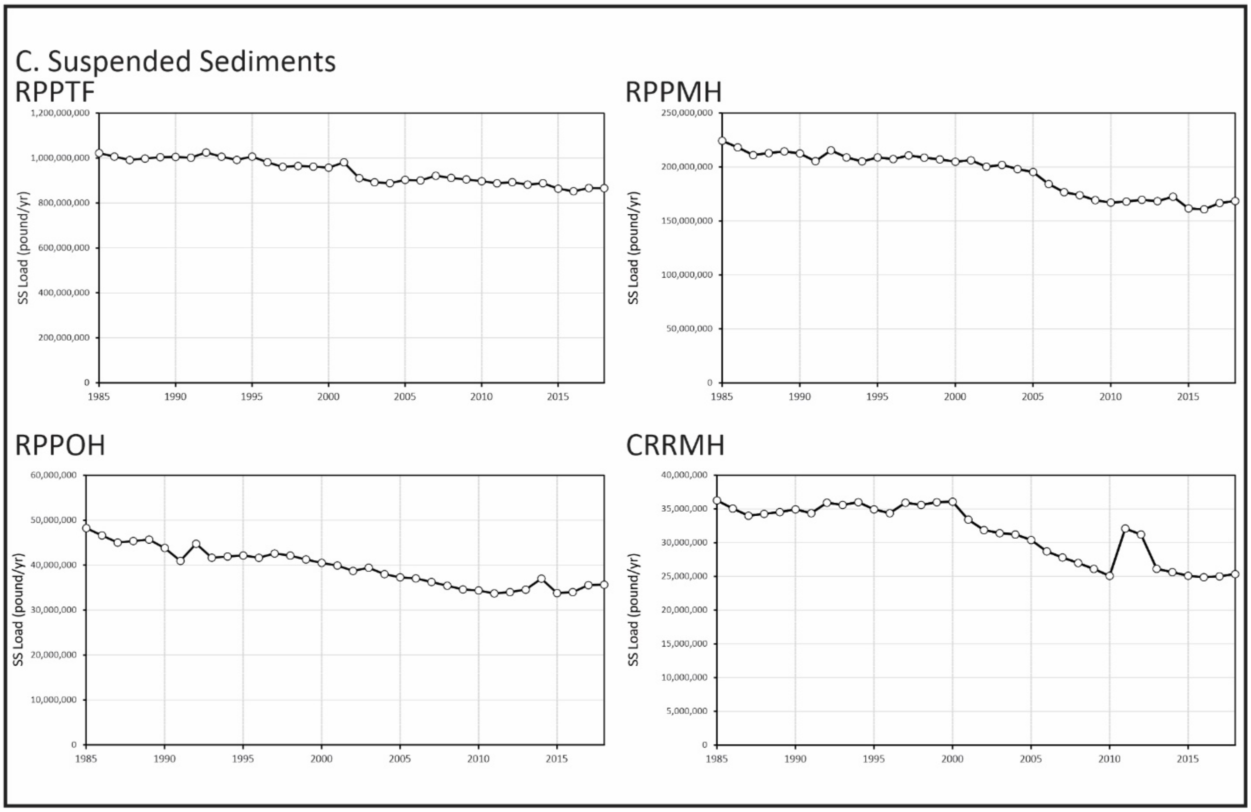


Figure 21 (continued). Estimated loads of A. Total Nitrogen (TN), B. Total Phosphorus (TP), and C. Suspended Sediment (SS) by CBP segment estimated by CAST (https://cast.chesapeakebay.net/). Shown are the USEPA 1985 through 2018 Progress load estimates for all agencies delivered at the edge of stream for each segment in the Rappahannock River for the period of 1985 through 2018. Estimates include all reported point source loads from all agencies combined with simulated non-point source loads.

in these parameters. Similarly, improvements in water clarity could be directly linked to reductions in suspended sediment loads. The mesohaline Rappahannock River also exhibits a similar linkage between reductions in total nitrogen loadings and trends in water quality concentrations however additional connections between trends in other water quality parameters and loads elsewhere in the Rappahannock River are more tenuous. The data here provide indirect support to conclusions of a recent study which indicated a statistical relationship between load reductions, most likely point source, in nitrogen at multiple stations in the Rappahannock River (Murphy et al., In Press)

5.1.3. Expected Effects of Changing Watershed Conditions

According to the Chesapeake Bay Program's Watershed Model accessed through the CAST website (https://cast.chesapeakebay.net, version CAST-19), changes in population size, land use, and pollution management controls between 1985 and 2019 were expected to result in overall decreases in nitrogen, phosphorus, and sediment loads to the tidal Rappahannock River of 12%, 33%, and 13%, respectively (Figure 22). As mentioned previously, CAST loads are based on changes in management only and do not include annual fluctuations in weather. CAST loads are calculated assuming no 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 decreased by 7% and the developed sector became the second largest nitrogen source. Overall, reductions in nitrogen loads from agriculture (25%), natural (7%), stream bed and bank (10%), and wastewater (28%) sources were partially offset by increases from developed and septic sources of 78% and 65%, respectively.

As of 2019, the two largest sources of phosphorus loads 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 were shoreline and stream bed and bank areas. These two sources declined by 1% and 25%, respectively between 1985 and 2019. Sediment loads from the agriculture sector declined by 57%, whereas sediment load from developed areas increased 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.

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-19). Reported BMP implementations on the ground as of 1985, 2009, and 2019 are compared to planned 2025 implementation levels in Figure 23 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.

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.

