Potomac Tributary Report:

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

December 18, 2020

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

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Contents

1. Purpose and Scope

The Potomac Tributary Report summarizes 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 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. Continuing to track water quality response and investigating these influencing factors are important steps to understanding water quality patterns and changes in the Potomac River.

2. Location

The Potomac River is the second largest tributary to Chesapeake Bay. Its watershed is approximately 38,000 km^2 and spans parts of four states and Washington, D.C. The tidal Potomac begins just upstream of Washington, D.C. at the boundary of the Coastal Plain and Piedmont (Figure 1).

2.1 Watershed Physiography

The Potomac River watershed extends across five major physiographic regions, namely, Valley and Ridge, Piedmont, Coastal Plain, Blue Ridge, and Mesozoic Lowland (Bachman *et al.*, 1998) (Figure 1). The Valley and Ridge physiography includes both carbonate and siliciclastic areas. The Piedmont physiography includes both carbonate and crystalline areas. The Coastal Plain physiography includes lowland, dissected upland, and upland areas. Implications of these physiographies for nutrient and sediment transport are summarized in Section 4.1.

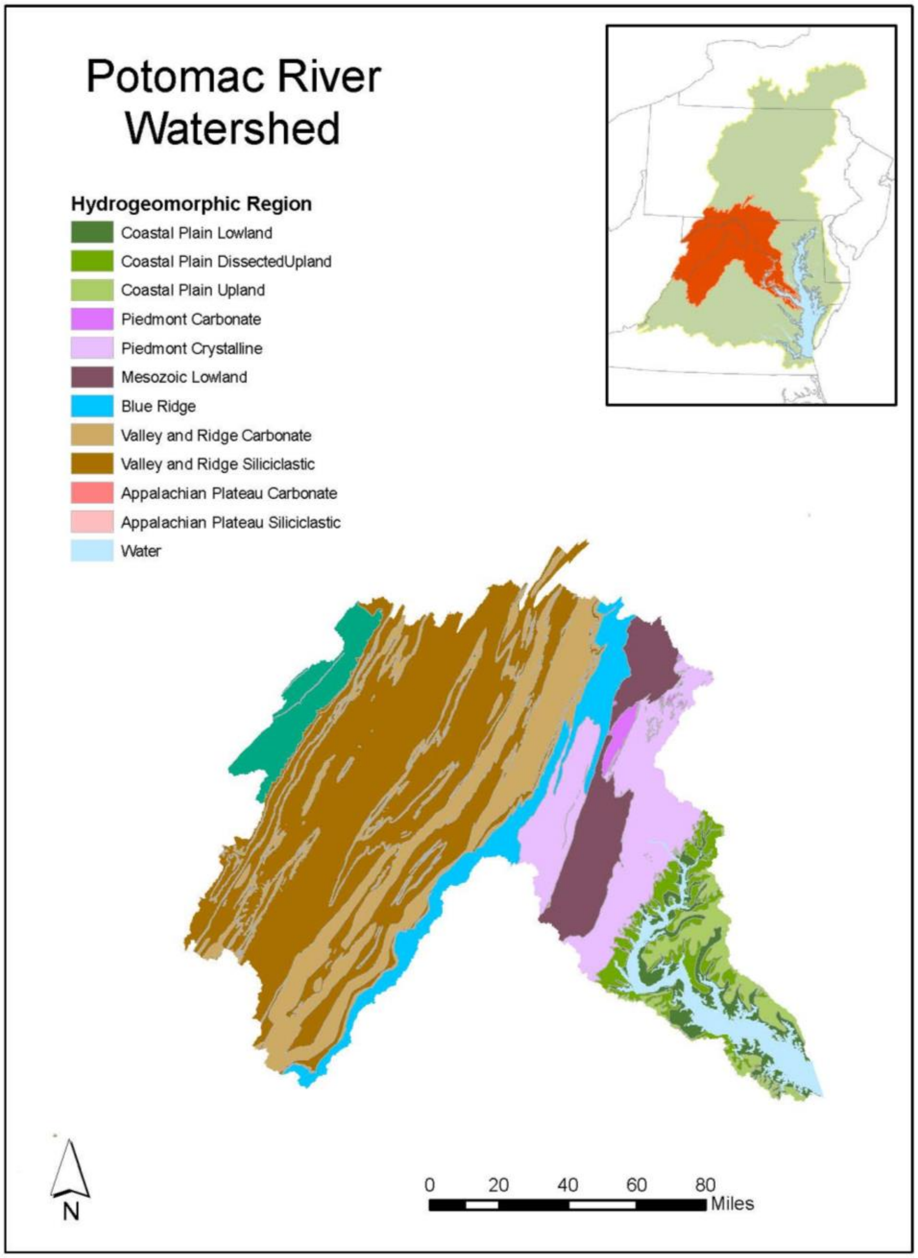

Figure 1. Distribution of physiography in the Potomac River watershed. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

2.2 Land Use

Land use in the Potomac River watershed is dominated (61%) by natural areas. Since 1985, urban and suburban land areas have increased by 596,640 acres (Chesapeake Bay Program, 2017). Correspondingly, the proportion of urban (developed) land in this watershed has increased from 10% in 1985 to 16% in 2018 (Figure 2).

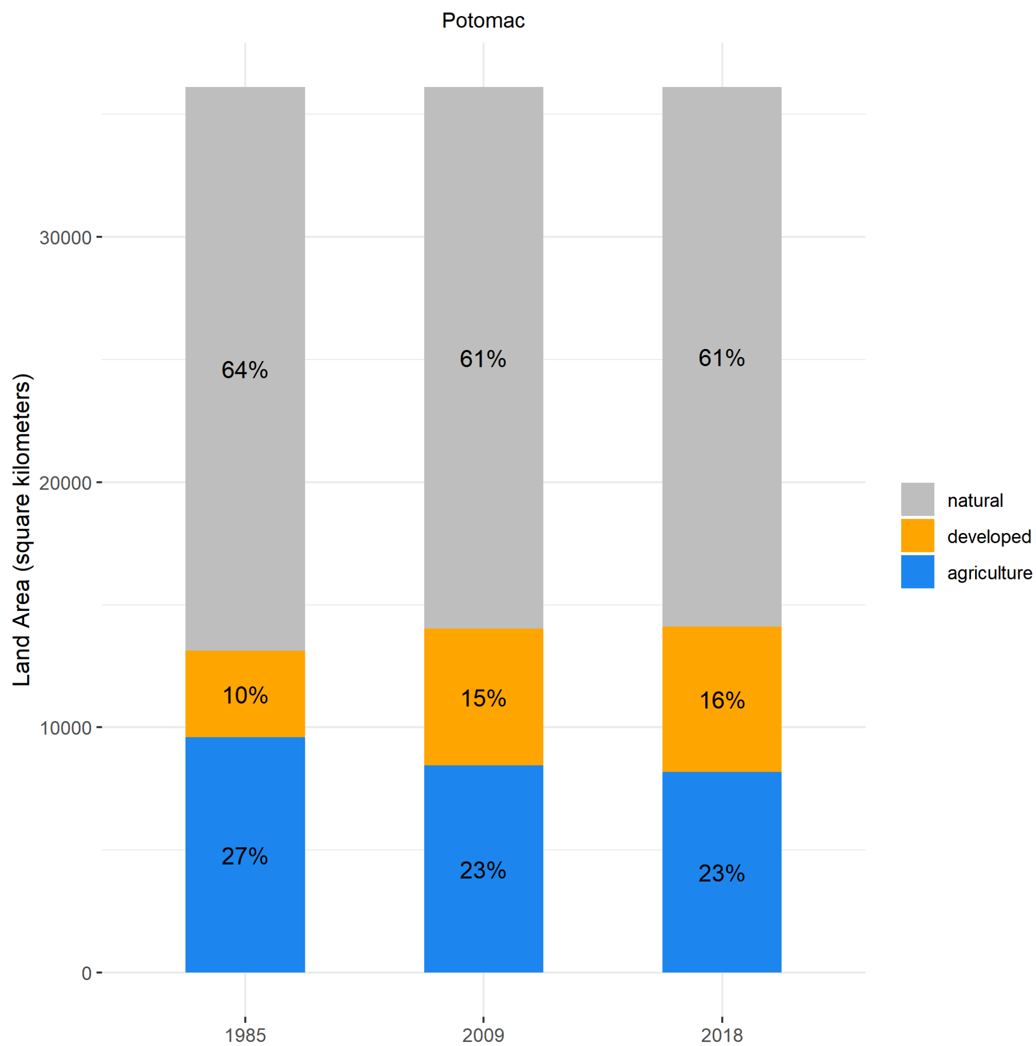

Figure 2. Distribution of land uses in the Potomac River watershed.

In general, developed lands in the 1970s were more concentrated in the Washington, D.C. metropolitan area with 49% of the developed and semi-developed areas contiguous to D.C. Since then, developed lands have expanded to regions both further upstream into the watershed and further downstream into the tidal areas (Figure 3). The impacts of land development differ depending on the use from which the land is converted (Keisman *et al.*, 2018; Ator *et al.*, 2019). Implications of changing land use for nutrient and sediment transport are summarized in Section 4.1.

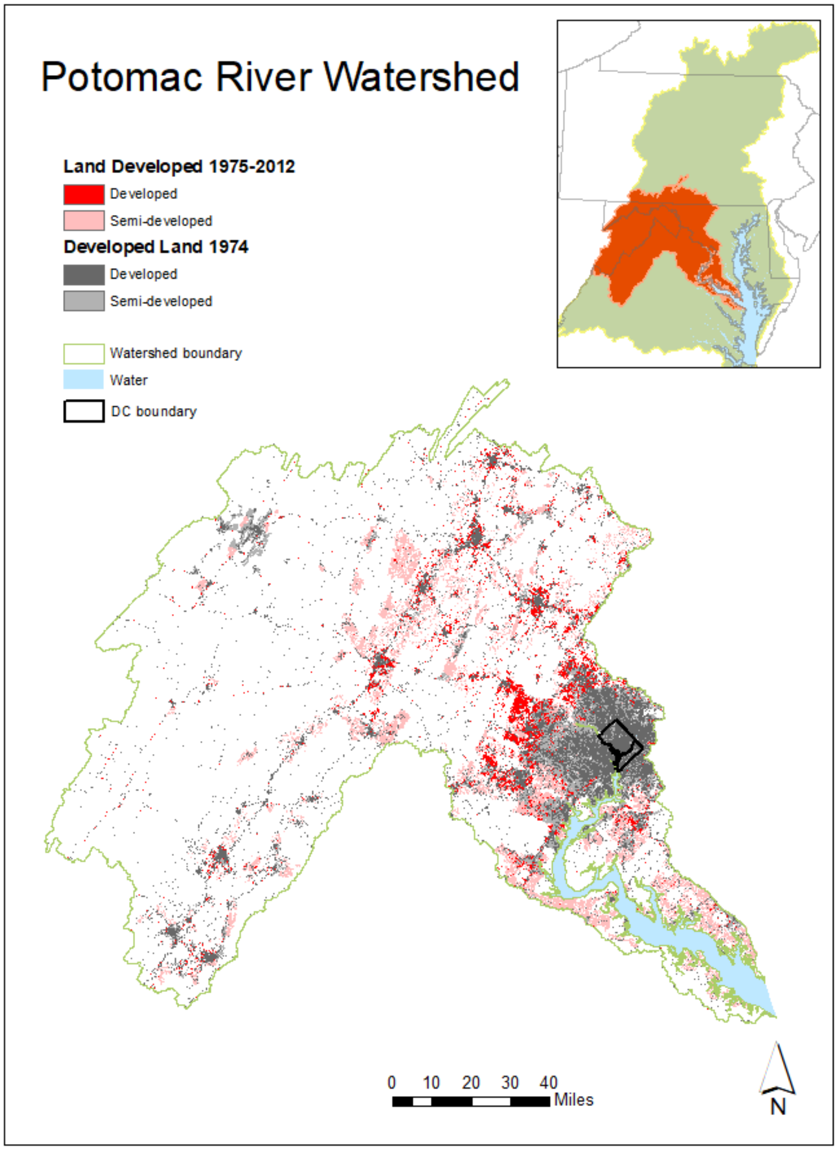

Figure 3. Distribution of developed land in the Potomac River watershed. Derived from Falcone (2015). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

2.3 Tidal Waters and Stations

For the purposes of water quality standards assessment and reporting, the tidal portion of the Potomac River is divided into multiple split segments (USEPA, 2004): Tidal Fresh in Washington, D.C. (DC), Maryland (MD), and Virginia (VA) (POTTF_DC, POTTF_MD, POTTF_VA), Oligohaline in MD and VA (POTOH1_MD, POTOH2_MD, POTOH3_MD, and POTOH_VA), and Mesohaline in MD and VA (POTMH_MH, POTMH_VA) (Figure 4). Three tributaries of the Potomac are also represented, including the tidal fresh Anacostia River in Maryland (ANATF_MD) and Washington, D.C. (ANATF_DC), the tidal fresh Piscataway River (PISTF), and the tidal fresh Mattawoman Creek (MATTF).

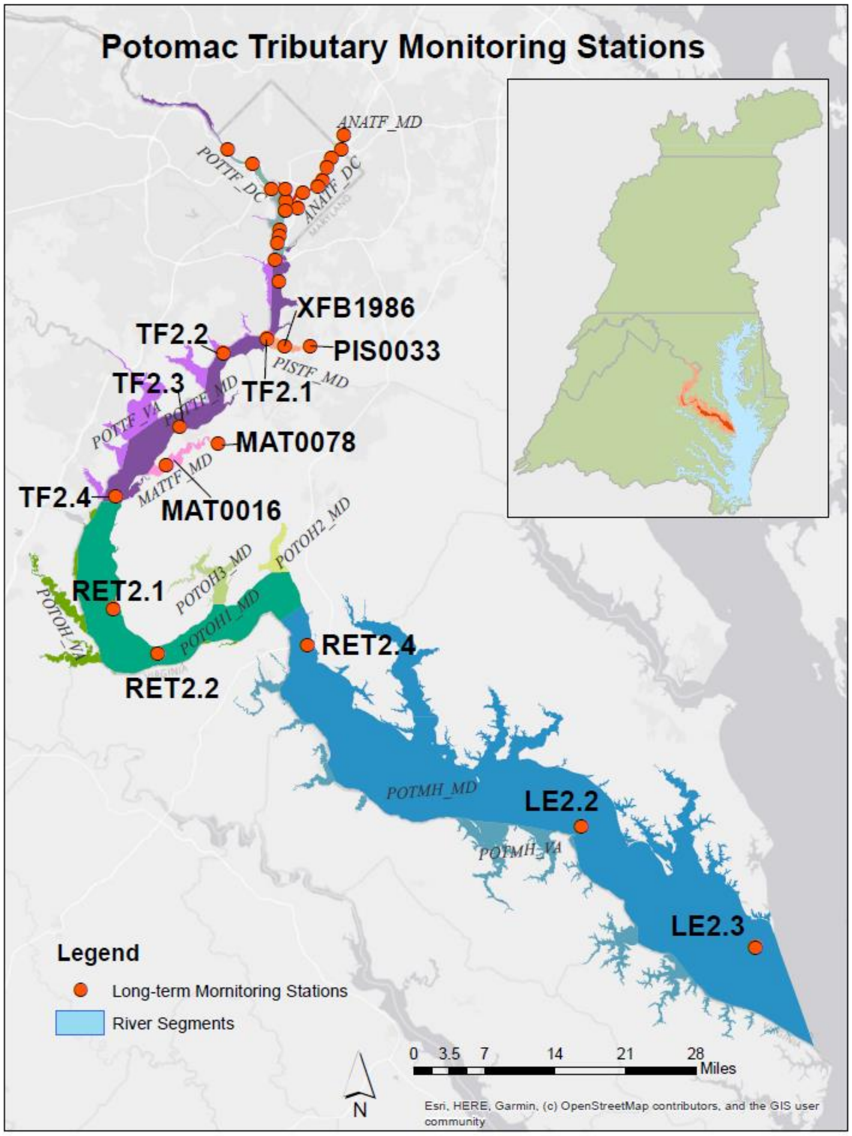

Figure 4. Map of tidal Potomac River segments and long-term monitoring stations. Base map credit Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community, World Geodetic System 1984.

