Patapsco and Back Tributaries Summary:

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

June 7, 2021

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

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

Contents

1. Purpose and Scope

The Patapsco and Back Tributary Summary outlines change over time in a suite of monitored tidal water quality parameters and associated potential drivers of those trends for the time period 1985 – 2018, and provides a brief description of the current state of knowledge explaining these observed changes. Water quality parameters described include surface (above pycnocline) total nitrogen (TN), surface total phosphorus (TP), spring and summer (June, July, August) surface chlorophyll *a*, summer bottom (below pycnocline) dissolved oxygen (DO) concentrations, and Secchi disk depth (a measure of water clarity). Results for annual surface water temperature, bottom TP, bottom TN, surface ortho-phosphate (PO4), surface dissolved inorganic nitrogen (DIN), surface total suspended solids (TSS), and summer surface DO concentrations are provided in an Appendix. Drivers discussed include physiographic watershed characteristics, changes in TN, TP, and sediment loads from the watershed to tidal waters, expected effects of changing land use, and implementation of nutrient management and natural resource conservation practices. Factors internal to estuarine waters that also play a role as drivers are described including biogeochemical processes, physical forces such as wind-driven mixing of the water column, and biological factors such as phytoplankton biomass and the presence of 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 Patapsco and Back Rivers.

2. Location

The Patapsco and Back River watersheds covers approximately 1%, of the Chesapeake Bay watershed. Their watershed is approximately 1,647 km^2 (Table 1.) and is contained within one state, Maryland (Figure 1).

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

Table 1. "Watershed areas for each of the thirteen tributary or tributary groups for which Tributary Trends summaries have been produced. All of the tributary summaries can be accessed at the following link: https://cast.chesapeakebay.net/Home/TMDLTracking#tributaryRptsSection".

2.1 Watershed Physiography

The Patapsco and Back River watersheds stretch across two major physiographic regions, namely, Piedmont and Coastal Plain (Bachman *et al.*, 1998) (Figure 1). The Piedmont physiography covers primarily crystalline areas. The Coastal Plain physiography covers lowland, dissected upland, and upland areas. Implications of these physiographies for nutrient and sediment transport are summarized in Section 5.1.1.