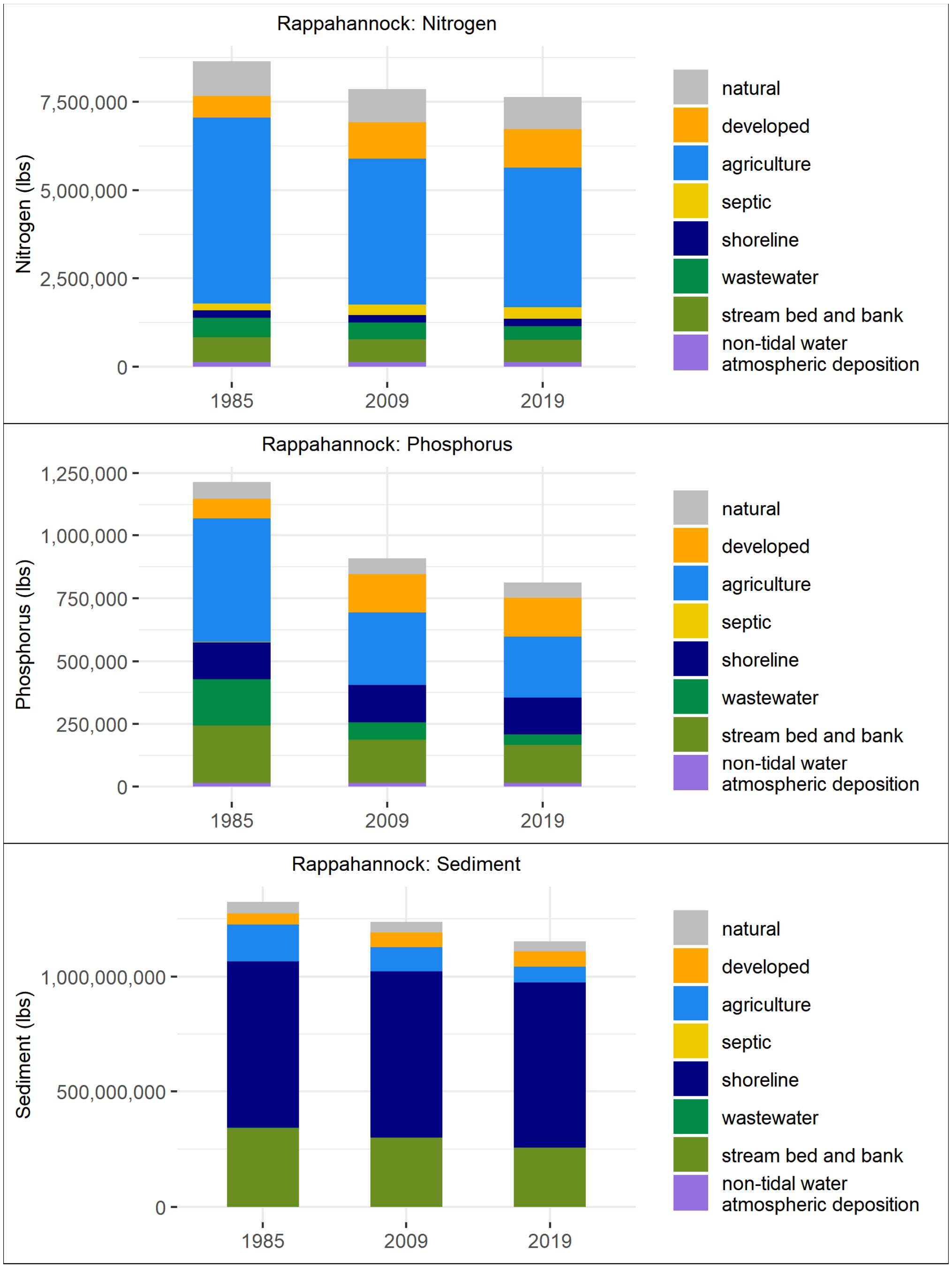


Figure 22. Expected changes in nitrogen, phosphorus, and sediment loads from different sources to the tidal Rappahannock, as obtained from the Chesapeake Assessment Scenario Tool (CAST-17d). Data shown are time-average delivered loads over the average hydrology of 1991-2000, once the steady state is reached for the conditions on the ground, as obtained from the 1985, 2009, and 2018 progress (management) scenarios.

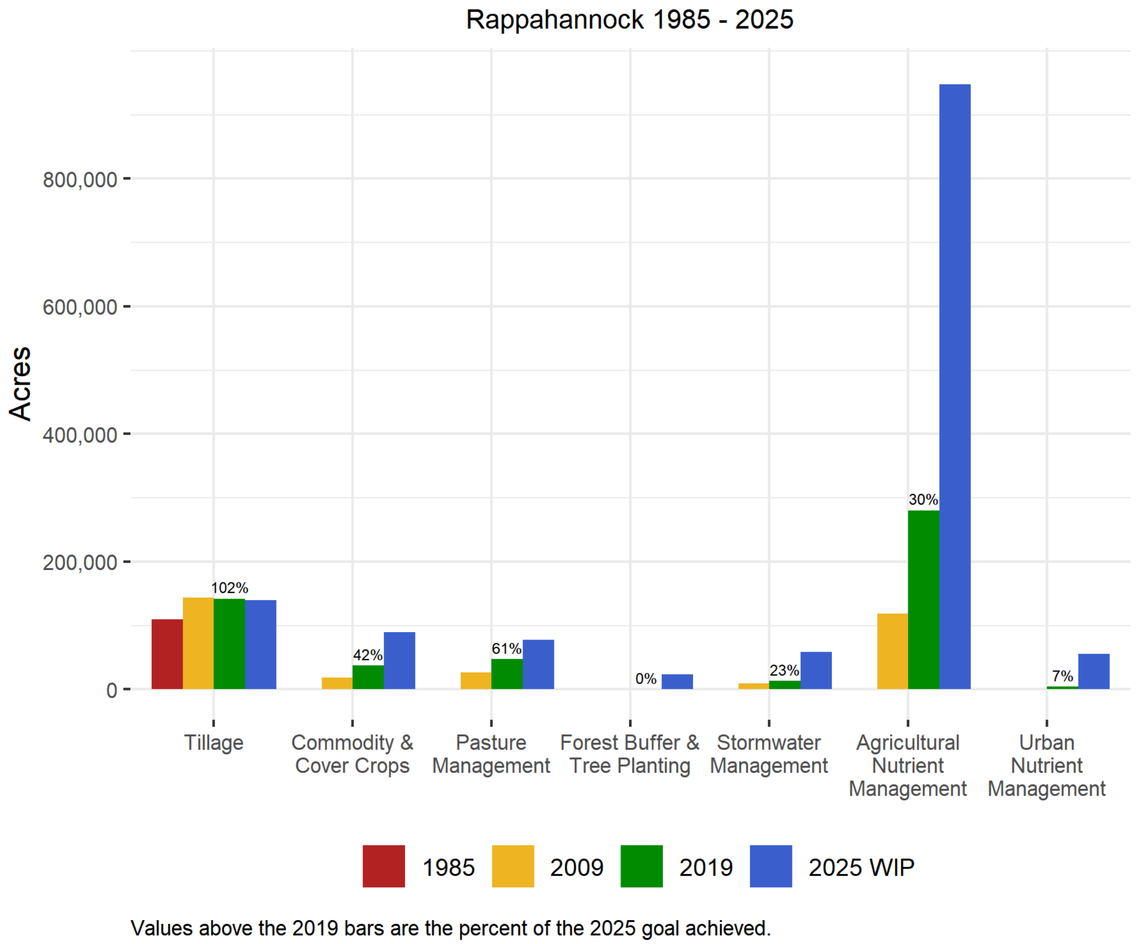


Figure 23. BMP implementation in the Rappahannock watershed.

5.2 Living Resources

5.2.1. Phytoplankton Communities

Phytoplankton communities respond rapidly to changes in water column nutrient concentrations and light availability. Excessive phytoplankton production can adversely affect the structure of ecosystem food webs and lead to low dissolved levels at the sediment-water interface. Algal blooms of toxic species can adversely affect both humans and living resource communities. As a result, phytoplankton communities have been monitored at three stations (TF3.3, RET3.1 and LE3.6) in the Rappahannock River since the mid-1980s. Status of phytoplankton communities was assessed using the phytoplankton index of biotic integrity or P-IBI (Buchanan, et al.,) and long-term changes in phytoplankton community health were assessed by GAM analyses similar to those conducted on the water quality using abundance levels of several important phytoplankton taxonomic groups (see Table 5).