Long-term trends in water quality are analyzed by the MD Department of Natural Resources at 13 stations extending from the Piscataway River to the mouth of the Potomac flowing into Chesapeake Bay. 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 report are available from the Chesapeake Bay Program Data Hub (Chesapeake Bay Program, 2018). Other monitoring is conducted in the Washington, D.C. tidal waters by the D.C. Department of Energy and Environment and used to assess water quality criteria for DO and chlorophyll *a*. Those observations are not included in subsequent trend graphics because they are not evaluated currently using the same statistical techniques. Similarly, shallow-water monitoring that has been conducted in some embayments along the VA Potomac shoreline and in some MD segments is included in the water quality criteria evaluation but not shown in the long-term trend graphics in subsequent sections because of its shorter duration.

3. Tidal Water Quality Status

Multiple water quality standards were developed for the tidal Potomac to protect aquatic living resources (U.S. Environmental Protection Agency, 2003; Tango and Batiuk, 2013). These standards include specific criteria for dissolved oxygen (DO), water clarity/underwater bay grasses, and chlorophyll *a*. For the purposes of this report, a record of the evaluation results indicating whether different Potomac segments have met or not met a subset of Open Water (OW), Deep Water (DW), and Deep Channel (DC) DO criteria over time is shown below (Zhang *et al.*, 2018a; Hernandez Cordero *et al.*, 2020). While analysis of water quality standards attainment is not the focus of this report, the results over time from the evaluation of these three DO criteria for each Potomac River monitoring segment are included here (Tables 1 and 2) to 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), seven out of 17 segment criterion-combinations that were evaluated met the 30-day mean OW summer DO, 30-day mean DW summer DO, and DC instantaneous minimum DO requirements (Zhang *et al.*, 2018b).

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Table 1. 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. "ND" indicates no data.

time period	ANATF_DC	ANATF_MD	PISTF	MATTF	POTTF_DC	POTTF_MD	POTTF_VA	POTOH1_MD	POTOH2_MD	POTOH3_MD	POTOH_VA	POTMH_MD	POTMH_VA
1985-1987							ND		ND	ND	ND		ND
1986-1988							ND		ND	ND	ND		ND
1987-1989							ND		ND	ND	ND		ND
1988-1990							ND		ND	ND	ND		ND
1989-1991							ND		ND	ND	ND		ND
1990-1992							ND		ND	ND	ND		ND
1991-1993							ND		ND	ND	ND		ND
1992-1994							ND		ND	ND	ND		ND
1993-1995							ND		ND	ND	ND		ND
1994-1996							ND		ND	ND	ND		ND
1995-1997							ND		ND	ND	ND		ND
1996-1998							ND		ND	ND	ND		ND
1997-1999							ND		ND	ND	ND		ND
1998-2000							ND		ND	ND	ND		ND
1999-2001							ND		ND	ND	ND		ND
2000-2002							ND		ND	ND	ND		ND
2001-2003							ND		ND	ND	ND		ND
2002-2004									ND	ND			
2003-2005									ND	ND			
2004-2006													
2005-2007													
2006-2008													
2007-2009													
2008-2010													
2009-2011									ND	ND			
2010-2012									ND	ND			
2011-2013									ND	ND			
2012-2014									ND	ND			
2013-2015									ND	ND			
2014-2016									ND	ND			
2015-2017									ND	ND			
2016-2018									ND	ND			

Table 2. Deep Water summer DO (30-day mean) and Deep Channel (Instantaneous) DO criteria evaluation results. Green indicates that the criterion was met. White indicates that the criterion was not met. “ND” indicates no data.

time period	Deep Water		Deep Channel	
	POTMH_MD	POTMH_VA	POTMH_MD	POTMH_VA
1985-1987		ND		ND
1986-1988		ND		ND
1987-1989		ND		ND
1988-1990		ND		ND
1989-1991		ND		ND
1990-1992		ND		ND
1991-1993		ND		ND
1992-1994		ND		ND
1993-1995		ND		ND
1994-1996		ND		ND
1995-1997		ND		ND
1996-1998		ND		ND
1997-1999		ND		ND
1998-2000		ND		ND
1999-2001		ND		ND
2000-2002		ND		ND
2001-2003		ND		ND
2002-2004				ND
2003-2005				ND
2004-2006				
2005-2007				
2006-2008				
2007-2009				
2008-2010				
2009-2011				
2010-2012		ND		ND
2011-2013				ND
2012-2014				ND
2013-2015				ND
2014-2016				ND
2015-2017				ND
2016-2018				ND

Comparing trends in station-level DO concentrations to the computed DO criterion status for a recent assessment period can reveal valuable information, such as whether progress is being made towards attainment in a segment that is not meeting the water quality criteria, or conversely the possibility that conditions are degrading even if the criteria are currently being met. To illustrate this, the 2016-2018 attainment status for the OW summer and DC instantaneous DO criteria shown in Tables 1 and 2 are overlain with the 1985-2018 change in summer surface DO concentration and the 1985-2018 change in bottom summer DO concentrations, respectively (Figure 5). The 30-day mean OW summer DO criterion was met in 6 of the 11 segments for the 2016-2018 period with sufficient data for assessment. Changes in surface and bottom oxygen were mixed, but mostly positive, across the tidal fresh stations where the criterion is met already. In the middle and lower Potomac segments, there are a few possible trends and there is also a mix of attainment status. There is, however, a possibility of improvement in the upper part of the mesohaline MD segment that is not currently meeting the DC instantaneous DO criterion.

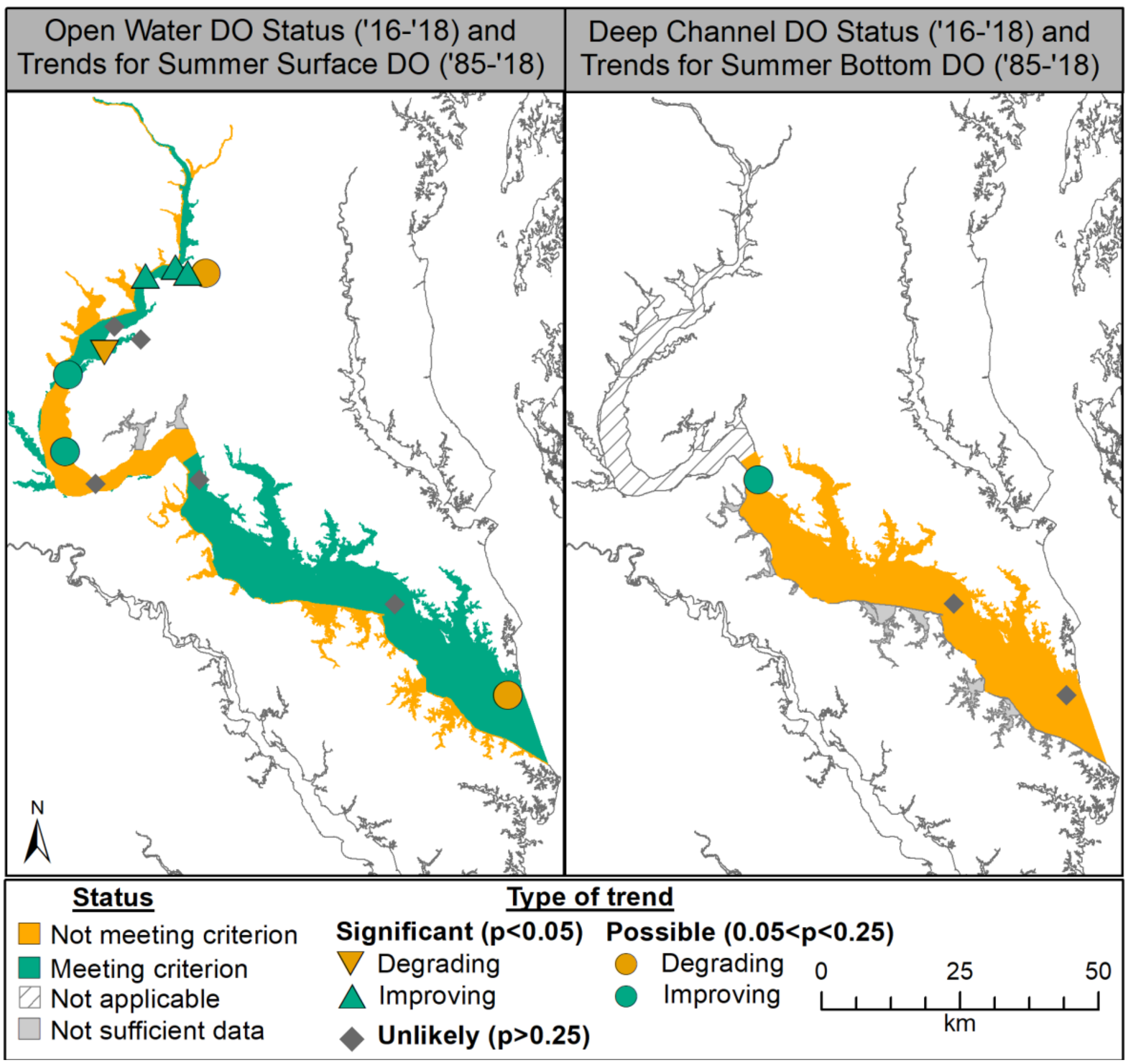


Figure 5. Pass-fail DO criterion status for 30-day OW summer DO and DC instantaneous DO designated uses in Potomac segments along with long-term trends in DO concentrations. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

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 13 tidal stations labeled in Figure 4. For more details on the GAM implementation that is applied each year by MD Department of Natural Resources for these stations in collaboration with the Chesapeake Bay Program and Virginia 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 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 average over the period of record. Note that depending on the location in the Potomac River, sometimes gaged river flow is use for this adjustment and sometimes salinity is used, but we refer to all of these results as "flow-adjusted" for simplicity.

For each trend computation, the level of statistical significance is determined and indicated on the maps. Change is called significant if $p < 0.05$ and possible if the p-value is up to 0.25. That upper limit is higher than usually reported for statistical tests but allows us to provide a more complete picture of the results, identifying locations where change might be starting to occur and should be investigated (Murphy *et al.*, 2019). In addition to the maps of trends, for each parameter, there is a set of graphs (e.g., Figure 7) that include the raw observations (dots on the graphs) and lines representing the mean annual or seasonal GAM estimates, without flow-adjustment. The flow-adjusted GAM line graphs are not shown.

4.1 Surface Total Nitrogen

Annual total nitrogen (TN) concentrations have declined from 1985 to 2018 at all 13 of the tidal Potomac stations, using both trends on concentration data alone and adjusting for flow (Figure 6). In the past 10 years, the majority, but not all, of the station concentrations show little change without flow adjustment (bottom left panel Figure 6). With flow-adjustment (bottom right panel), however, many of the tidal fresh and oligohaline stations show a decrease. This suggests that the degrading and insignificant changes in the bottom left panel were highly influenced by patterns in the freshwater flow.

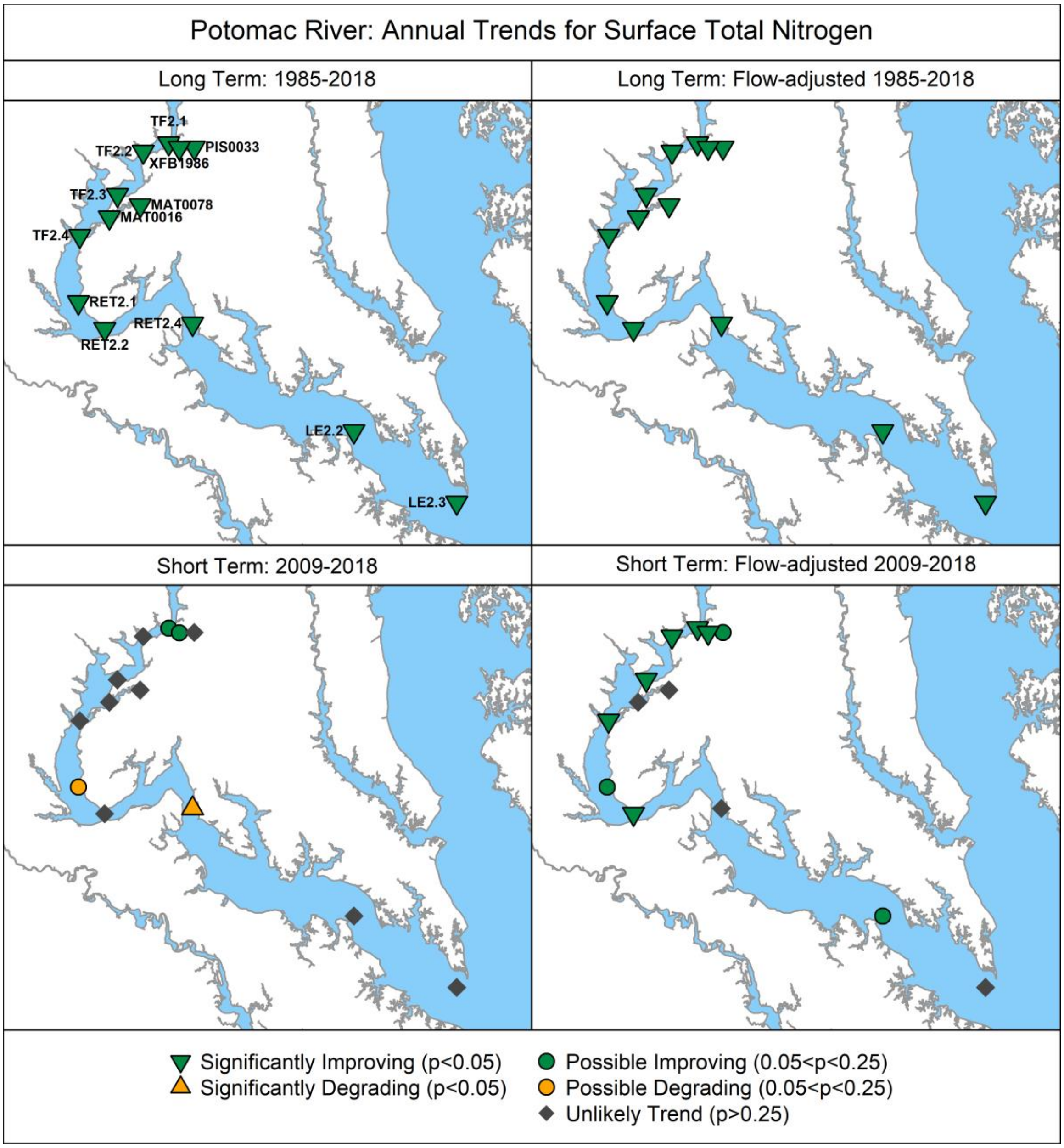


Figure 6. Surface TN Trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

The long-term decreasing TN trends are evident in both the data and the non-flow-adjusted mean annual GAM estimates presented in Figure 7. The upswing in TN concentrations in 2018 is clear in many of these graphs as well, which likely influenced the trends in Figure 6. Vertical blue dotted lines represent a laboratory and method change (May 1, 1998) that was tested for its impact on data values. A statistical intervention test within the GAM models showed that these changes were significant at most stations. This is evident by the vertical jump in the mean annual GAM estimates shown with the lines. With this technique, we can estimate long-term change after accounting for the artificial jump from the method change (Murphy *et al.*, 2019).