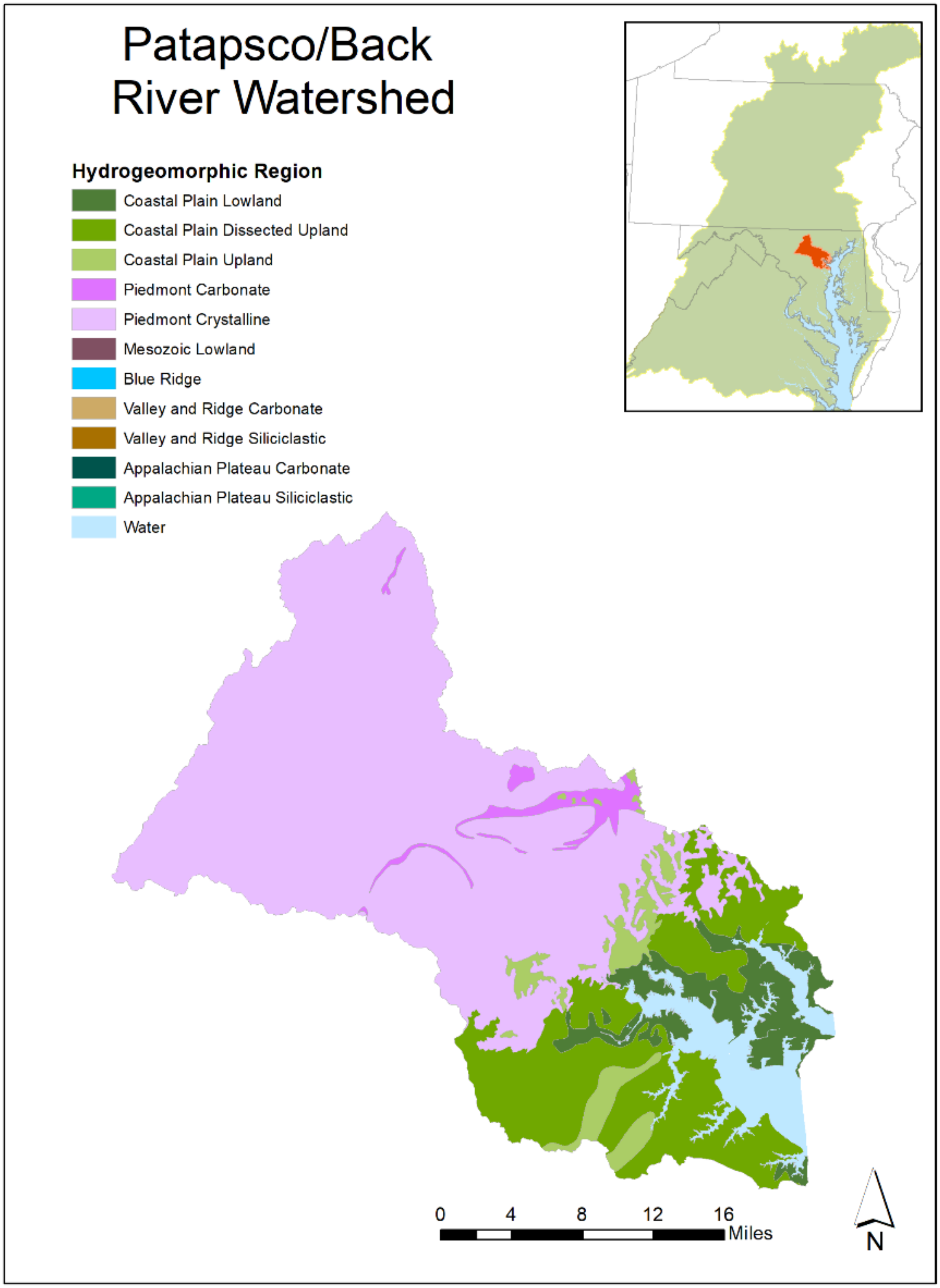

Figure 1. Distribution of physiography in the Patapsco and Back River watersheds.

2.2 Land Use

Land use in the Patapsco and Back River watersheds is dominated (52%) by developed areas. Urban and suburban land areas have increased by 54,693 acres since 1985, agricultural lands have decreased by 22,180 acres, and natural lands have decreased by 32,760 acres. Correspondingly, the proportion of urban land in this watershed has increased from 38% in 1985 to 52% in 2019 (Figure 2).

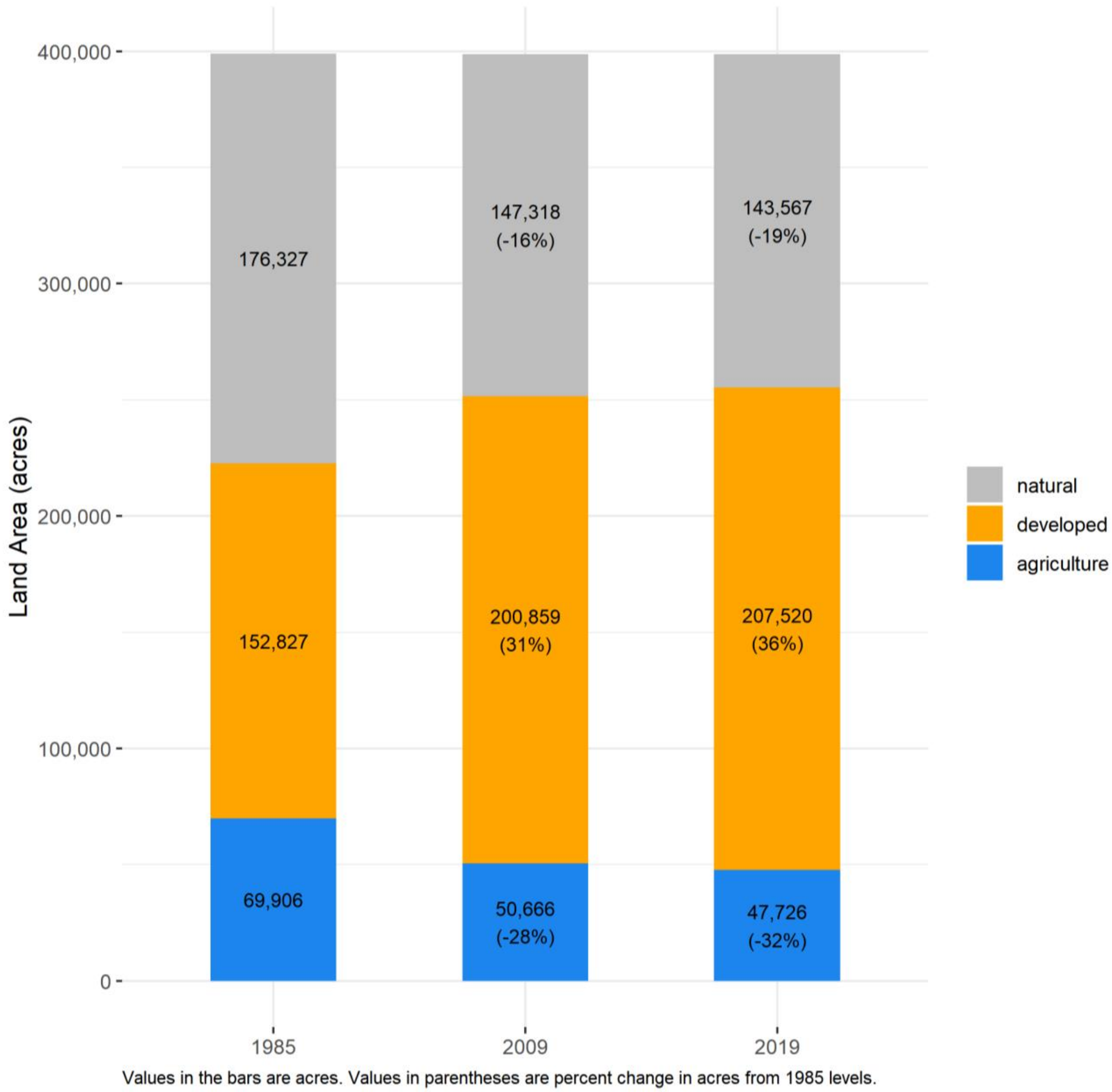

Figure 2. Distribution of land uses in the Patapsco and Back River watersheds. Percentages are the percent change from 1985 for each source sector.