Status of phytoplankton communities based on the phytoplankton IBI was degraded or severely degraded at all stations in the Rappahannock although community condition was somewhat better at station LE3.6

in the mesohaline portion of the river. Results of the GAM analyses indicate that significant increases in the predicted mean abundance of multiple taxonomic groups have increased substantially at all of the monitoring stations in the Rappahannock River with the largest increases concentrated primarily at stations TF3.3 and RET3.1 which both saw significant (p ≤0.05) and potentially significant increases in cyanobacteria and chlorophytes (Table 5). Stations LE3.6 and TF3.3 also saw significant and potentially significant increases in dinoflagellates while a significant increase was observed at station TF3.3. The only significant decline in predicted abundance observed was for diatom abundance at station LE3.6.

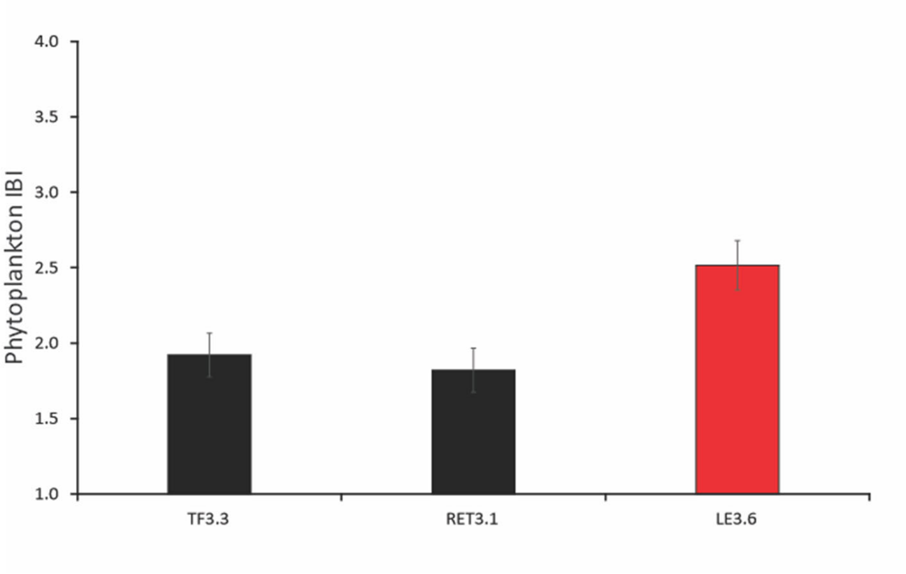


Figure 24. Status of phytoplankton communities at stations in the Rappahannock River for the period of 2017 through 2019 based on the P-IBI (Buchanan et al.,). Shown are mean values for the assessment period ± one standard error.

Table 5. Long term change in mean abundances of taxonomic groups at stations in the Rappahannock River.

		Long term Change in Mean		
Station	Taxonomic Group	Percent	Absolute (#/L)	p Value
TF3.3		**95**	**734504**	**0.013**
RET3.1	Diatoms	6	69348	0.834
LE3.6		-79	-1686737	**<0.001**
TF3.3		530	14377	0.104
RET3.1	Dinoflagellates	-59	-92646	0.372
LE3.6		**111**	**135109**	**0.032**
TF3.3		**286**	**732114**	**0.033**
RET3.1	Cyanobacteria	269	238463	0.136
LE3.6		44	54	0.777
TF3.3		**918**	**468736**	**<0.001**
RET3.1	Chlorophytes	**3889**	**281404**	**<0.001**
LE3.6		523	5304	0.109

Plots of the observed data and model predictions for these groups the reflect the generalized trend directions observed as well as a high degree of seasonality and in many cases increasing variability in the seasonality over time (Figure 25-27). Model results indicated significant seasonal and/or seasonal interaction effects for each group analyzed with many groups exhibiting increasing variability in later years. The long-term pattern in several of the groups, in particular dinoflagellates and chlorophytes, either alone or perhaps in combination appear to mirror that of the chlorophyll *a* observed at the same stations however the match is not necessarily exact. The results indicate that phytoplankton production is generally increasing, highly variable, and that the variability is increasing. The long-term patterns for some groups (e.g chlorophytes at station TF3.3) seem to correspond roughly to changes in nutrients (i.e. total phosphorus) suggesting nutrient inputs are at least in part responsible for the increased phytoplankton counts. The reduced suspended sediment loads mentioned above could reduce light limitation which in turn would allow for the increase in phytoplankton production and the reduction in Secchi depths observed – an effect referred to as the Organic Fog (Turner et al., 2021). Finally, the increased variability observed could be the result of increased temperatures associated with climate change or seasonal variability in nutrient inputs or some combination of each of the effects listed. Whatever the source, phytoplankton communities show poor general status and an indication of increased eutrophication which could be linked to the low dissolved oxygen levels described above.

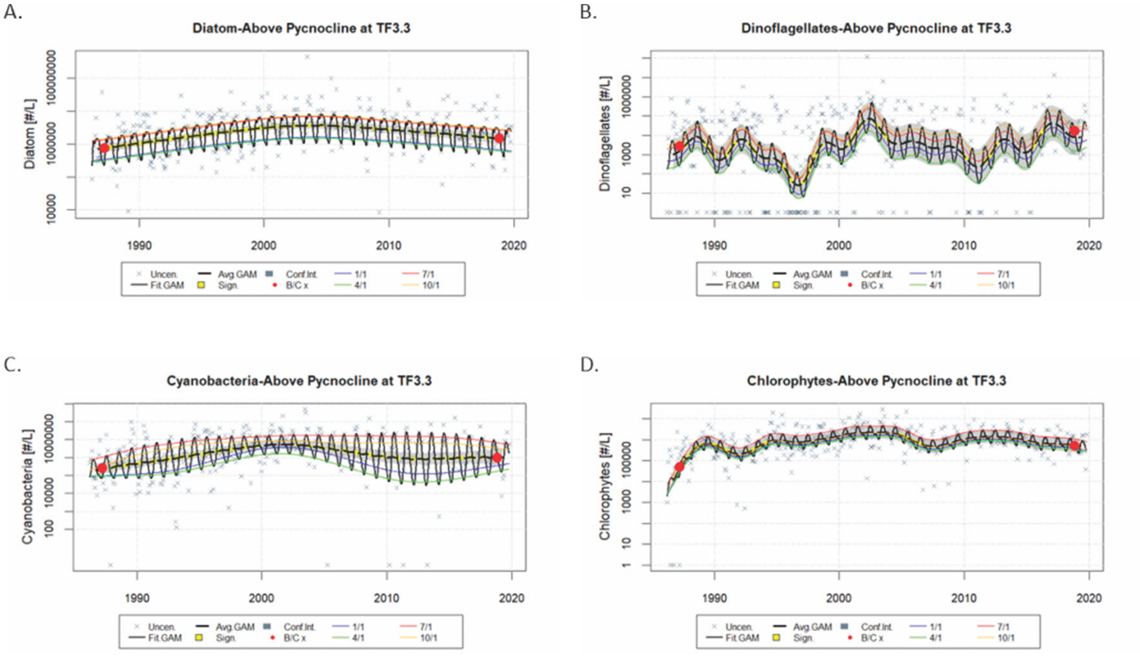


Figure 25. Long term changes in A. Diatom, B. Dinoflagellate, C. Cyanobacteria, and D. Chlorophyte abundance (#/L) based on the GAM model output for station TF3.3 in the oligohaline Rappahannock River for the period of 1986 through 2019. Plots show the annual average predicted value and confidence interval, the full model and seasonal predictions for each of the taxonomic groups shown. Yellow lines on the plot indicate periods of significant change in direction. Red circles are the baseline and current mean values based on model predictions.