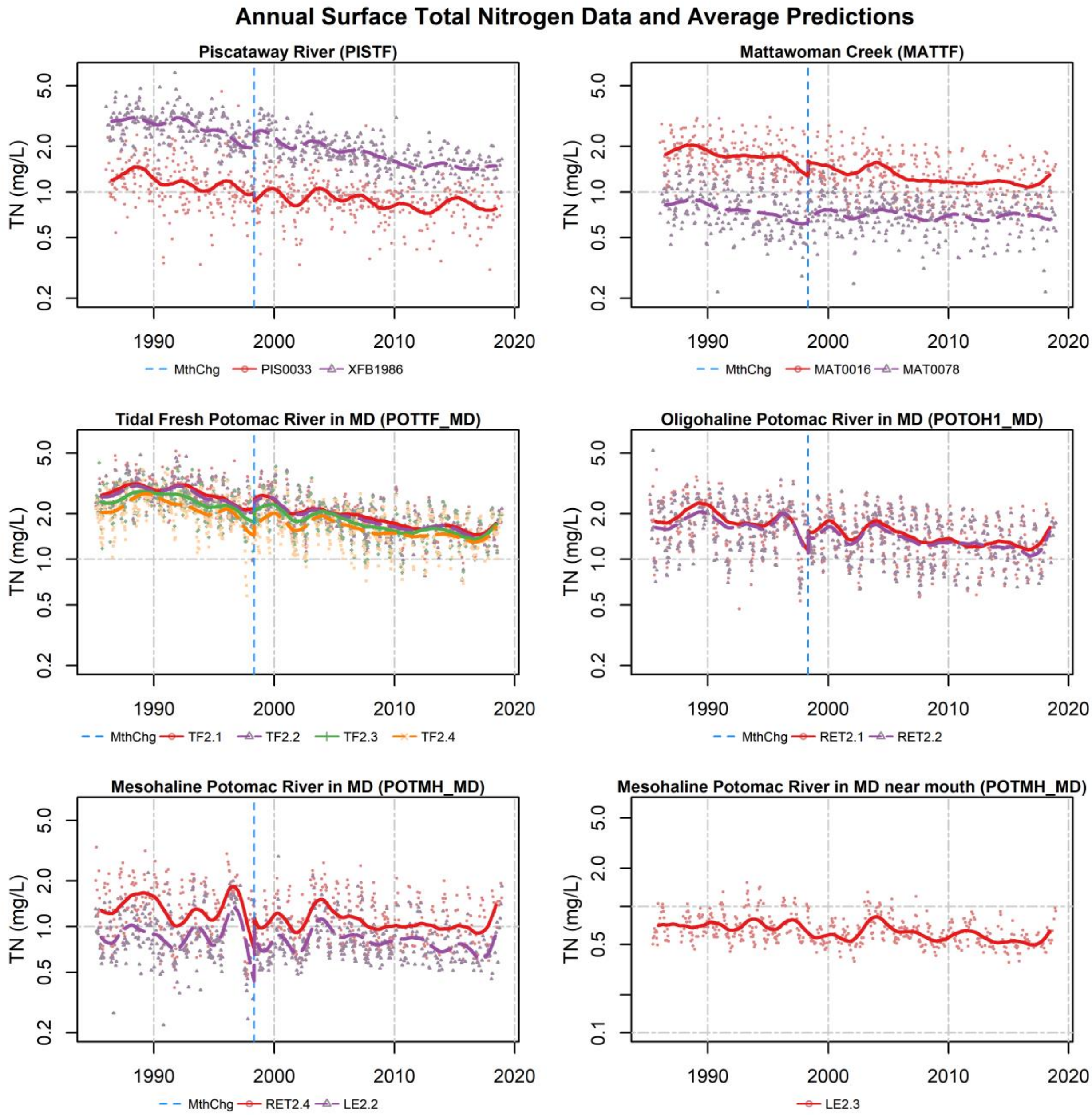


Figure 7. Surface TN data (dots) and average long-term pattern generated from non-flow-adjusted GAMs. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations. Vertical blue dotted lines represent timing of changes in laboratory and/or sampling methods.

4.2 Surface Total Phosphorus

Surface total phosphorus (TP) is also improving at most stations over the long-term, both with and without flow-adjustment (Figure 8). In the short-term, there is still consistent improvement in the tidal fresh region with both techniques, but differences exist in the oligohaline and mesohaline stations. At the oligohaline stations, improving short-term trends only exist on the non-adjusted results, suggesting that decrease in TP in the last 10 years in that region may be linked to patterns in freshwater flow.

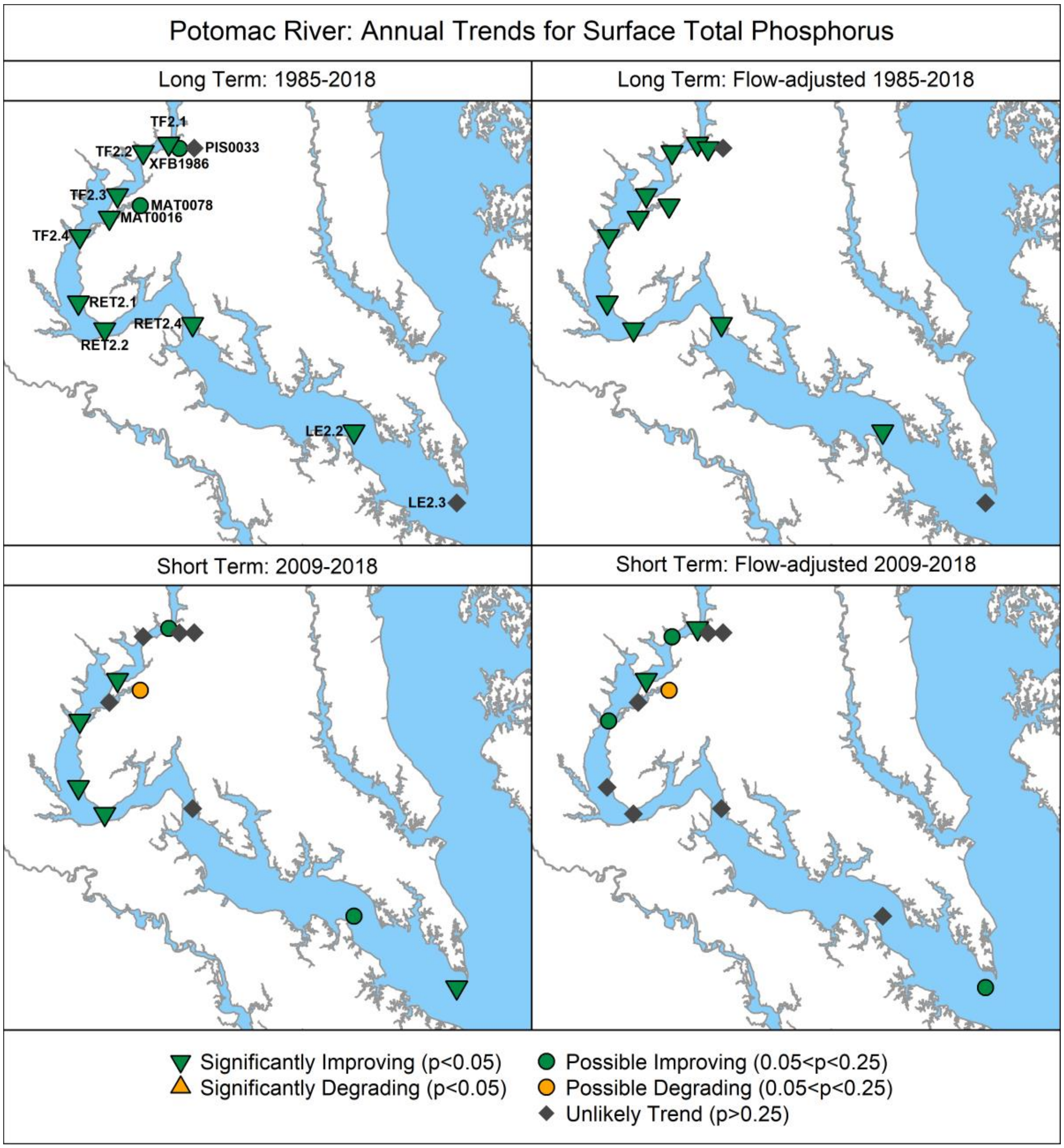


Figure 8. Surface TP Trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

The most noticeable decrease in TP concentrations occurs at the beginning of the record at many stations (Figure 9), but a gradual decrease is occurring at most stations throughout the record.

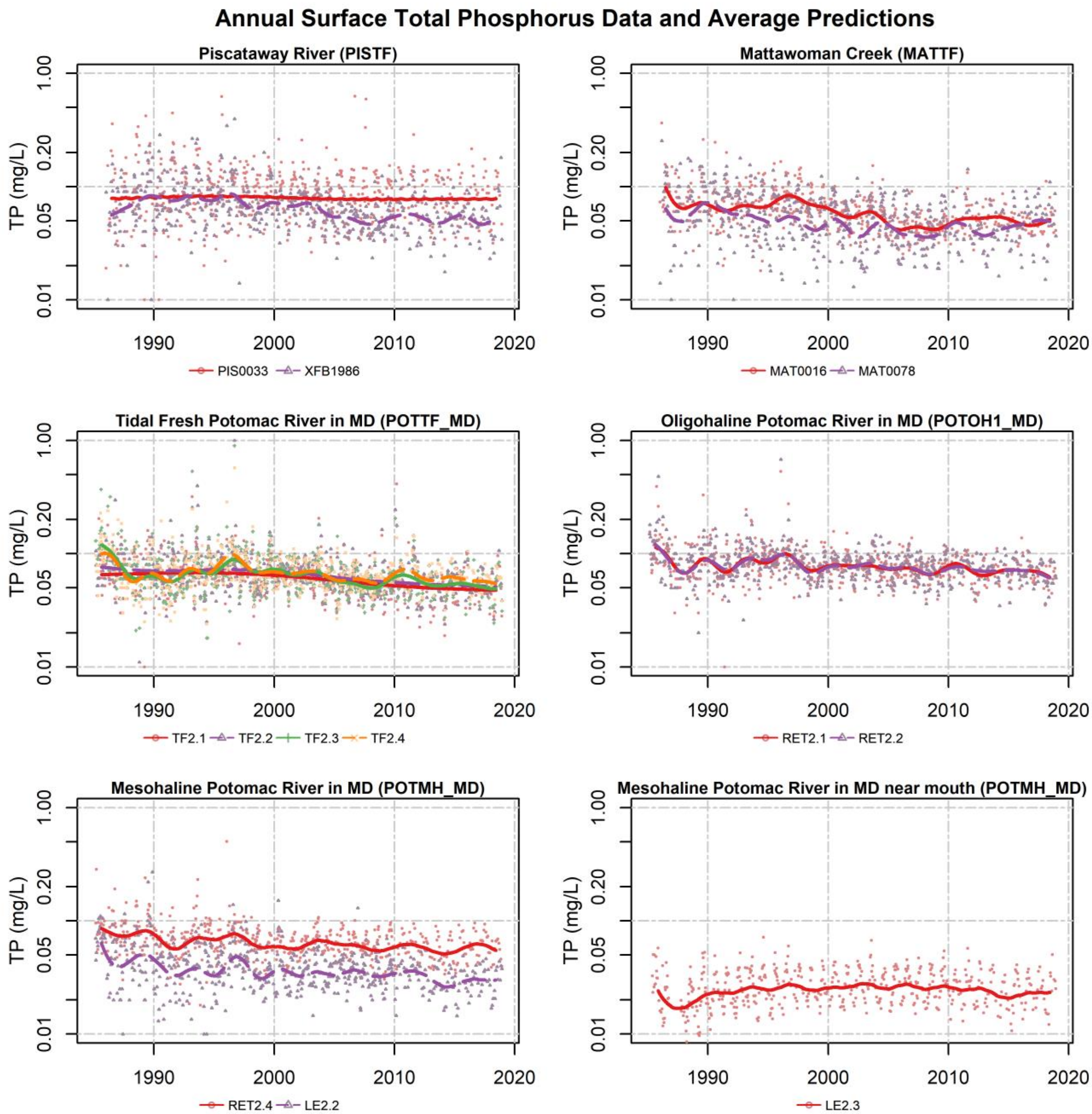


Figure 9. Surface TP data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

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

Trends for chlorophyll *a* are split into spring and summer to analyze chlorophyll *a* during the two seasons when phytoplankton blooms are commonly observed in different parts of Chesapeake Bay (Smith and Kemp, 1995; Harding and Perry, 1997). Spring trends (Figure 10) are mixed – with long-term results either mostly degrading or showing no change except for two improving or possibly improving stations in the Piscataway and tidal fresh Potomac. Short-term changes are mixed as well with possible improvements or no trends in the upper tidal fresh stations, degrading trends in the middle of the river, and improving trends after flow adjustment in the mesohaline stations.

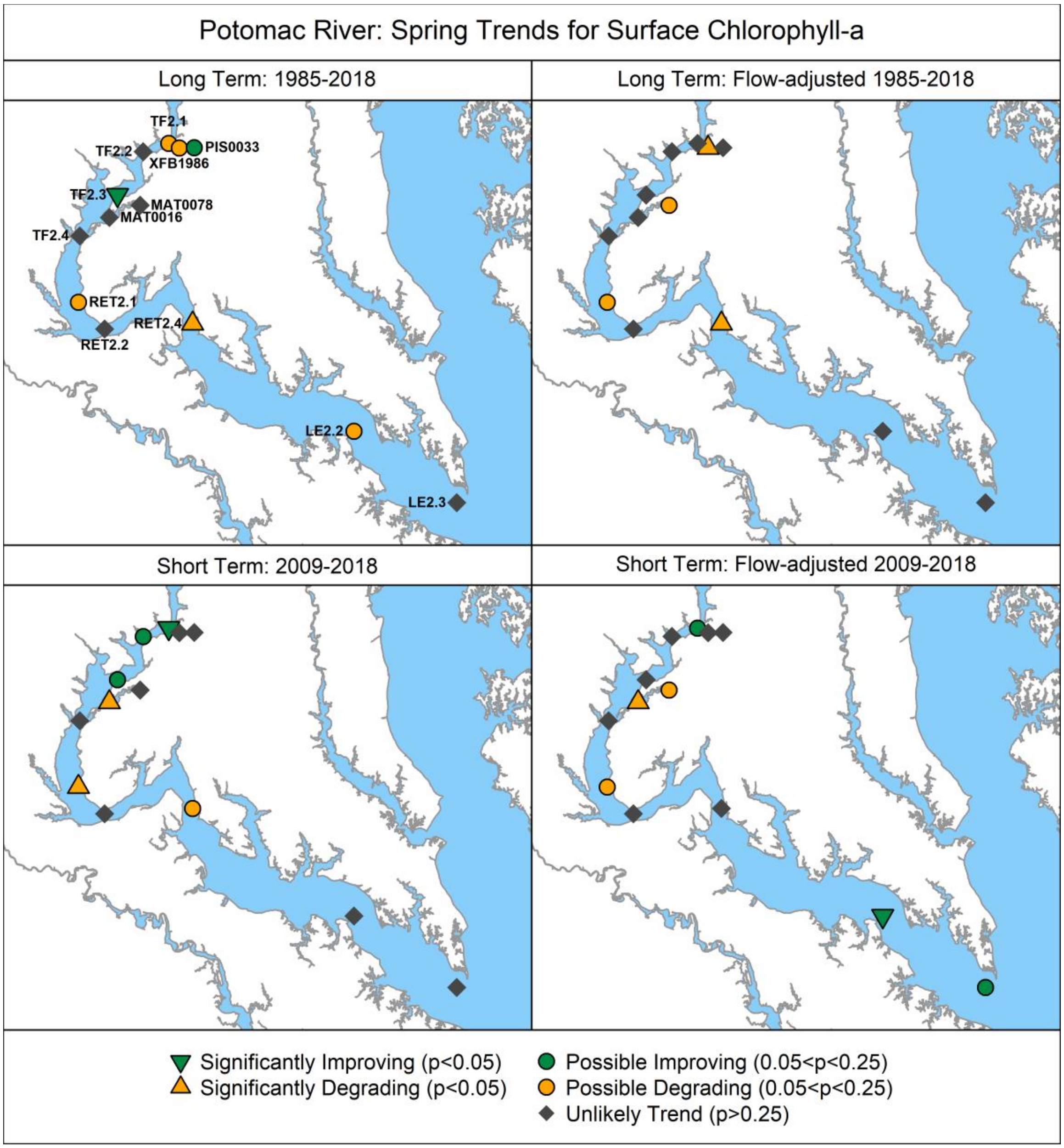


Figure 10. Surface spring (March-May) chlorophyll *a* trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

A high amount of variability exists in the long-term patterns of some of the chlorophyll *a* data sets and average spring GAM estimates (Figure 11). Notably, the tidal fresh variability in the last half of the record has influenced the short-term changes. The three riverine-estuarine transition (RET) stations show the most persistent degradations (Figure 10), and those increases in concentrations are clear in these graphs.

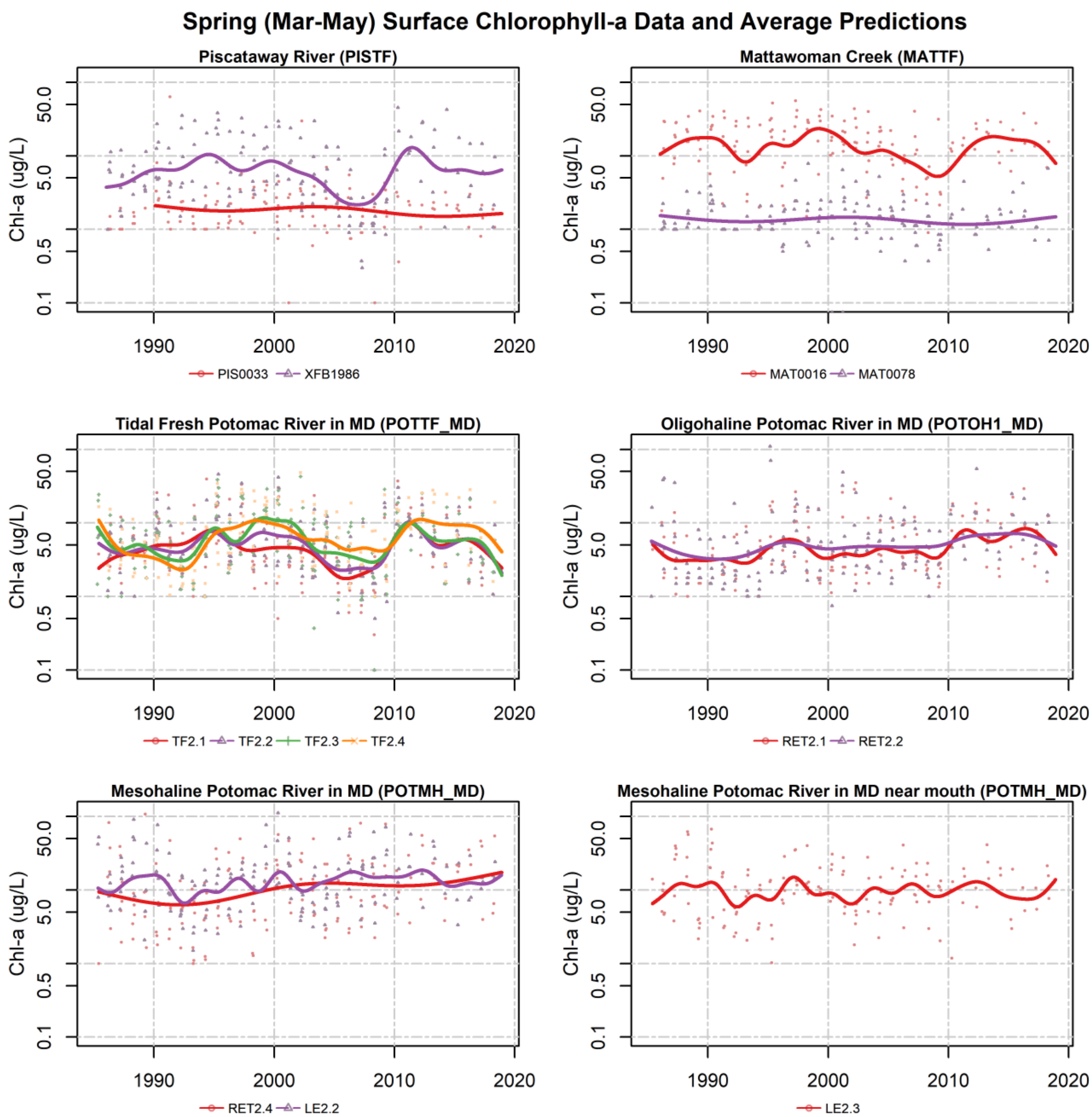


Figure 11. Surface spring chlorophyll *a* data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent March-May data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean spring GAM estimates for the noted monitoring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

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

The spatial patterns in summer long-term chlorophyll *a* changes (Figure 12) are fairly similar to spring changes (Figure 10), with the difference being that there are more significant trends in the summer than in the spring. The summer chlorophyll *a* concentrations at tidal fresh stations show improvements over the long- and short-term without adjustment, but with flow adjustment, both the tidal fresh and oligohaline stations are mostly degrading. The mesohaline station shows the least likely change over time in summer chlorophyll *a*.

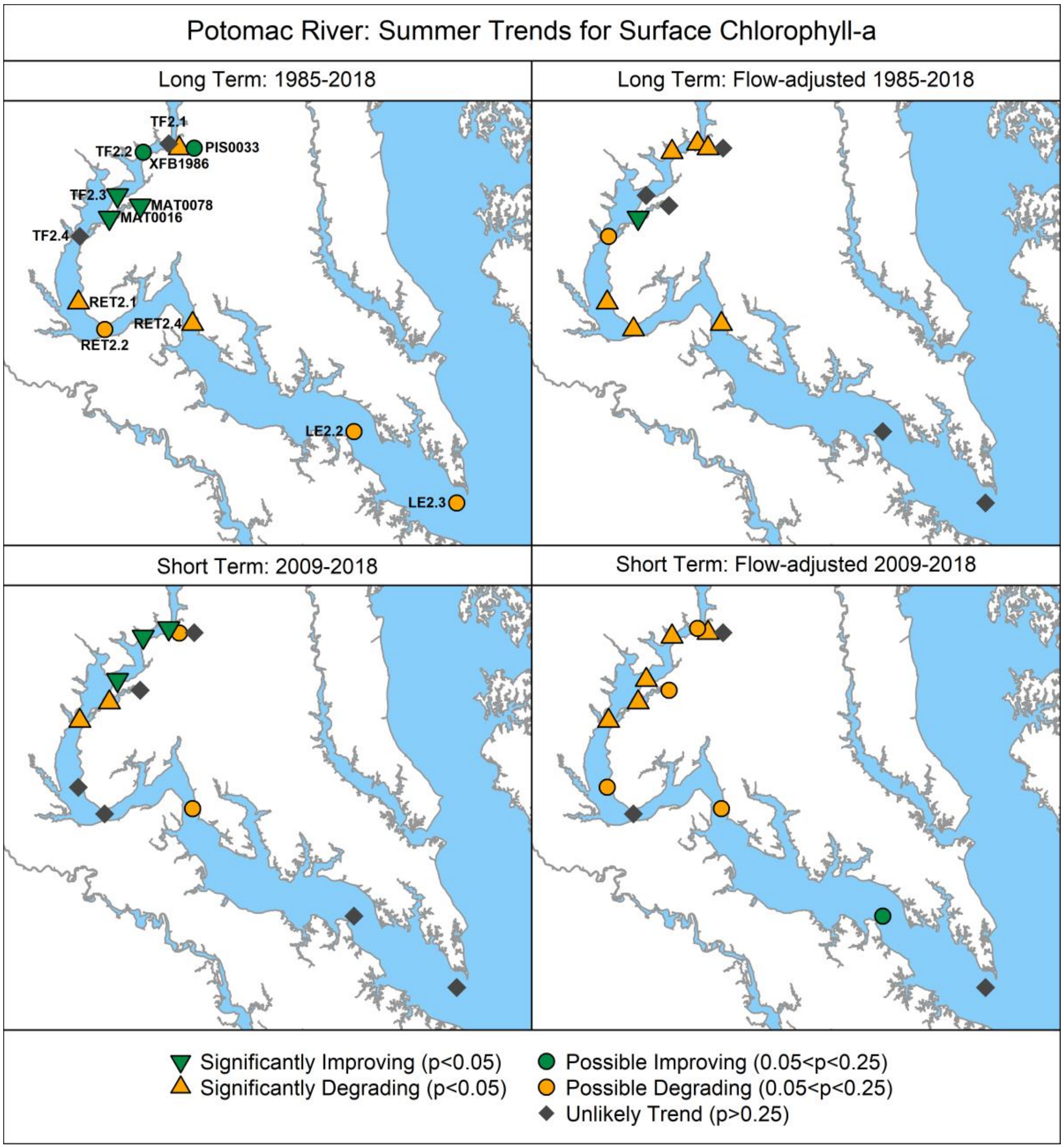


Figure 12. Surface summer (July-September) chlorophyll *a* trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Summer chlorophyll *a* concentrations are higher in the tidal fresh stations (Figure 13) than in the spring (Figure 11) and are also quite variable over time. The most dramatic decrease in concentrations is at MAT0016 with much lower maximum concentrations in recent years than in the 1980s and 1990s. The degradations at the oligohaline (RET) stations appear slight but are clear from these graphs as well.

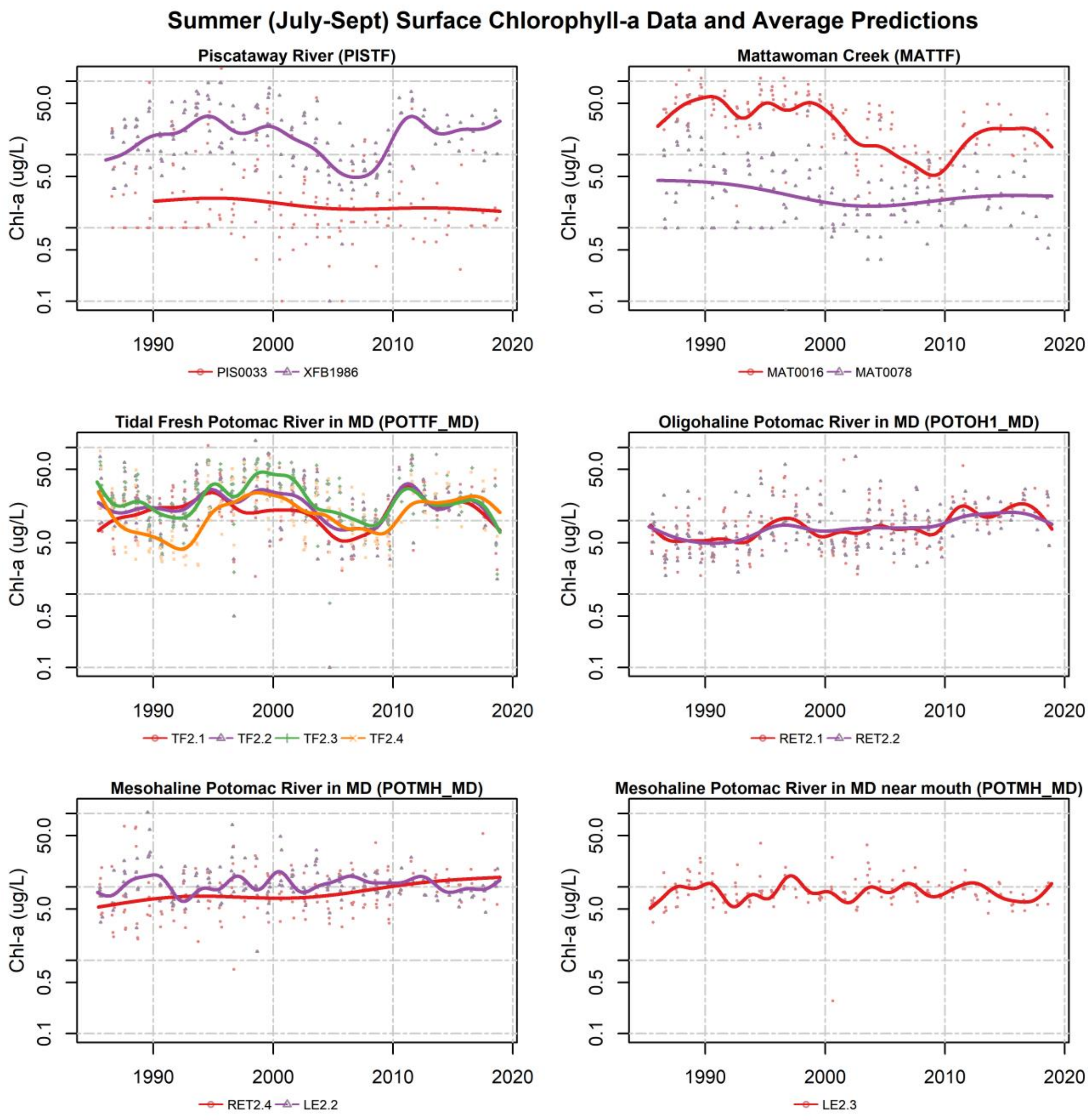


Figure 13. Surface summer chlorophyll *a* data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent July-September data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean summer GAM estimates for the noted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

4.5 Secchi Disk Depth

Trends in Secchi disk depth, a measure of visibility through the water column, are degrading at many of the stations, particularly the tidal fresh and oligohaline stations, over both the short- and long-term (Figure 14). Long-term improvements have occurred in the Mattawoman River and nearby TF2.3 after flow adjustment.

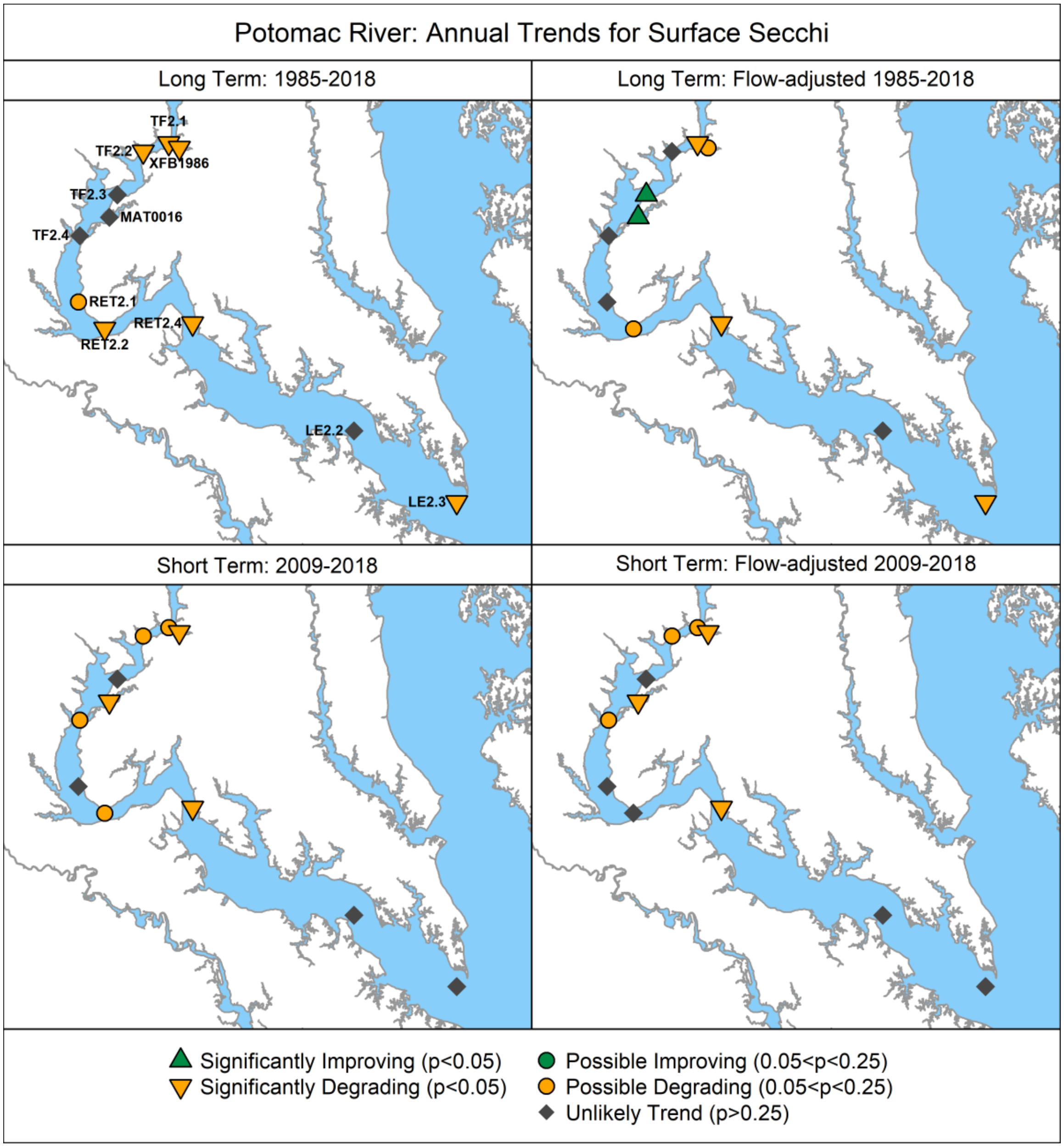


Figure 14. Annual Secchi depth trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Secchi depth is generally less than 1 meter throughout the tidal Potomac, except for the lower Potomac stations where it is closer to 1.5-2 meters on average. Thus, the changes that appear in the trend map (Figure 14) are hard to see in some of the data sets (dots on the graphs) and average annual GAM estimates (lines on the graphs) (Figure 15). The Mattawoman increase does appear to be a slight improvement throughout the record, with two increases in visibility in the 2000s.