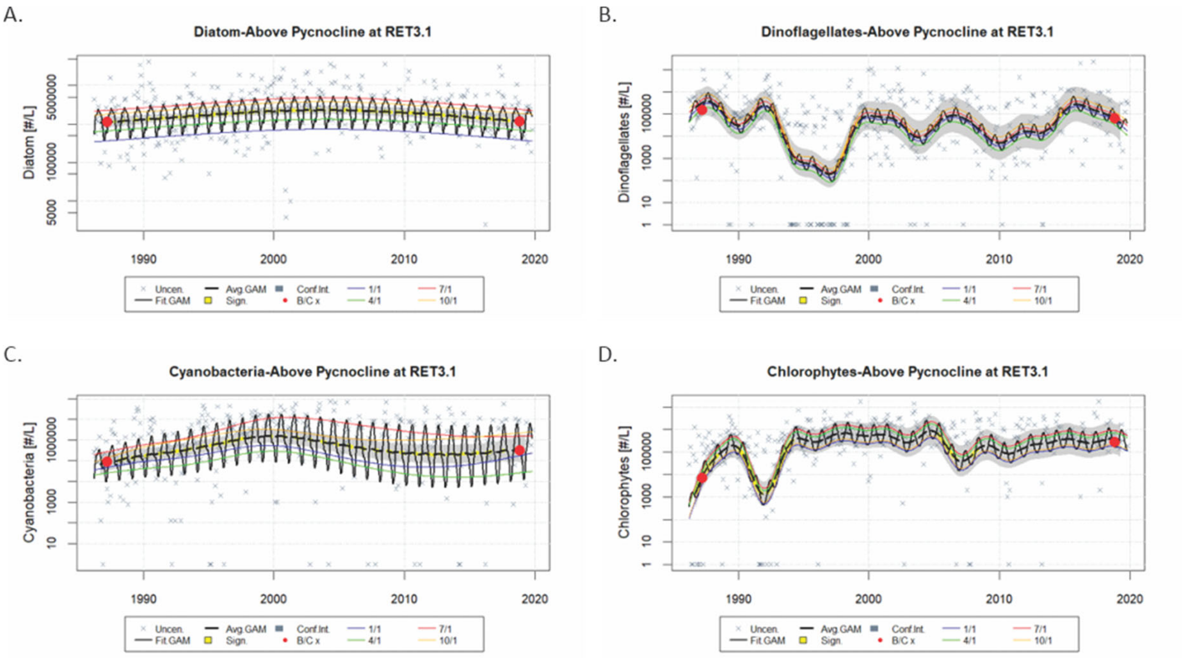


Figure 26. Long term changes in A. Diatom, B. Dinoflagellate, C. Cyanobacteria, and D. Chlorophyte abundance (#/L) based on the GAM model output for station RET3.1 in the low mesohaline Rappahannock River for the period of 1986 through 2019. See Figure 25 for details.

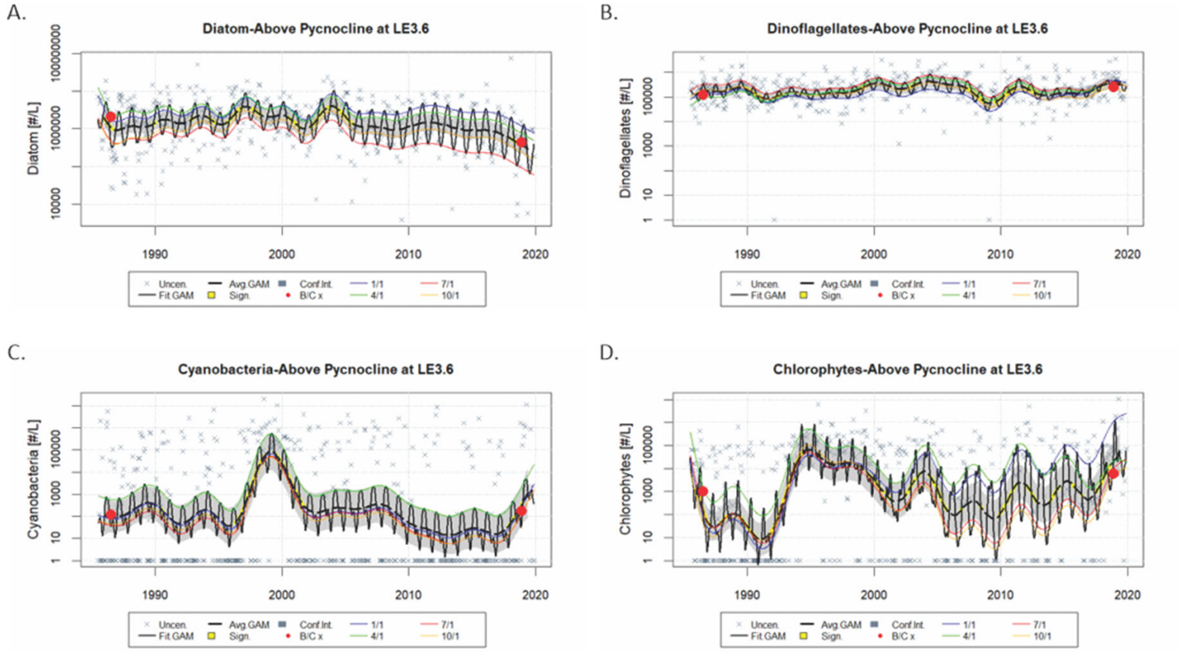
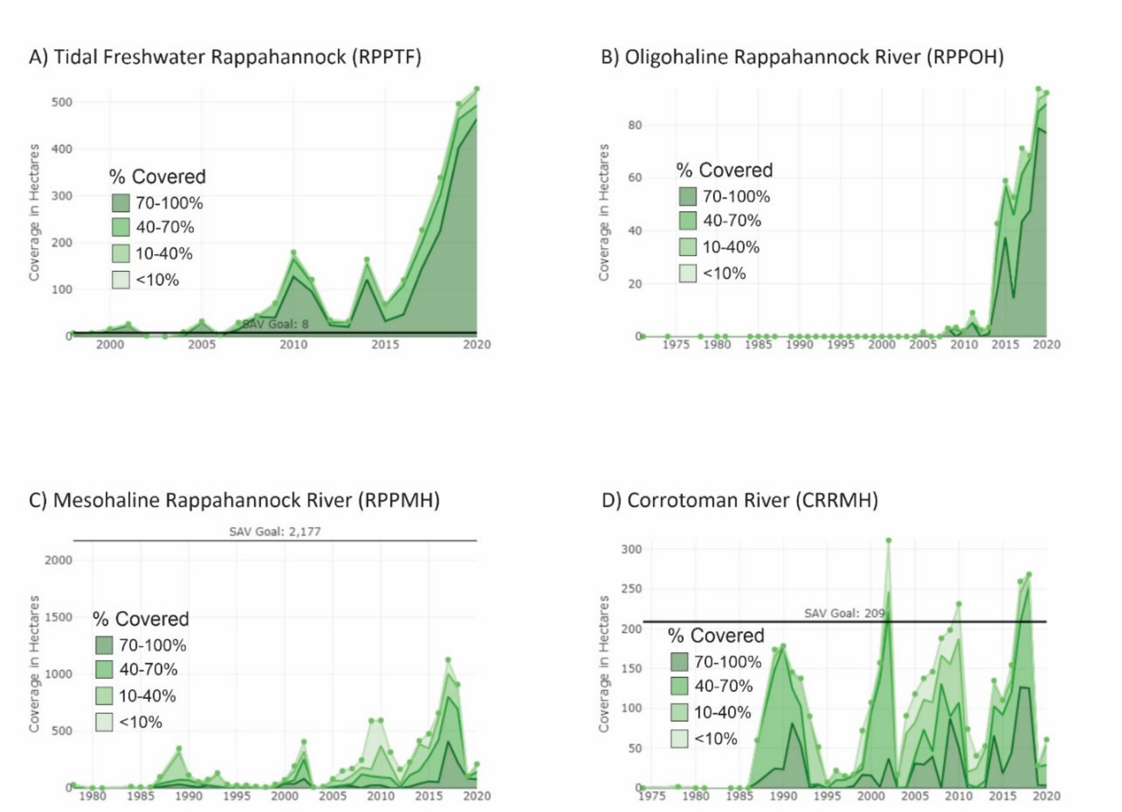