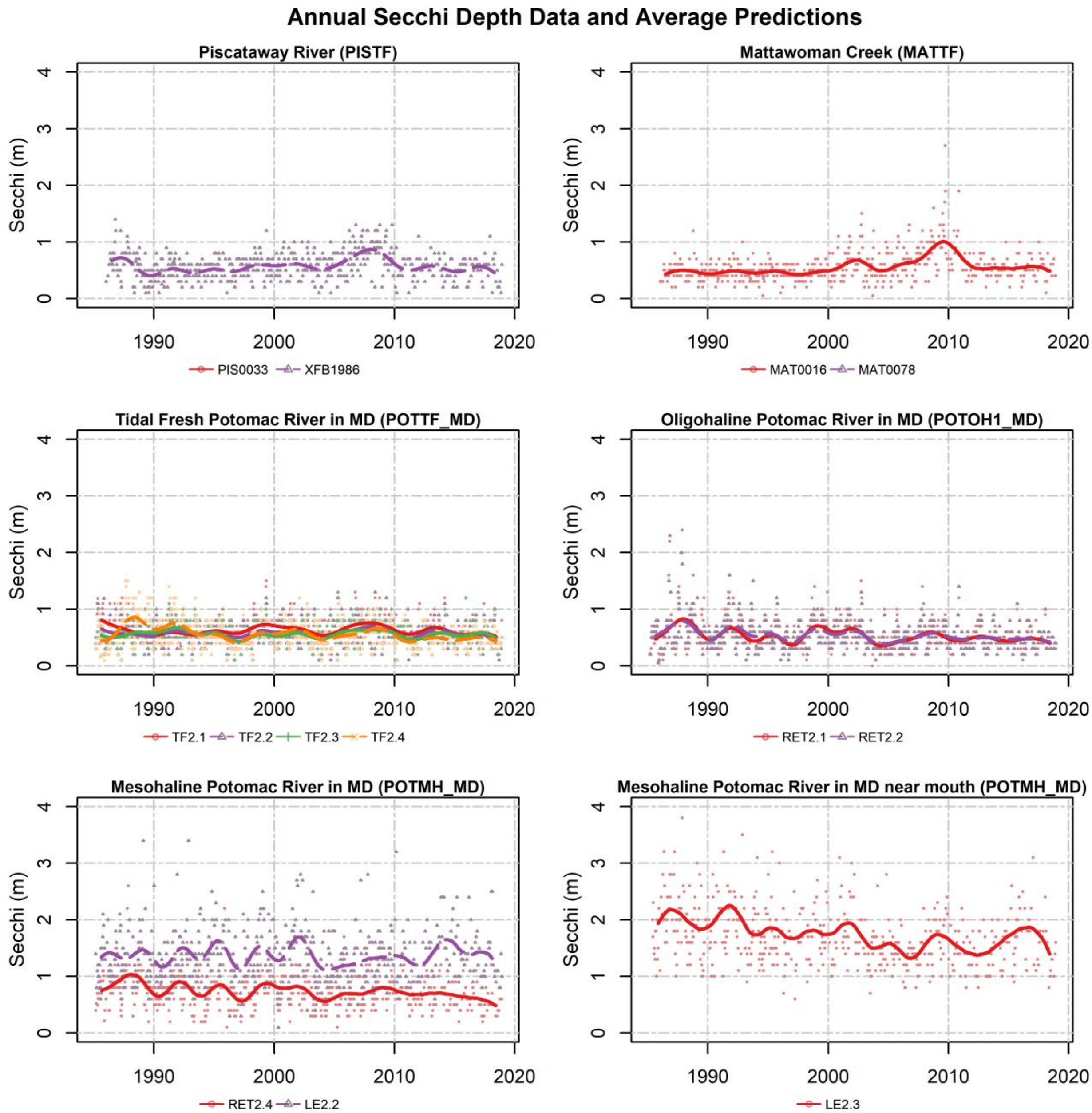


Figure 15. Annual Secchi depth data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

4.6 Summer Bottom Dissolved Oxygen

Tidal fresh Potomac bottom oxygen concentrations have improved at many stations both over the long- and short-term (Figure 16). The oligohaline stations have more mixed trends, but the mesohaline stations, where Deep Water and Deep Channel oxygen criteria exist, shows a possible improvement in the short-term.

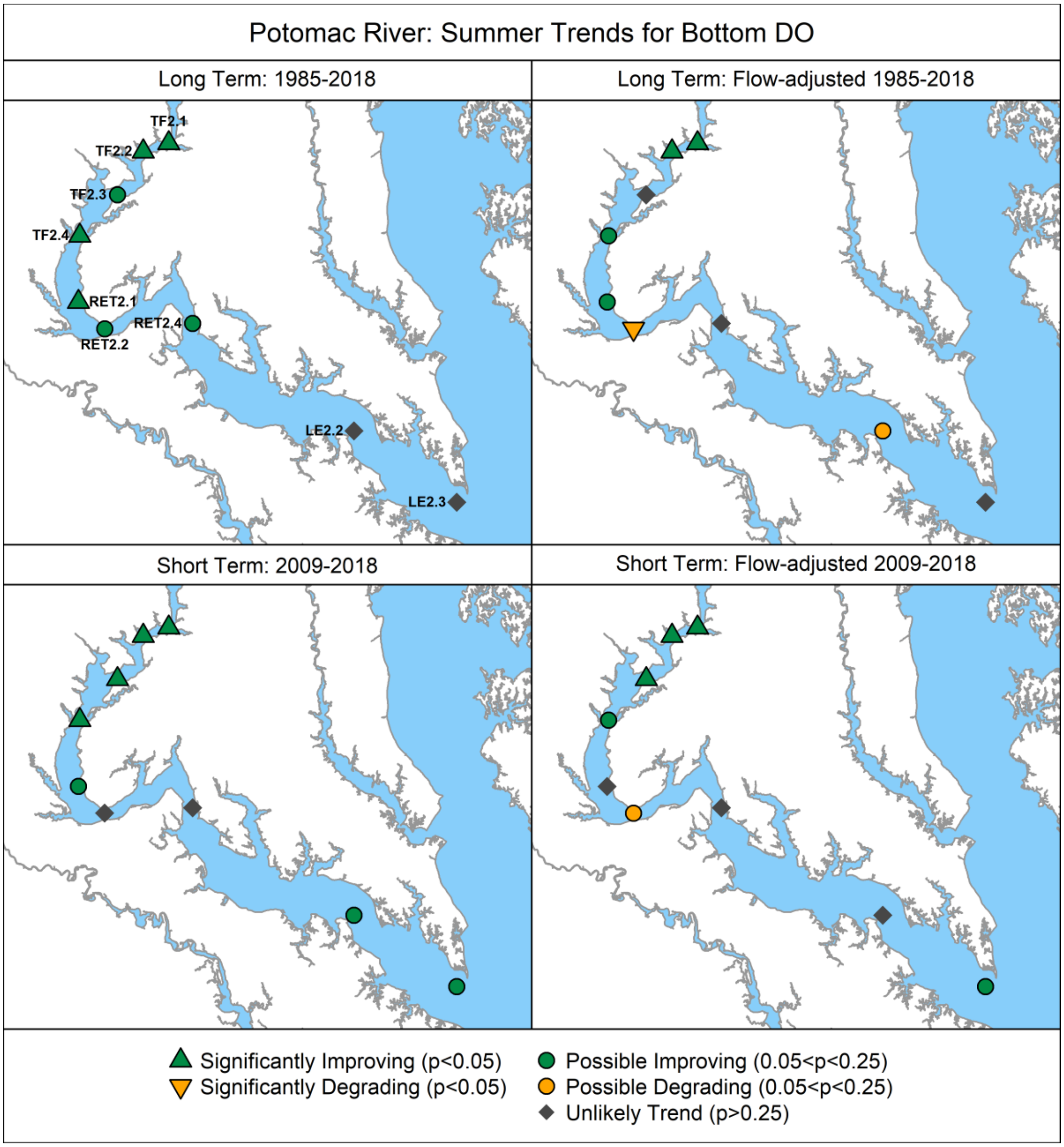


Figure 16. Summer (June-September) bottom DO trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Plots of the summer data and average summer GAM estimates demonstrate the spatial variability in bottom DO concentrations (Figure 17). Concentrations in the tidal fresh and oligohaline Potomac are much higher than in the mesohaline Potomac, although they do decline below the 5 mg/L summer Open Water 30-day mean DO criterion. Concentrations at LE2.2 and LE2.3 frequently are below the Deep Channel instantaneous criterion of 1 mg/L. Lower concentrations were observed in the tidal fresh in the early part of the record, as well as some slightly higher concentrations in recent years, leading to the improving trends in this region. Both LE2.2 and LE2.3 appear to have very slight improvements in recent years. These slight changes result in the possible improving trends shown in Figure 16.

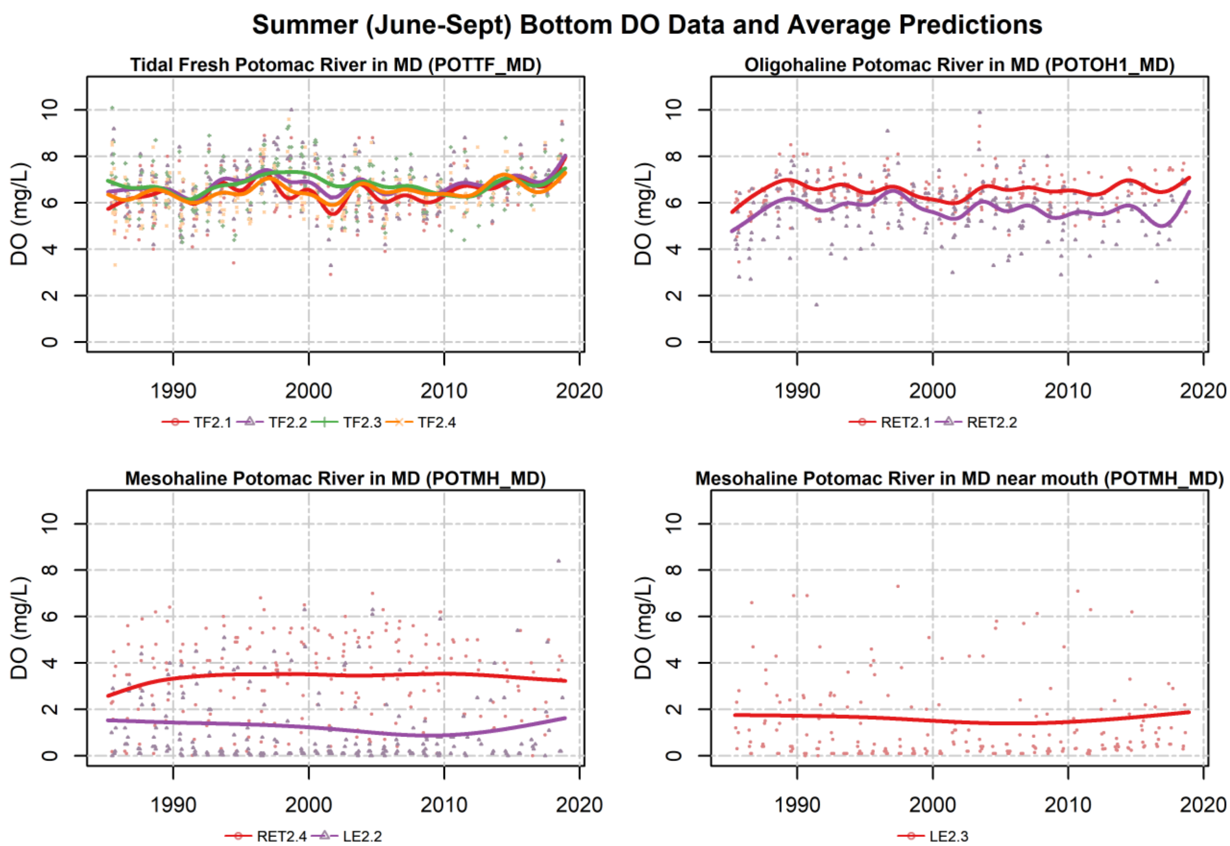


Figure 17. Summer (June-September) bottom DO data (dots) and July 1 long-term pattern generated from non-flow adjusted GAMs. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean summer GAM estimates for the noted monitoring stations.

5. Factors Affecting Trends

5.1 Watershed Factors

5.1.1. Effects of Physical Setting

The geology of the Potomac River watershed and its associated land use affects the quantity and transfer of nitrogen, phosphorus, and sediment delivered to non-tidal and tidal streams (Brakebill *et al.*, 2010; Ator *et al.*, 2011; Ator *et al.*, 2019; Ator *et al.*, 2020; Noe *et al.*, 2020). Flow-normalized load estimates remove most interannual variability associated with differences in streamflow, permitting a closer examination of responses to factors that change nutrient sources or transport (such as best management practices). Flow-normalized nitrogen, phosphorus, and sediment trends in load are mixed throughout non-tidal streams in the Potomac River watershed and result from changes in nutrient applications, delivery from the landscape to streams, and in-stream loss or retention (Table 3) (Moyer and Langland, 2020).

Table 3. Trends (2009 – 2018) in flow normalized total nitrogen (TN), total phosphorus (TP), and suspended sediment (SS) for nontidal network monitoring locations in the Potomac River watershed.

Parameter	No. of stations	Value	Trend direction		
			degrading	improving	no trend
TN	28	n	7	14	7
		median %	15.4%	-5.8%	1.1%
TP	18	n	0	12	6
		median %	-	-28.9%	8.5%
SSC	18	n	5	5	8
		median %	23.7%	-24.4%	5.2%

<u>Nitrogen</u>

Groundwater is the primary delivery pathway of nitrogen to most streams in the Chesapeake Bay watershed (Lizarraga, 1997; Bachman *et al.*, 1998; Ator and Denver, 2012). The proportion of nitrogen in groundwater that reaches freshwater streams and/or tidal waters is heavily dependent on location in the watershed (Figure 18). Concentrations of groundwater nitrogen, primarily as nitrate, are typically highest in the Potomac River watershed in portions of the Valley and Ridge physiographic province underlain by carbonate rocks and in areas of the Coastal Plain with permeable, oxic, well-drained soils (Greene *et al.*, 2005; Terziotti *et al.*, 2017). The geology of these areas provides suitable land for agriculture, but has little potential for denitrification (Böhlke and Denver, 1995; Lizarraga, 1997; Miller *et al.*, 1997; Sanford and Pope, 2013), so nitrogen that is not removed by plants or exported in agricultural products can move relatively efficiently to groundwater (where denitrification can occur as well) and to streams. The typical residence time of groundwater delivered to streams in the Chesapeake Bay watershed is about 10 years, but ages vary from less than 1 year to greater than 50 years based on bedrock structure, groundwater flow paths, and aquifer depths (Lindsey *et al.*, 2003). In general, groundwater ages tend to be relatively short (0-10 years) in carbonate settings, where permeable soils and solution-enlarged fractures enhance groundwater connectivity (Lindsey *et al.*, 2003). 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 days to months (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 in the Potomac River watershed typically occur in agricultural areas (Ator *et al.*, 2011) where inputs of manure and fertilizer exceed crop needs. Some sedimentary rocks in the Potomac Piedmont province contain large phosphorus reservoirs (Terziotti, 2019), and while these natural sources contribute to in-stream loads, most is insoluble and only represent a dominant source in undeveloped watersheds. Reducing soil phosphorus concentrations can take multiple decades (Kleinman *et al.*, 2011) and, until this occurs, watershed phosphorus loads may appear to 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 Potomac River watershed, but in-stream concentrations are typically highest in Piedmont watersheds (Brakebill *et al.*, 2010). The erosivity of Piedmont soils results from its unique topography and from the prevalence of agricultural and urban land uses (Trimble 1975, Gellis et al. 2005, Brakebill et al. 2010). Factors affecting streambank erosion are highly variable throughout the Potomac River 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 from the non-tidal watershed

The delivery of nitrogen, phosphorus, and sediment in non-tidal Potomac River streams to tidal waters 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 and temporally throughout the Potomac River watershed and typically increase with soil moisture and temperature (Pilegaard, 2013). Differences in time of travel mean that more nitrogen load generated in the agricultural watersheds of Virginia’s Shenandoah Valley can be removed through denitrification before reaching tidal waters than loads from urban areas surrounding Washington D.C., which are closer to the Potomac River (Ator *et al.*, 2011). There are no chemical processes to remove phosphorus or sediment from streams, but sediment, and associated phosphorus, can be stored behind impoundments or 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). While some fine sediments can be mobilized downstream from shallow streambeds in days to years (Gellis *et al.*, 2017), delivery to tidal waters can take decades to centuries as sediment moves in and out of different storage zones during transport (Skalak and Pizzuto, 2010).

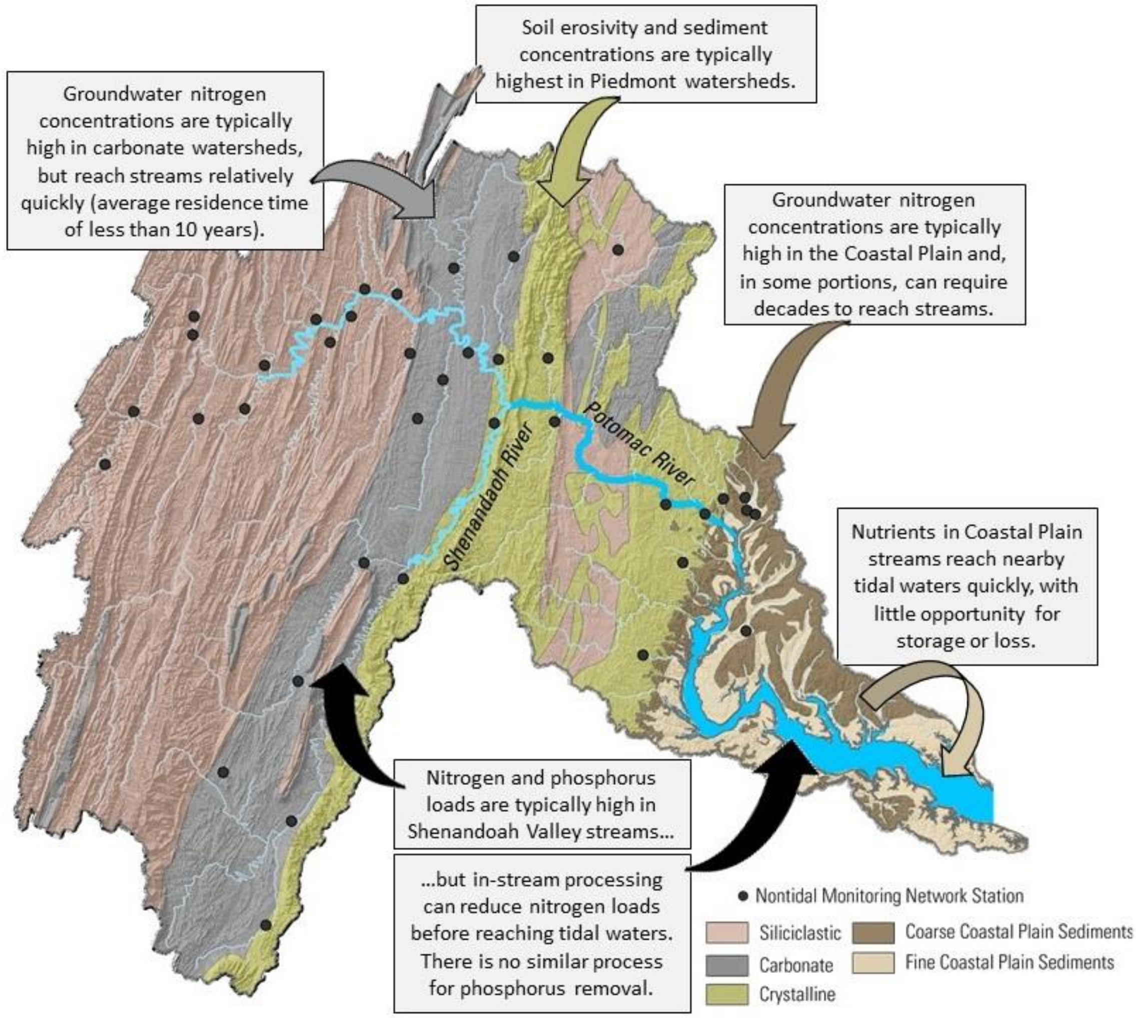


Figure 18. Effects of watershed hydrogeomorphology on nutrient transport to freshwater streams and tidal waters. Base map modified from King and Biekman, 1974 and Ator and others, 2005, North American Datum 1983

5.1.2. Estimated Nutrient and Sediment Loads

Estimated loads to tidal portions of Chesapeake Bay tributaries are a combination of monitored fluxes from 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, phosphorus, and suspended sediment loads to the tidal Potomac were primarily from the RIM areas, although contributions from the below-RIM areas were also substantial (Figure 19). Over the period of 1985-2018, 1.1, 0.08, and 75 million tons of nitrogen, phosphorus, and suspended sediment loads were exported through the Potomac River watershed, with 67%, 76%, and 58% of those loads from the RIM areas, respectively.

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

Nitrogen

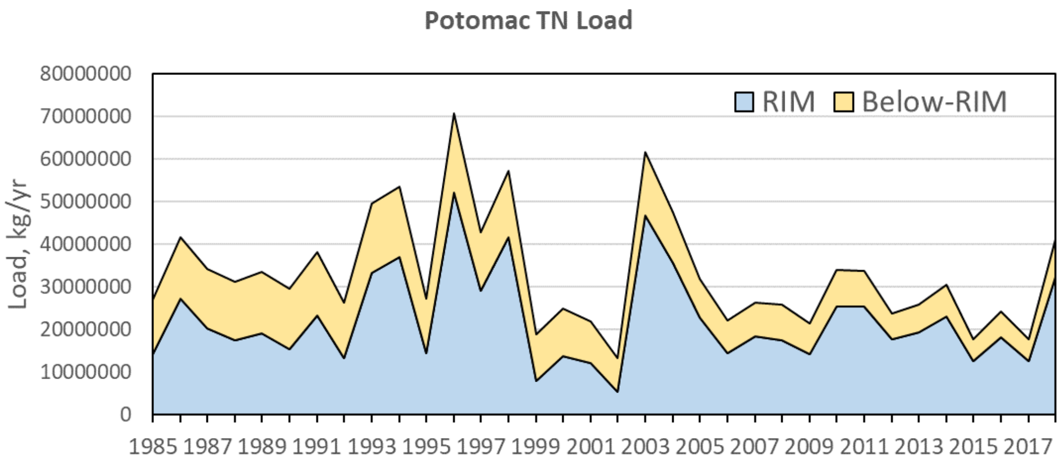
Estimated TN loads showed an overall decline of -349 ton/yr in the period between 1985 and 2018, which is statistically significant ($p < 0.05$). This reduction reflects a combination of reductions in RIM loads (-47 ton/yr; $p = 0.73$) and below-RIM loads (-306 ton/yr; $p < 0.01$). The below-RIM reduction is driven by below-RIM point sources (-316 ton/yr, $p < 0.01$), and to a lesser extent, by atmospheric deposition to the tidal waters (-7.6 ton/yr, $p < 0.01$). In contrast, the below-RIM nonpoint source load showed an increase in this period (13 ton/yr), although it is not statistically significant ($p = 0.53$). The significant below-RIM point source reductions in TN are a result of substantial efforts to reduce nitrogen loads from several major wastewater treatment facilities in the D.C.-metropolitan areathe Blue Plains treatment plant, by implementing biological nutrient removal in the late 1990s (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).

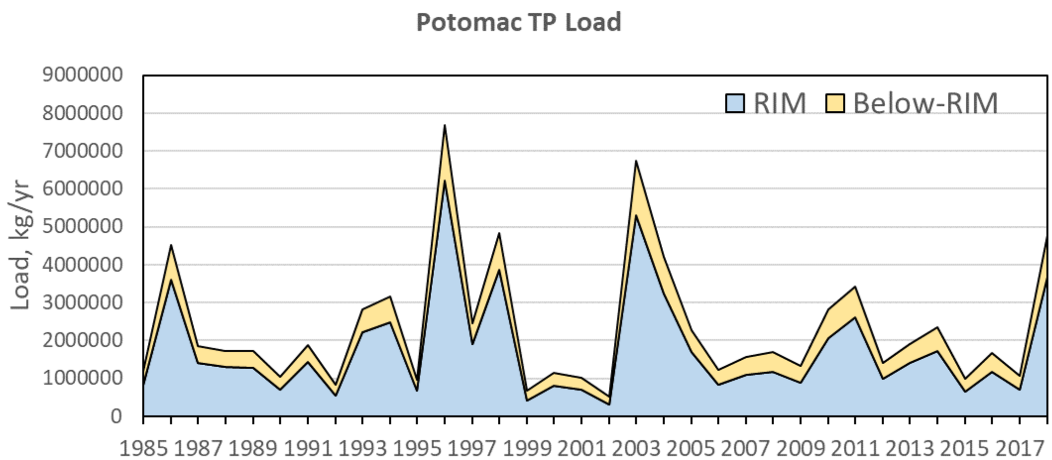
Phosphorus

Estimated TP loads showed an overall increase of 1.6 ton/yr in the period between 1985 and 2018, although it is not statistically significant ($p = 0.93$). Both the RIM and below-RIM loads showed lack of reductions, and both are not statistically significant. Within the below-RIM load, point sources showed a statistically significant decline in this period (-1.8 ton/yr; $p < 0.05$). 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 decline of -4,988 ton/yr in the period between 1985 and 2018, although it is not statistically significant ($p = 0.74$). Both the RIM and below-RIM loads showed reductions, 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 (-138 ton/yr; $p < 0.05$).





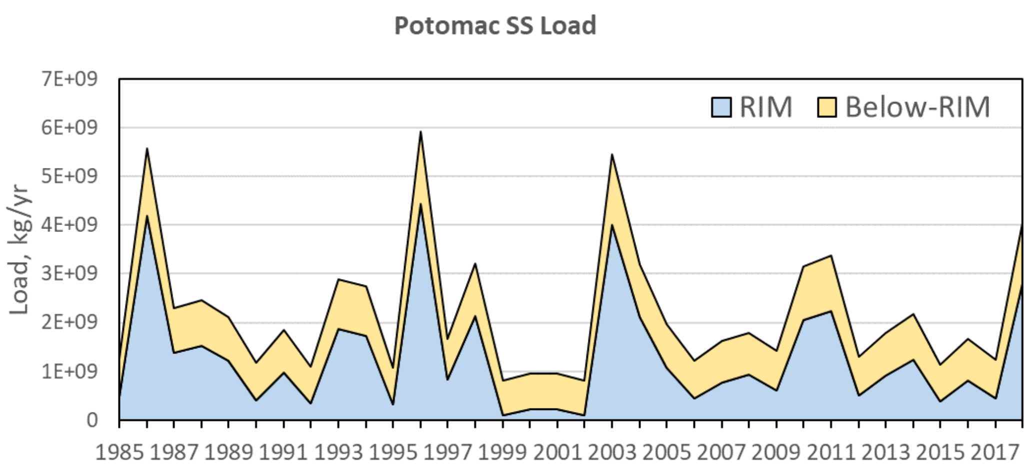


Figure 19. Estimated total loads of nitrogen (TN), phosphorus (TP), and suspended sediment (SS) from the RIM and below-RIM areas of the Potomac River. RIM refers to the USGS River Input Monitoring site located just above the head of tide of this tributary, which includes upstream point source loads.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

RIM estimates are a combination of simulated non-point source, atmospheric deposition, and reported point-source loads.

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

Variable	Trend, metric ton/yr	Trend p-value
TN		
Total watershed	-349	< 0.05
RIM watershed [1]	-47	0.73
Below-RIM watershed [2]	-306	< 0.01
Below-RIM point source	-316	< 0.01
Below-RIM nonpoint source [3]	13	0.53
Below-RIM tidal deposition	-7.6	< 0.01
TP		
Total watershed	1.6	0.93
RIM watershed	0.0	1.00
Below-RIM watershed	2.4	0.48
Below-RIM point source	-1.8	< 0.05
Below-RIM nonpoint source	4.7	0.22
SS		
Total watershed	-4,988	0.74
RIM watershed	-6,426	0.72
Below-RIM watershed	-280	0.91
Below-RIM point source	-138	< 0.01
Below-RIM nonpoint source	-152	0.98

[1] Loads for the RIM watershed were estimated loads at the USGS RIM station 01646580 (Potomac River at Chain Bridge, at Washington, D.C.; 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 Watershed Model accessed through the Chesapeake Assessment Scenario Tool (CAST; https://cast.chesapeakebay.net/, version CAST-17d), changes in population size, land use, and pollution management controls between 1985 and 2018 were expected to change nitrogen, phosphorus, and sediment loads to the tidal Potomac River by -33, -39, and –14% , respectively (Figure 20). In contrast to the annual load analysis above, CAST loads are based on changes in management only and factor out any changes in weather. They are also calculated assuming no lag times for delivery of pollutants or lags related to best management practices becoming fully effective after installation. In 1985, agriculture and wastewater were the two largest sources of nitrogen loads. By

2018, agriculture remained the largest nitrogen source; however, wastewater nitrogen loads had decreased by -74% and the developed sector had instead become the second largest nitrogen source. Overall, decreasing nitrogen loads from agriculture (-27%), natural (-7%), stream bed and bank (-11%), and wastewater (-74%) sources were partially counteracted by increases from developed (56%) and septic (58%) sources.

The two largest sources of phosphorus loads, as of 2018, were the agriculture and developed sectors. Overall, expected phosphorus declines from agriculture (-43%), natural (-10%), stream bed and bank (-33%), and wastewater (-79%) sources were partially counteracted by increases from developed (56%) and septic (114%) sources.

For sediment, the largest sources are stream bed and bank and shoreline areas: these two sources changed by -16% and 0%, respectively, between 1985 and 2018. Sediment loads from the agriculture sector decreased by 47%, whereas sediment load from developed areas increased by 28%.