Figure 27. Long term changes in A. Diatom, B. Dinoflagellate, C. Cyanobacteria, and D. Chlorophyte abundance (#/L) based on the GAM model output for station TF3.3 in the low mesohaline Rappahannock River for the period of 1986 through 2019. See Figure 25 for details.

5.2.2. Submerged Aquatic Vegetation

Submerged aquatic vegetation (SAV) monitoring has enabled the region's state agencies and research community to collaborate on quantifying change over time in these important biological communities. Members of the Chesapeake SAV research community recently engaged in an effort to summarize changes over time in SAV abundance across all Chesapeake tidal regions. Their findings are available from at https://www.vims.edu/research/units/programs/sav/. They noted that in the tidal fresh and oligohaline portions of the Rappahannock, there was no evidence of the extent of SAV bends prior to 1978, when a ground survey revealed a limited amount of SAV in the tidal wetland areas and several secondary creeks of the mainstem of the Rappahannock River. Historically, the shoal areas of the lower Rappahannock and the Corrotoman rivers were dominated by dense beds of eelgrass and widgeongrass. As in other areas of the Chesapeake, these beds reached peak biomass in the 1960s and declined sharply after Tropical Storm Agnes in 1972. Little SAV was observed through the 1980s, after which SAV abundance in the area experienced a series of fluctuations.


A) Tidal Freshwater Rappahannock (RPPTF)

B) Oligohaline Rappahannock River (RPPOH)

C) Mesohaline Rappahannock River (RPPMH)

D) Corrotoman River (CRRMH)

Figure 28. Long term change (1985-2020) and current status relative to Chesapeake Bay Program goals of submerged aquatic vegetation (SAV) in the Rappahannock River by segment. SAV coverages are provided in hectares with densities expressed as hectares in percent coverage from very sparse (<10%), to sparse (10-40%), dense (40-70%) or very dense (70-100%) SAV coverage for each segment of the Rappahannock River. Solid lines indicate established areal goals for a given segment in hectares (Note: there is no established goal for segment RPPOH). Modified from figures provided at https://www.vims.edu/research/units/programs/sav/.

Chesapeake Bay wide aerial SAV surveys expanded to include the upper and middle Rappahannock beginning in 1998. Since that time, SAV beds in the tidal fresh region have expanded and contracted depending on water quality conditions. SAV has populated the tidal wetland area formed by the meandering river channel, the tributary creeks and the large, shallow shoals found along the main river channel. The tidal fresh segment has regularly exceeded its SAV restoration goal of 66 acres, although this goal is likely artificially low due to limited historical coverage data. In the middle Rappahannock, SAV was not observed again until 2005, and its abundance remained low until 2014 when coverage suddenly increased. Almost all of the SAV in this segment of the Rappahannock is located inside the tributaries and small creeks entering the mainstem river or in and around marshes, all of which provide protection from the high-energy environment characteristic of the mainstem.

The Chesapeake Bay Program has established regional goals for SAV restoration in each of the major segments of the Rappahannock River. As of 2020, only the tidal freshwater Rappahannock River (RPPTF) currently and substantially exceeds these goals. In fact, SAV areal coverage and density have been slowly increasing in the last two decades in this segment (Figure 28A) perhaps in response to the reductions in loads mentioned above and concomitant improvements in nutrient concentrations and water clarity. The remaining segments have shown similar albeit smaller and/or more unstable responses that have either not attained the SAV goals (segment RPPMH; Figure 28C) or briefly attained them only to precipitously decline thereafter (segment CRRMH; Figure 28D). The dynamics observed particularly in the mesohaline segments of the river may be the result of a change in the dominant seagrass species *Ruppia martitima* which could alternatively respond positively to increasing temperature associated with climate change and negatively to increases in chlorophyll *a*, and/or water clarity and negatively to fluctuations in salinity (Richardson, et al., 2018; Moore et al., 2014). Future studies within the river should examine potential interactions between SAV coverage and the stressors mentioned above.

5.2.3 Benthos

Because benthic communities respond to multiple anthropogenic stressors, have relatively long lifespans, and limited mobility, and as such they are ideal communities for monitoring and assessing the level of impairment of the habitats in which they live. Benthic monitoring began in the Rappahannock River in 1985, with the establishment of four fixed point monitoring stations each corresponding to existing water quality stations (TF3.3, RET3.1, LE3.2, LE3.4; see Figure 4). Status and long-term trends in benthic community health were assessed for these stations using the Benthic Index of Biotic Integrity (B-IBI; Weisberg et al., 1997). In 1996, 25 probability-based stations were added to the Rappahannock River to supplement data collected at fixed-point stations and allow a tributary-wide assessment of community health and progress towards restoration goals based on the B-IBI (Ranasinghe et al., 1994; Weisberg et al., 1997; Alden et al., 2002; Llanso et al.,2009).

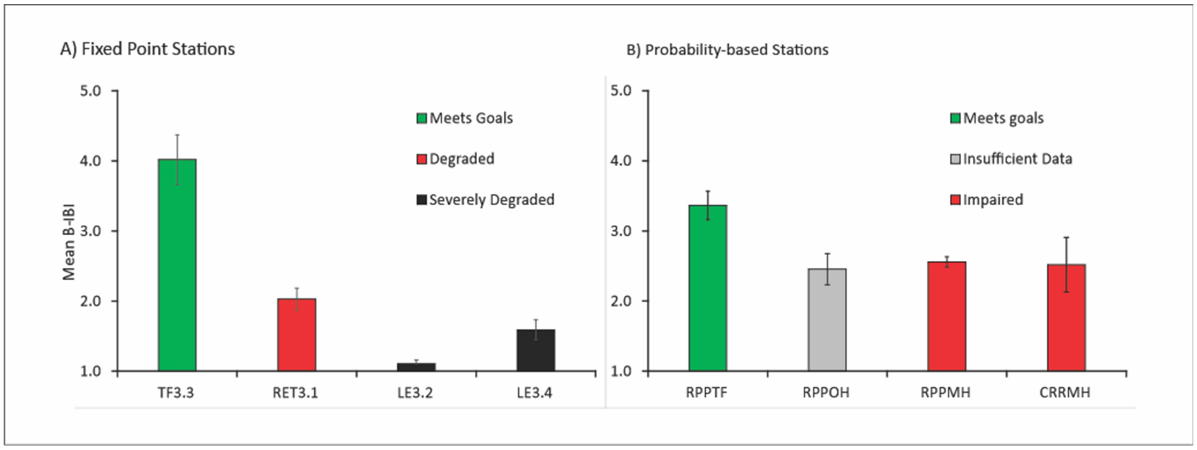


Figure 29. Status of benthic communities at A. Fixed Point Stations and B) Probability-based Stations in the Rappahannock River for the period of 2018 through 2020. Shown are station and segment B-IBI means ± one standard error. Impairment for probability-based samples was assessed using methods described in Llanso et al., 2009.

Station TF3.3 in the oligohaline portion of the Rappahannock River was the only fixed-point station that met the B-IBI restoration goals (Figure 29). The remaining stations were degraded or severely degrading with a minimum value at station LE3.2 in the mesohaline portion of the estuary (Figure 29A). Status assessments. Probability-based data used to assess impairment at the scale of the segment showed a similar generalized spatial trend. Benthic communities meet restoration goals in the tidal freshwater portion of the river (segment RPPTF) but were generally impaired in mesohaline reaches of the estuary (Figure 29B).

A series of GAM analyses was conducted on the B-IBI and some of its component metrics to identify long-term patterns of change in benthic community condition and potential relationships of that condition to water column stressors including measures of dissolved oxygen, freshwater flow, salinity, and temperature. This text provides only a brief synopsis of the important results rather than a complete summary of all analytical results. When discussed below, a significant relationship refers to the prediction resulting from a generalized additive model (GAM) between a response variable (the B-IBI or its component metrics) and a predictor (time or the stressors listed above), for which at least one term of the model (linear or smoother) was statistically significant ($p \leq 0.05$). For the sake of brevity, results of significance tests, R^2 and other statistical test criteria presented are provided in the appendices rather than referenced in the text.

Benthic condition as measured by the B-IBI fluctuated substantially over time at station TF3.3 in the although there was a generalized trend of improving community condition in this portion of the river (Figure 30A). A significant relationship between the B-IBI and freshwater flow was detected at this station and the predicted values from the model appear to track the observed fluctuations in the B-IBI as do annual mean values of Spring/Summer flow (Figure 30B). The B-IBI appears to decline below the restoration goal periodically but peaks above it when freshwater inputs rise above levels of 1500-2000 m^3/sec (Figure 30B). These results suggest that flow acts as a mediating factor for maintaining benthic community conditions at levels above the restoration goals (B-IBI≥3.0) at station TF3.3.

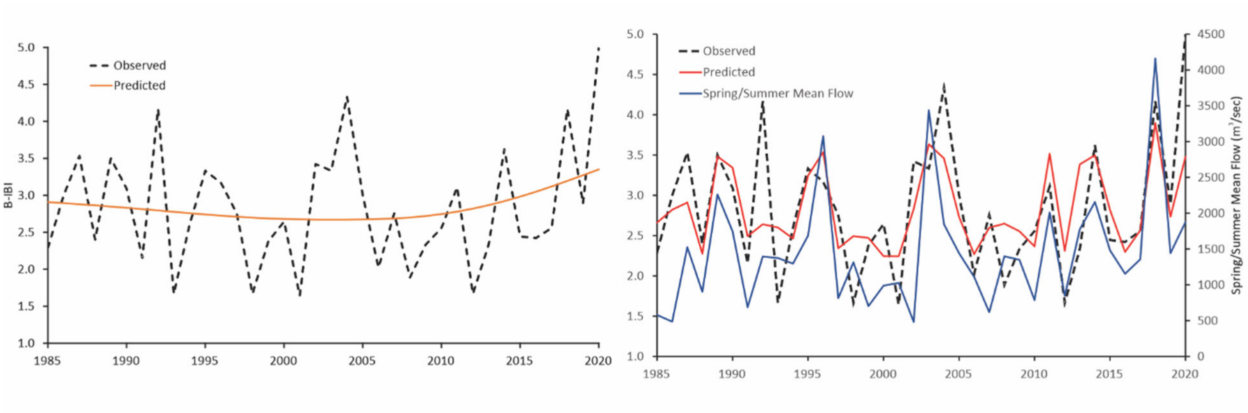


Figure 30. Change in the B-IBI at Station TF3.3 in the oligohaline Rappahannock River A. over time in years and B. over time in relation to change in flow. Plot A shows the observed data (dashed line) and prediction due to time while Plot B shows the change in observed B-IBI values (dashed line) and values predicted by a significant relationship to Spring/Summer mean annual flow (red line) in combination with the predictor variable (blue line) over time.

Although the B-IBI met the restoration goals at the start of monitoring, community condition at station RET3.1 has generally declined to degraded levels and is continuing worsened over time (Figure 31A). A significant relationship between the B-IBI and bottom summer temperature indicates that the decline in benthic community condition may be due to an increase in water temperature over the long-term (Figure 31B.). Plots of predicted values due to temperature show a steady decline that parallels although does not completely overlap that of the observed values while summer temperatures show a steady increase(Figure 2xB). Temperature may directly or indirectly apply adverse pressure on the component metrics of the B-IBI which in combination could cause the observed degrading patterns.

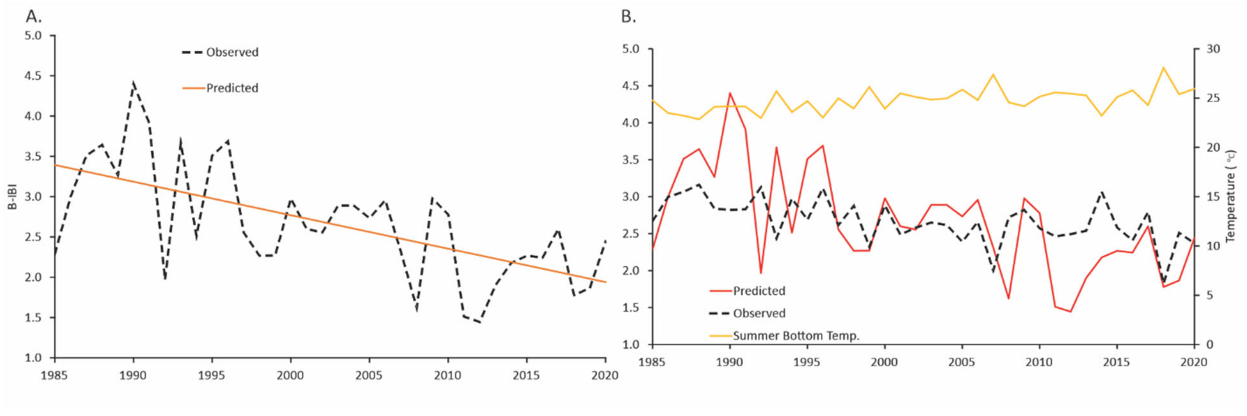


Figure 31. Change in the B-IBI at Station RET3.1 in the oligohaline Rappahannock River A. over time and B. over time in relation to change in summer mean temperature. Plot A shows the observed data (dashed line) and prediction due to time while Plot B shows the change in observed B-IBI values (dashed line) and values predicted by a significant relationship to Summer mean annual temperature(red line) in combination with the predictor variable (yellow line).