Overall, CAST indicates that changing watershed conditions and management actions between 1985 and 2018 are expected to have resulted in the agriculture, natural, stream bed and bank, and wastewater sectors achieving reductions in nitrogen, phosphorus, and sediment loads, whereas the developed and septic sectors are expected to increase in nitrogen, phosphorus, and sediment loads. As noted above, CAST does not attempt to account for lag times between a change and its impact.

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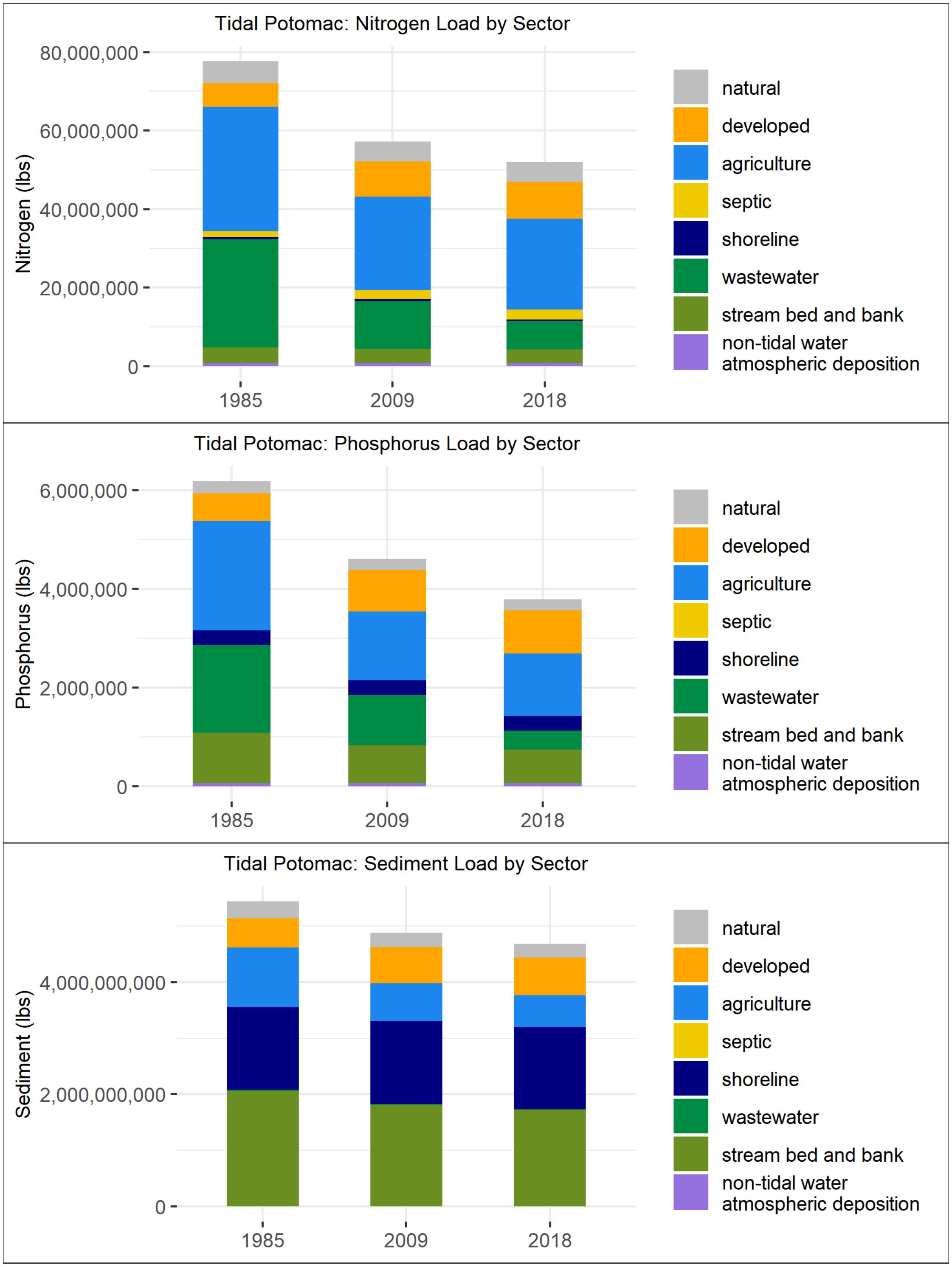

Figure 20. Expected long-term average loads of nitrogen, phosphorus, and sediment from different sources to the tidal Potomac, as obtained from the Chesapeake Assessment Scenario Tool (CAST-17d). Data shown are time-average delivered loads over the average hydrology of 1991-2000, once the steady state is reached for the conditions on the ground, as obtained from the 1985, 2009, and 2018 progress (management) scenarios.

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-17d). Reported BMP implementations on the ground as of 1985, 2009, and 2018 are compared to planned 2025 implementation levels in Figure 21 for a subset of major BMP groups measured in acres. As of 2018, tillage, cover crops, pasture management, forest buffer and tree planting, stormwater management, agricultural nutrient management, and urban nutrient management were credited for 473, 152, 222, 5, 304, 1,125, and 274 thousand acres, respectively. Implementation levels for some practices are already close to achieving their planned 2025 levels: for example, 93% of planned acres for tillage had been achieved as of 2018. In contrast, about 58% of planned urban nutrient management implementation had been achieved as of 2018.

Stream restoration and animal waste management systems are two important BMPs that cannot be compared directly with those above because they are measured in different units. However, progress towards implementation goals can still be documented. Stream restoration (agricultural and urban) had increased from 235 feet in 1985 to 511,151 feet in 2018. Over the same period, animal waste management systems treated 3,395 animal units in 1985 and 1,279,283 animal units in 2018 (one animal unit represents 1,000 pounds of live animal). These implementation levels represent 42% and 60% of their planned 2025 implementation levels, respectively.

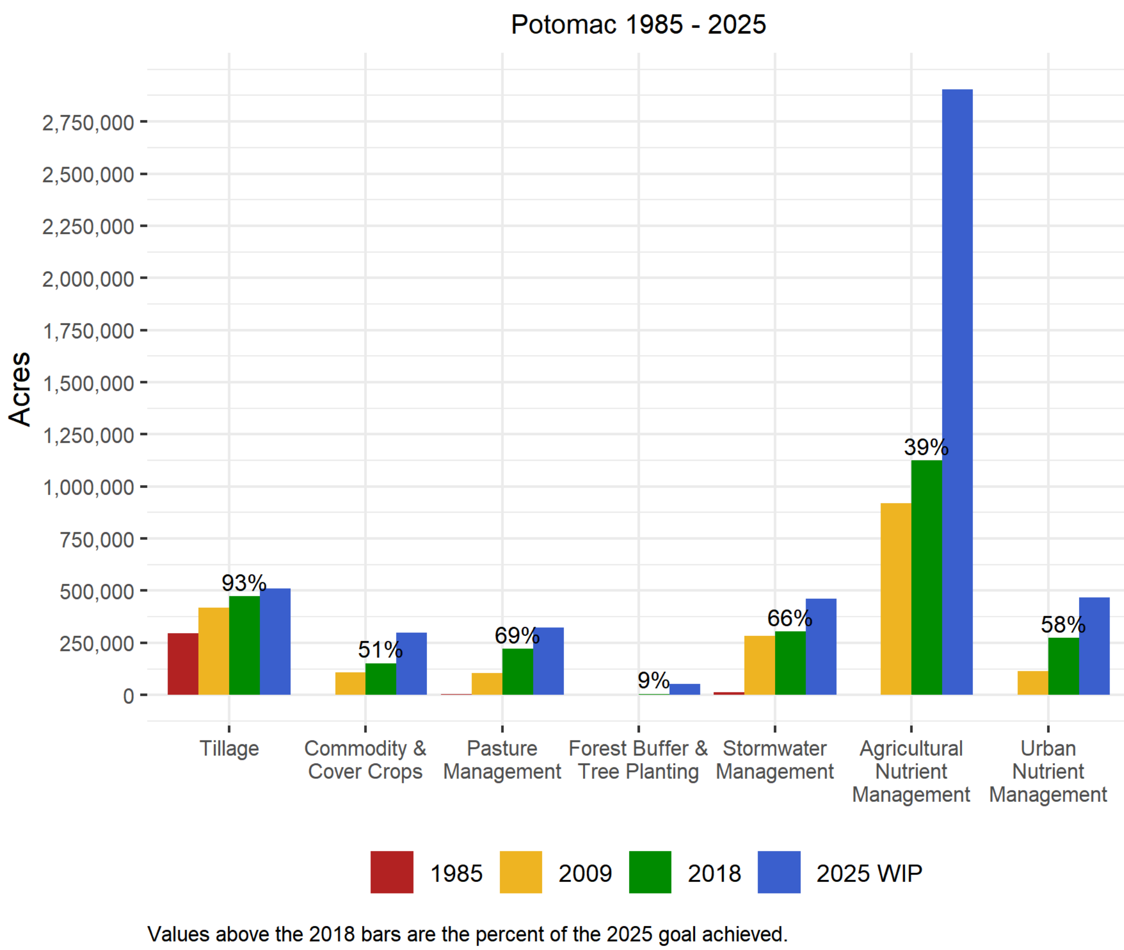

Figure 21. BMP implementation in the Potomac watershed.

5.2 Tidal Factors

Once pollutants reach tidal waters, a complex set of environmental factors interact with them to affect key habitat indicators like algal biomass, DO concentrations, water clarity, submerged aquatic vegetation (SAV) abundance, and fish populations (Figure 22) (Kemp *et al.*, 2005; Testa *et al.*, 2017). For example, phytoplankton growth depends not just on nitrogen and phosphorus (Fisher *et al.*, 1992; Kemp *et al.*, 2005; Zhang *et al.*, 2021), but also on light and water temperature (Buchanan *et al.*, 2005; Buchanan, 2020). In general, the saline waters of the lower 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).

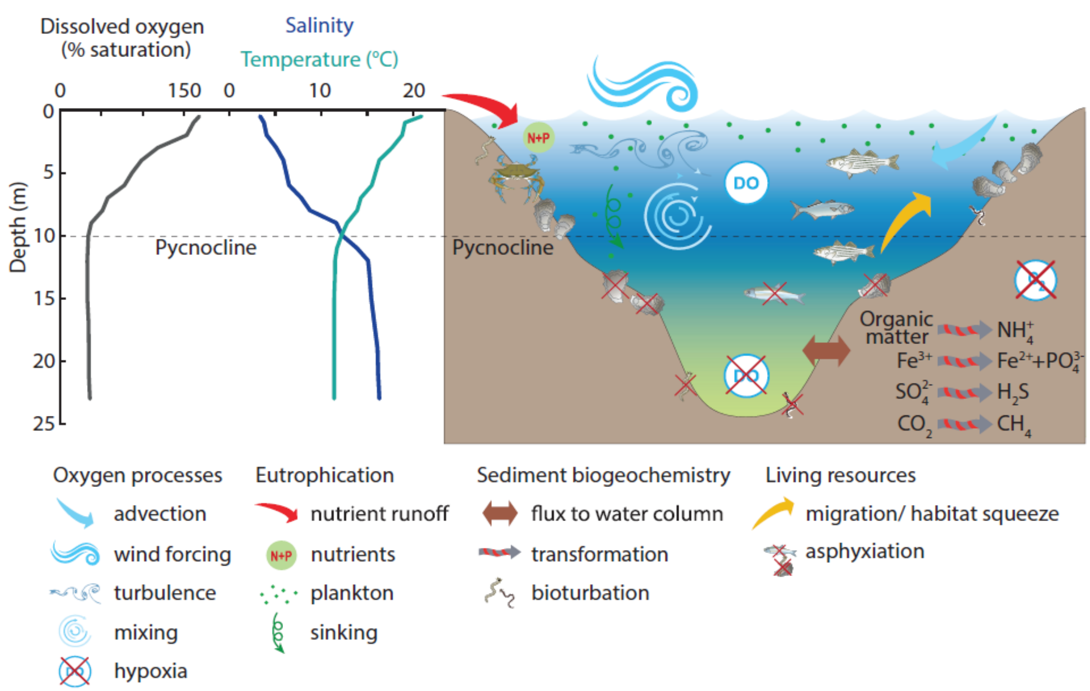

Figure 22. Conceptual diagram illustrating how hypoxia is driven by eutrophication and physical forcing, while affecting sediment biogeochemistry and living resources. From Testa *et al.* (2017).

5.3 Insights on Changes in the Potomac

Wastewater has been a major nitrogen and phosphorus source directly into the tidal Potomac, and it has decreased substantially in recent decades due to upgraded treatment processes (Table 4 and Figure

20). The nitrate and total nitrogen concentrations in the tidal waters near Blue Plains wastewater treatment facility declined dramatically with full implementation of biological nutrient removal in 2000. However, even using post-2000 data, nitrate originally from wastewater is still a major source in the Potomac (Figure 23). In fact, significant concentrations of wastewater-derived nitrate were detected at the mouth of the Potomac River where it meets Chesapeake Bay, at varying percentages depending on the time of year. A study conducted in 2010-2011 estimated that in the summer and fall, almost half of the nitrate measured at the mouth of the Potomac was from wastewater discharge (Pennino *et al.*, 2016). In winter and spring, nonpoint sources dominated and a much smaller percentage (6-7%) was originally from wastewater. Pennino *et al.'s* work shows not only the potential reach of point source loads, but also the importance of considering both time of year and location in analyses to explain changes in aquatic conditions.

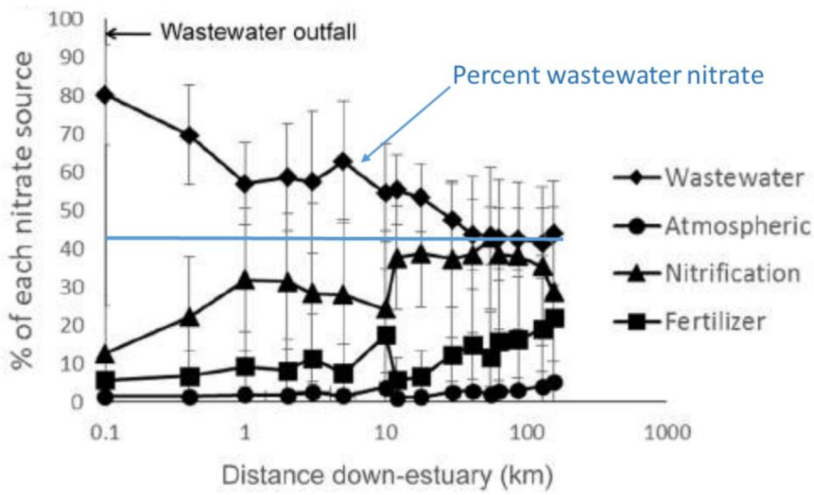

Figure 23. Mean annual change in the percent contribution of nitrate from wastewater, fertilizer, atmospheric deposition, and nitrification, based on an isotope mixing model, with distance down-estuary from wastewater treatment plant output. Adapted from Pennino *et al.* (2016).

Responses to reductions in nutrient loads from smaller local point sources have been observed in some of the Potomac tributaries evaluated here as well. In Mattawoman Creek, the impact of major point source reductions in the early 1990s and 2000s was investigated by Boynton *et al.* (2014). Point sources went from being the largest nitrogen source in the watershed to a small fraction of the total load by 2010. These load reductions were linked to water quality improvements through 2010 such as decreased chlorophyll *a* concentrations and increased water clarity and SAV (Figure 24). Those changes from the mid-1990s to 2010 in nitrogen and chlorophyll *a* concentrations, as well as Secchi depth, are apparent in the Mattawoman graphics in this report (Figures 7, 11, 13, 15, top right panels). After 2010, however, there was degradation again in chlorophyll *a* and Secchi depth. It is not clear why this pattern has appeared since 2010, but it is consistent across the Potomac tidal fresh stations, not just in Mattawoman Creek.