For example, increased temperature could increase water column stratification, bacterial respiration rates or phytoplankton production inputs any of which could lead to reduced dissolved oxygen and therefore impacts on the benthos. Alternatively, temperature increases could induce changes in the overall species composition of the community as different taxa will exhibit different temperature tolerances. The data reveal evidence of both of these potential effects.

There was a significant positive relationship between in-situ (collected with benthic samples) dissolved oxygen and Shannon-Weiner diversity and plots of the predicted values of this metric show a long-term decline that closely parallels both the observed data and in-situ dissolved oxygen (Figure 32). The observed relationship indicated that observed values of dissolved oxygen somewhere between 5-6 mg/L result in diversity values that lower its metric scores for the B-IBI to levels indicative of degraded conditions (Figure 32). Changes in of the overall structure of the community are evident when composition of various taxonomic groups were closely examined over time. From the start of monitoring through the 1990s and most of the early 2000s, total abundance remained at levels above or below the criteria indicative of unimpacted conditions for this metric and the community was comprised of a mixture of bivalves, infaunal crustaceans and tubificid oligochaetes all typical of low mesohaline habitats (Figure 2x). Beginning in the mid 2000s total abundance began to climb above the upper criterion indicative of degraded conditions as the result of increasing abundance of several groups including tubificid oligochaetes, spionid polycheates, the capitellid *Mediomastus ambiseta*, and the Pilargid polychaete *Hermundura* sp. A a recent migrant species from the Gulf Coast (Figure 33). These changes were accompanied by reductions in abundance in both bivalves and infaunal crustacean (Figure 33). Increases in the opportunistic taxa listed could be the result of trends in either temperature, dissolved oxygen, or increased phytoplankton production (chlorophyll a) observed in the water quality data. Loss of bivalve and crustacea both in termsof abundance and numbers of species are likely a response to reductions in dissolved oxygen.

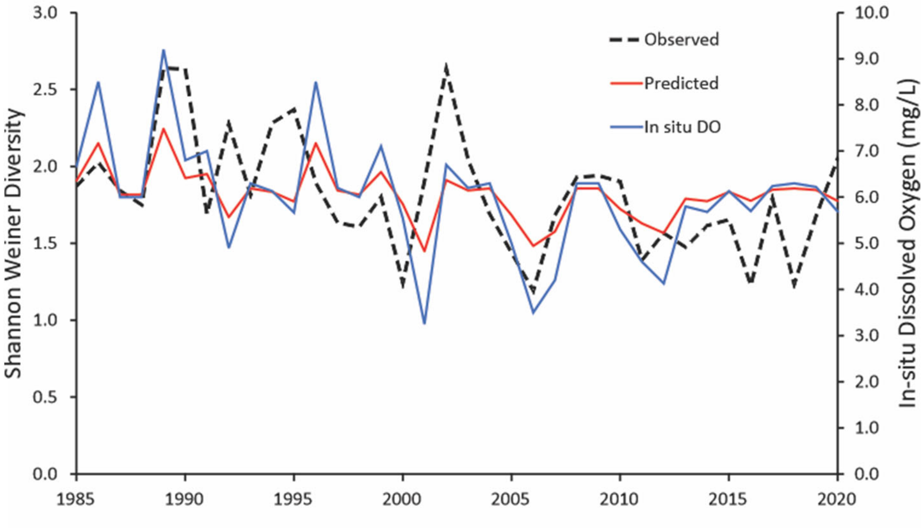


Figure 32. Change in diversity at Station RET3.1 in the oligohaline Rappahannock River and over time in relation to in-situ dissolved oxygen. Shown are observed data (dashed line) and prediction due to dissolved oxygen (red line) in combinaton with the predictor variable, in-situ dissolved oxygen (blue line).

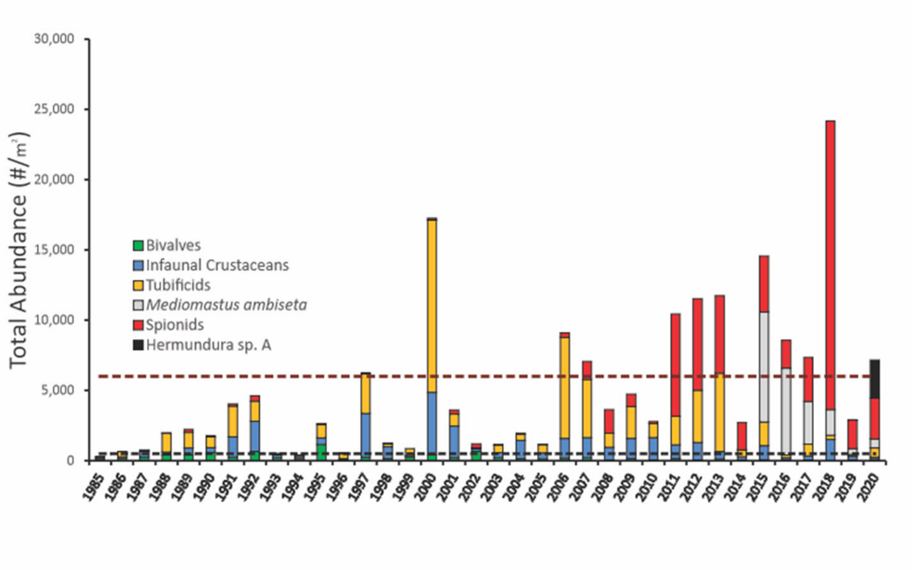


Figure 33. Change in total abundance and abundances of dominant taxa at Station RET3.1 in the oligohaline Rappahannock River. Dashed lines indicate the upper and lower criterion values indicative of degraded levels for total abundance per m^2 in low mesohaline habitats.