This pattern of local recovery after wastewater treatment upgrades was also observed in Gunston Cove, an embayment of the tidal freshwater Potomac located in Virginia, where a steep decline in nitrogen loads from the Noman Cole wastewater treatment facility between 2000 and 2005 was correlated with a decline in algal biomass, improving Secchi depth, and resurgence of SAV acreage (Figure 25) (Jones *et* *al.*, 2017). The remarkable similarity of response trajectories between Mattawoman Creek and Gunston Cove provides a useful benchmark for expectations of local response to management practices in similar systems across the Chesapeake Bay.

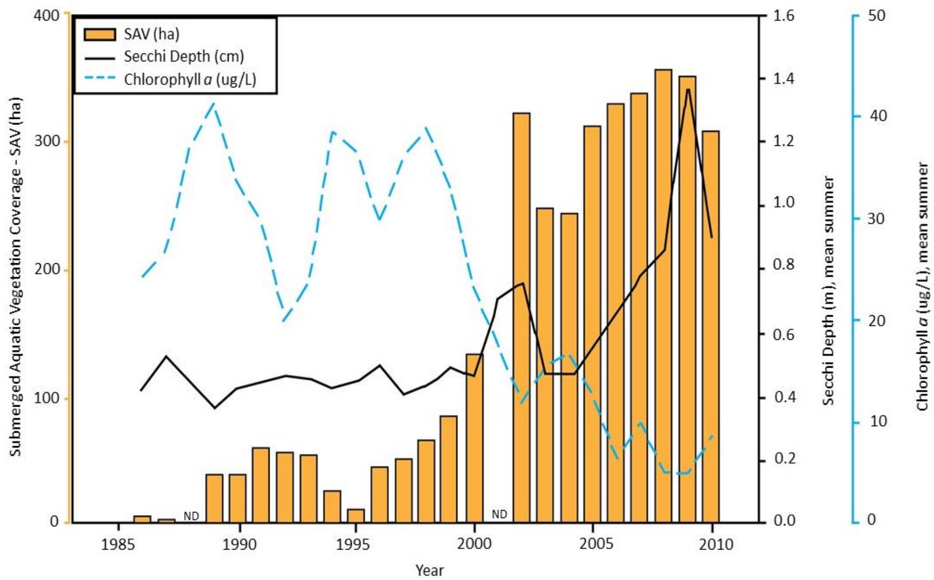

Figure 24. Annual summary of SAV coverage (ha), water clarity (Secchi disk depth), and algal biomass (chlorophyll *a* concentration) for the period 1986-2010 in Mattawoman Creek. Note the large change in SAV coverage and water clarity associated with the large decline in algal biomass. From Boynton *et al.* (2014).

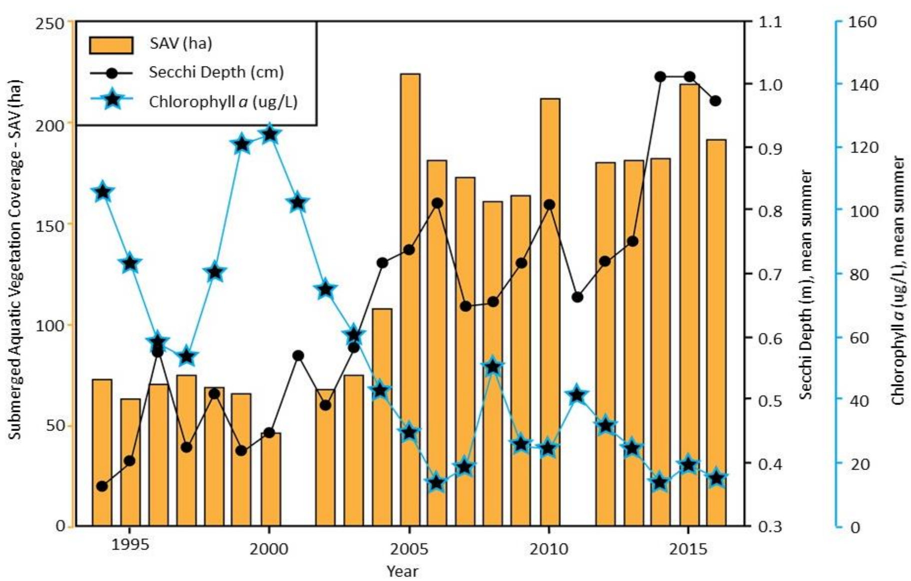

Figure 25. Algal biomass (as chlorophyll *a*), Secchi depth, and SAV acreage for the period 1994 – 2016 in Gunston Cove. From Jones *et al.* (2017).

Despite the overall improvements in both nitrogen and phosphorus concentrations observed in these studies and in the current trend results, many of the chlorophyll *a* and Secchi depth trends at tidal Potomac River stations are still degrading (Figures 10-15). Research suggests that there are "saturation limits" for phytoplankton use of nitrogen and phosphorus (Fisher and Gustafson, 2003; Buchanan *et al.*, 2005). If dissolved nitrogen and phosphorus concentrations are above their saturation limits, the nutrients are in such excess that the phytoplankton cannot use them all. There may not be a decline in phytoplankton in response to nutrient reductions unless the dissolved nitrogen or phosphorus concentrations cross under their saturation limits. Dissolved nutrient concentrations at most of the tidal Potomac stations are still above these limits (Figure 26), which could possibly explain the observed lack of improving chlorophyll *a* trends.

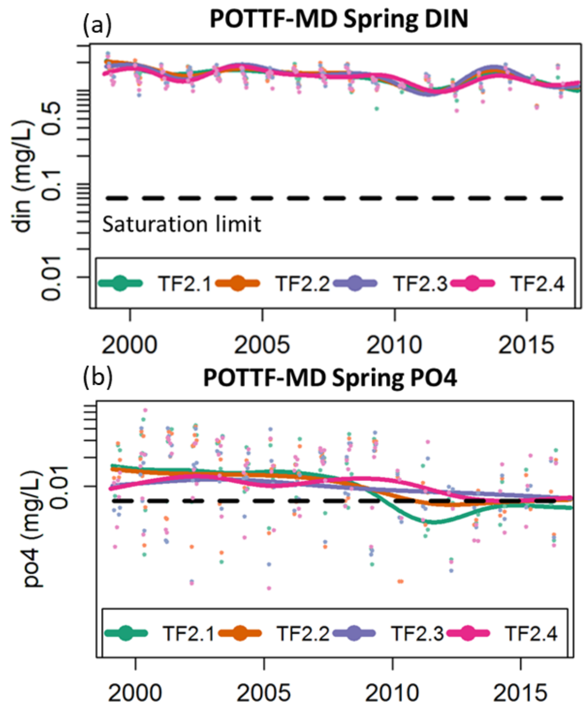

Figure 26. Spring dissolved inorganic nitrogen (a) and spring phosphate (b) at monitoring stations in the tidal Potomac River from 1999 to 2018. Black dotted lines represent nutrient saturation thresholds. Courtesy Rebecca Murphy.

In addition, other factors such as import of nutrients from the mainstem Bay (Pennino *et al.*, 2016), varying bivalve populations (Phelps, 1994), SAV populations, and temperature increases (Ding and Elmore, 2015) could all be playing a role in the response trajectory of the Potomac River for all of these parameters. For example, a dramatic increase in the Asiatic clam population observed in the tidal fresh Potomac between 1978 and 1984 may have caused a substantial but transient increase in water filtration capacity. Phelps (1994) estimated that the summer 1986 clam population could filter 50-100% of the local water volume in 3-7 days. This population boom was accompanied by a resurgence of local SAV beds, which declined again coincident with declining clam populations (Figure 27). Around the same time, Carter *et al.* (1988) observed significantly greater water clarity at three separate monitoring stations within a dense Potomac SAV bed compared to a fourth monitoring site outside the bed. A similar phenomenon has been observed nearby, in tidal fresh waters of the upper Chesapeake Bay. In

2013, Gurbisz *et al.* (2016) noted improved clarity of water exiting the Susquehanna Flats SAV bed relative to water entering the bed upstream. They also observed greater light penetration through water near the center of the SAV bed compared to outside its boundaries.

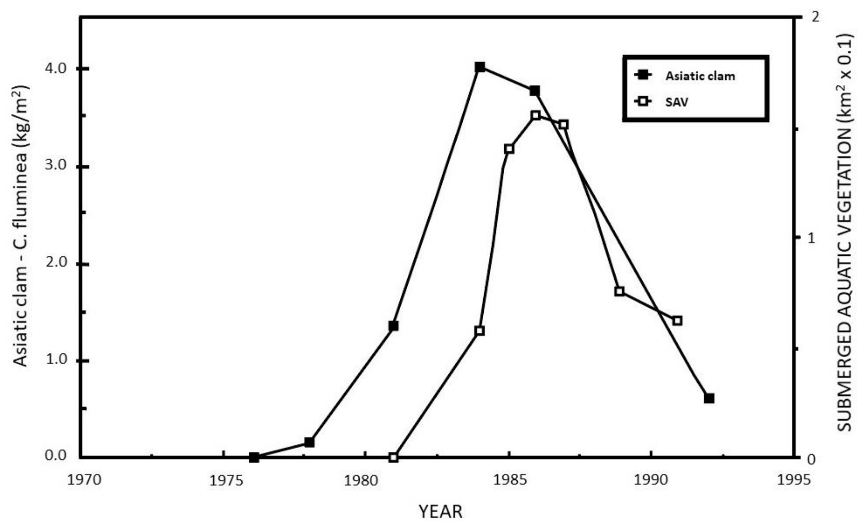

Figure 27. *Corbicula fluminea* abundance and submerged aquatic vegetation acreage in the Potomac River estuary near Washington, D.C., 1970-1992. Adapted from Phelps (1994).

Sustained benthic and SAV monitoring programs have 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 Bay SAV research community recently engaged in an effort to summarize changes over time in SAV abundance across all Chesapeake tidal regions. These changes have been documented in a series of SAV Fact Sheets, available from the Chesapeake Bay Watershed Data Dashboard, Tidal Waters section (https://gis.chesapeakebay.net/wip/dashboard/). In the Potomac, the Fact Sheets describe sustained recovery of SAV beds in shallow waters of the tidal fresh region, along both the Virginia and Maryland shorelines (Figure 28). This recovery is attributed at least in part to upgrades at the Blue Plains wastewater treatment plant.

Similarly, historically diverse SAV communities along the Virginia shoreline and in Aquia and Potomac Creeks of the oligohaline Potomac have persisted for many years and continue to surpass the local acreage target. SAV beds in Maryland shoal areas have approached target levels in the past. Their acreage has been declining in recent years, but the beds remain relatively dense. While water clarity in this portion of the Potomac has historically been low and is static or degrading (Figures 14 and 15), the canopy-forming SAV species found in this segment are typically more resistant to the naturally high turbidities found here (Batiuk *et al.*, 2000). In contrast, SAV acreage in the mesohaline Potomac probably achieved maximum coverage since surveys have been taken in the 1960s, and has not reached that level of coverage again since Tropical Storm Agnes in 1972 (Orth and Moore, 1984). A moderate resurgence in shoal areas of MD waters occurred from the mid-1990s through 2005, but coverage has declined in recent years.

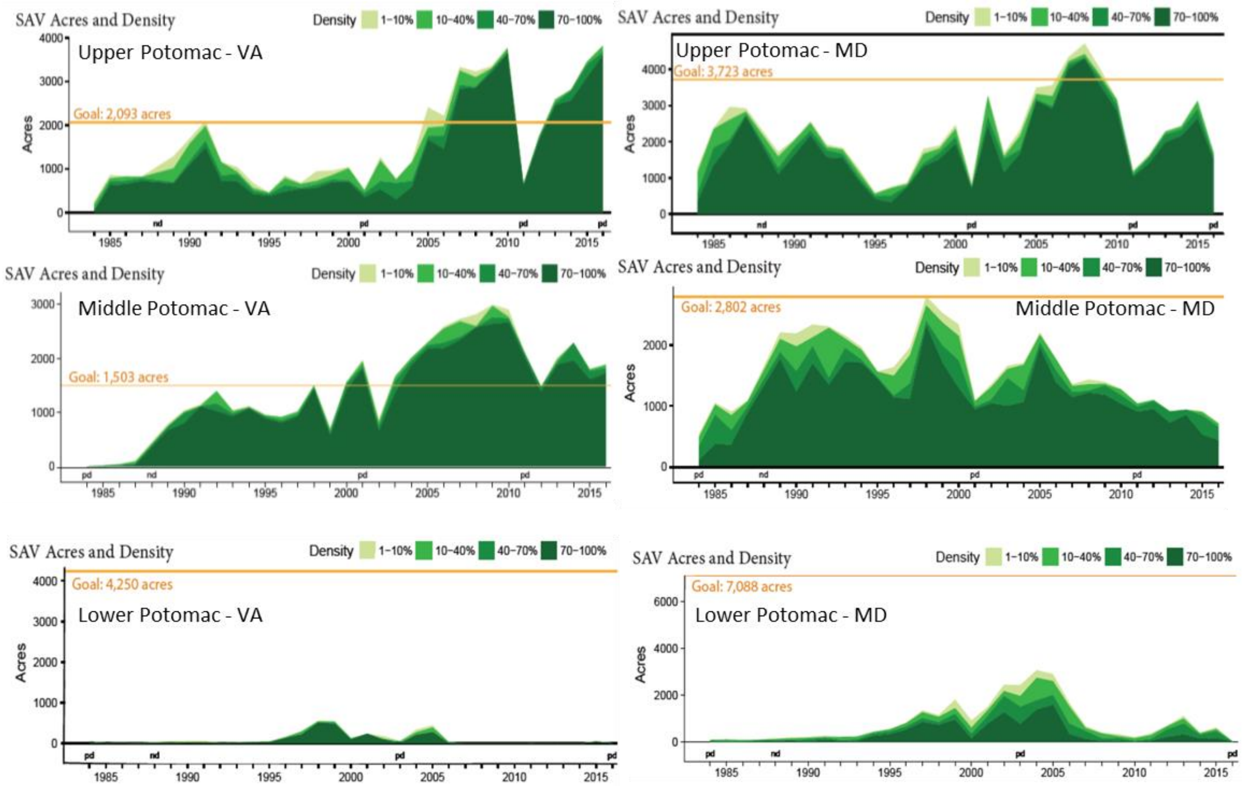

Figure 28. Changes in SAV acreage and density over time across salinity zones of the tidal Potomac River. Graphs and interpretation presented here are excerpted from the SAV Synthesis Effort and the Chesapeake Bay Program's SAV Fact Sheets, available through the Chesapeake Bay Watershed Data Dashboard, Tidal Waters section (https://gis.chesapeakebay.net/wip/dashboard/).

6. Summary

Total nutrient concentrations have been decreasing at most stations in the Potomac River over the long-term, with improvements persisting in the last 10 years as well (Figures 6-9). These trends follow from the decreasing discharge from TN and TP sources in the watershed (Figure 19, Table 4). The TP source reductions are not as apparent in the direct loads to the river, which may be part of the reason that tidal nutrient concentrations are not decreasing at as many stations in the short-term as the long-term.

While degrading chlorophyll *a* and Secchi depth trends at several Potomac monitoring stations are concerning, recent improvements in summer oxygen concentrations (Figures 16 and 17) are promising. The findings that chlorophyll *a* concentrations in the lower Potomac have either leveled out or improved (Figures 10 and 12, LE stations) may suggest a smaller amount of phytoplankton biomass available to fuel summer oxygen depletion.

As discussed in the previous section, the response of chlorophyll *a*, Secchi depth, and bottom DO is mixed in the Potomac tidal waters, but there are multiple possible reasons for this lag in response. Continuing to track water quality response and investigating these possibilities are important steps to understanding water quality patterns and changes in the Potomac River.

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Appendix

GAM results for the following parameters are provided in a separate Appendix document:

- Bottom Total Phosphorus (TP)
- Bottom Total Nitrogen (TN)
- Surface Ortho-Phosphate (PO4)
- Surface Dissolved Inorganic Nitrogen (DIN)
- Surface Total Suspended Solids (TSS)
- Surface Dissolved Oxygen (DO)
- Surface Temperature