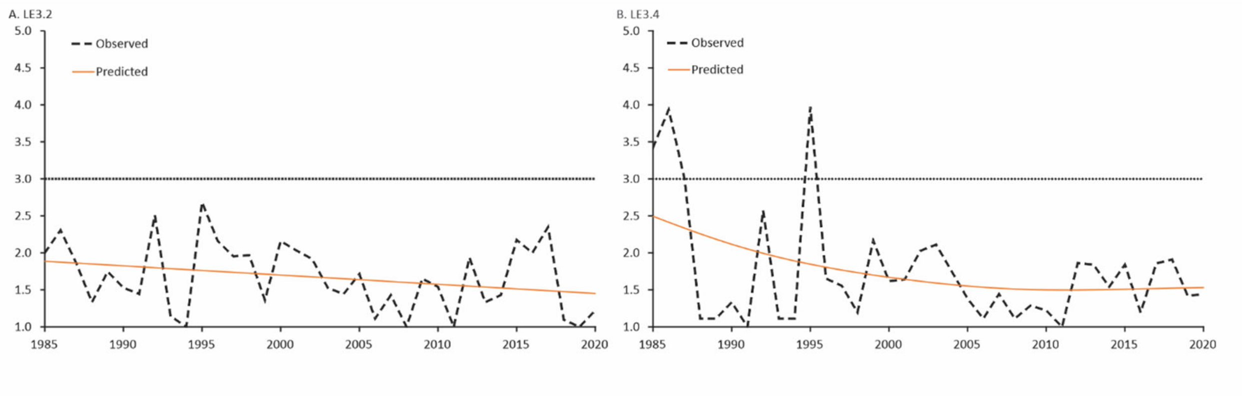


Figure 34. Long-term change in the B-IBI at station A. LE3.2 and station B. LE3.4 in the Rappahannock River from the start of monitoring through 2020. Showing are the observed data and predicted values of a generalized model between the B-IBI and time in years.

The B-IBI at both stations LE3.2 and LE3.4 in the lower mesohaline portion of the river nearly always remained below the restoration goal and appears in both cases to be continuing to decline as indicated by the GAM analyses (Figure 34). Benthic communities at these two stations are chronically degraded likely due to low dissolved oxygen events triggered by increasing inputs of phytoplankton production. Benthic communities are likely to remain degraded at these two stations as there is either an indication continued decline in dissolved oxygen concentrations or no improvement. Although there is no direct evidence of temperature induced effects on community structure, the upward change in both temperature and phytoplankton production observed will likely continue to exacerbate dissolved oxygen problems at these two stations.

6. Summary and Insights on Change

At first glance, the results of this study seem somewhat at odds with established conceptual models of estuarine eutrophication. Once pollutants reach tidal waters, multiple environmental factors interact with them to affect key habitat indicators such as algal biomass, DO concentrations, water clarity, SAV abundance, and fish populations (Testa et al. 2017; Figure 35). For example, phytoplankton growth depends not just on nitrogen and phosphorus, but also on light and water temperature (Buchanan 2020, Buchanan et al. 2005). In general, the more saline waters of an estuary will tend to be more transparent than tidal-fresh regions (Testa et al. 2019), and waters closer to nutrient inputs are more affected by them than more distant regions. Plant and bacterial respiration and the decomposition of phytoplankton are the primary drivers of dissolved oxygen concentrations, but they can also be negatively affected by salinity and temperature stratification of the water column. Conversely, wind-driven and flow advected mixing can positively influence dissolved oxygen concentrations. When anoxia occurs at the water-sediment interface, nitrogen and phosphorus stored in the sediments can be released through anaerobic chemical reactions further increasing phytoplankton production (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 (Gurbisz and Kemp 2014, Phelps 1994, Cloern 1982).

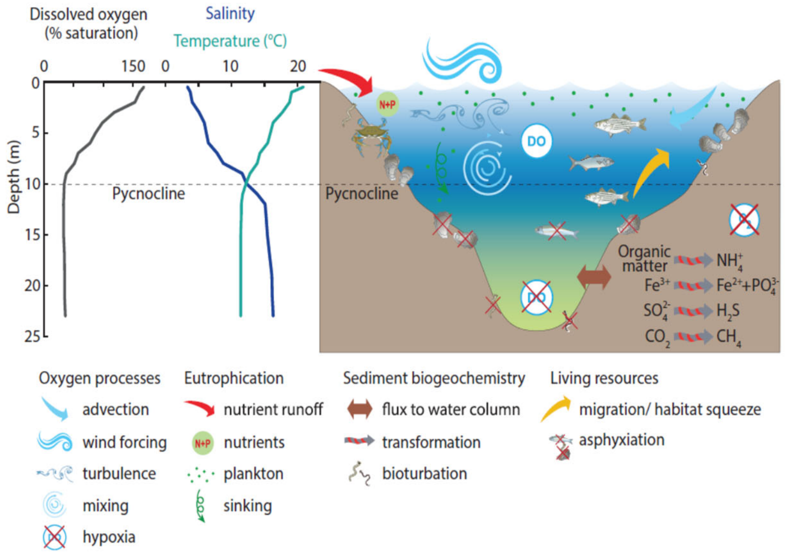


Figure 35. Conceptual diagram illustrating how hypoxia is driven by eutrophication and physical forcing, while affecting sediment biogeochemistry and living resources. From Testa et al. (2017).

Overall, the results of this study indicate that the Rappahannock River has experienced some improvements in nutrients concentrations and probably due to point source management strategies and other factors within the tidal portion of the watershed (Murphy et al., In Press). Despite these apparent improvements in nutrients, increased phytoplankton production was evidenced in the form of both increases in both chlorophyll *a* concentrations and abundances of several dominant phytoplankton taxa at multiple stations. Previous studies suggest that there is a "saturation limit" for phytoplankton use of nutrients (Buchanan et al., 2005; Fisher and Gustafson, 2003). If dissolved concentrations are above this limit, the nutrients are in such excess that the phytoplankton cannot use them all. There may not be a response in phytoplankton to nutrient reductions unless the dissolved nitrogen or phosphorus concentrations cross under their saturation limits. Spring dissolved inorganic nitrogen concentrations have remained well above the saturation limit for nitrogen, but spring phosphate concentrations have dipped below the saturation limit in recent years (see Appendices). This may partially explain the improving spring chlorophyll *a* concentrations and Secchi depths at the tidal fresh Rappahannock stations. Interestingly, depending on which estimate are assessed phosphorus loads from the watershed may or may not have declined, over the same period. Other factors may influence phytoplankton production within the estuary. Declining sediment loads may increase light availability allowing for increased plankton production while still accounting for the decreasing Secchi depth as per the Organic Fog effect (Turner et al., 2021).

The excess phytoplankton production in combination with and possibly exacerbated by increasing temperatures are likely adversely affecting both SAV and benthic communities in multiple areas of the estuary. At least for the benthos and possibly for the SAV, freshwater flow may be ameliorating the adverse effects of increased production in the tidal freshwater portions of the estuary. Freshwater flow did not seem to have the same beneficial effects on the benthos in the lower portions of the river that it had in the tidal fresh. This may occur because the Rappahannock widens and meanders substantially, reducing flow velocity and perhaps lessening any of its ameliorating effects. An examination of water column stratification and/or continuous monitoring data (if available) could provide additional insight.

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Appendix

This will be a separate document, but a map and panel plot each for:

- Surface PO4
- Surface DIN
- Surface TSS
- Surface DO
- Surface Temperature
- *And bottom for all applicable parameters too?*