The Patapsco and Back River watersheds had already experienced significant development by the mid-1970s (Figure 3). Since then, developed and semi-developed lands have continued to expand into previously undeveloped regions. The impacts of land development differ depending on the use from which the land is converted (Keisman *et al.*, 2019; Ator *et al.*, 2019). Implications of changing land use for nutrient and sediment transport are summarized in Section 5.1.3.

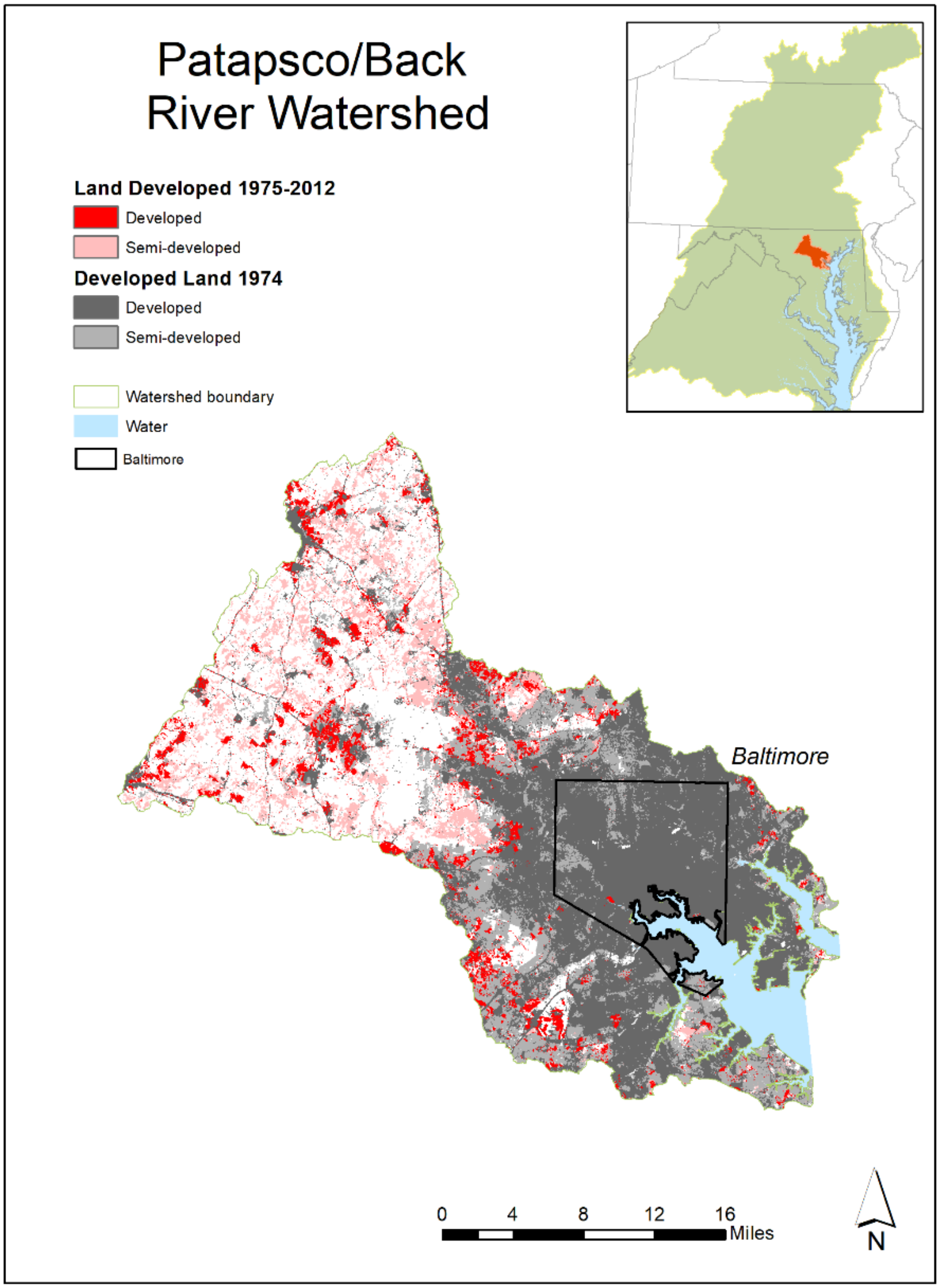

Figure 3. Distribution of developed land in the Patapsco and Back River watersheds. Derived from Falcone (2015). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

2.3 Tidal Waters and Stations

For the purposes of water quality standards assessment and reporting, the tidal waters associated with the Patapsco and Back Rivers are divided into two segments (U.S. Environmental Protection Agency, 2004): the Oligohaline Back River (BACOH) and the Mesohaline Patapsco River (PATMH) (Figure 4).

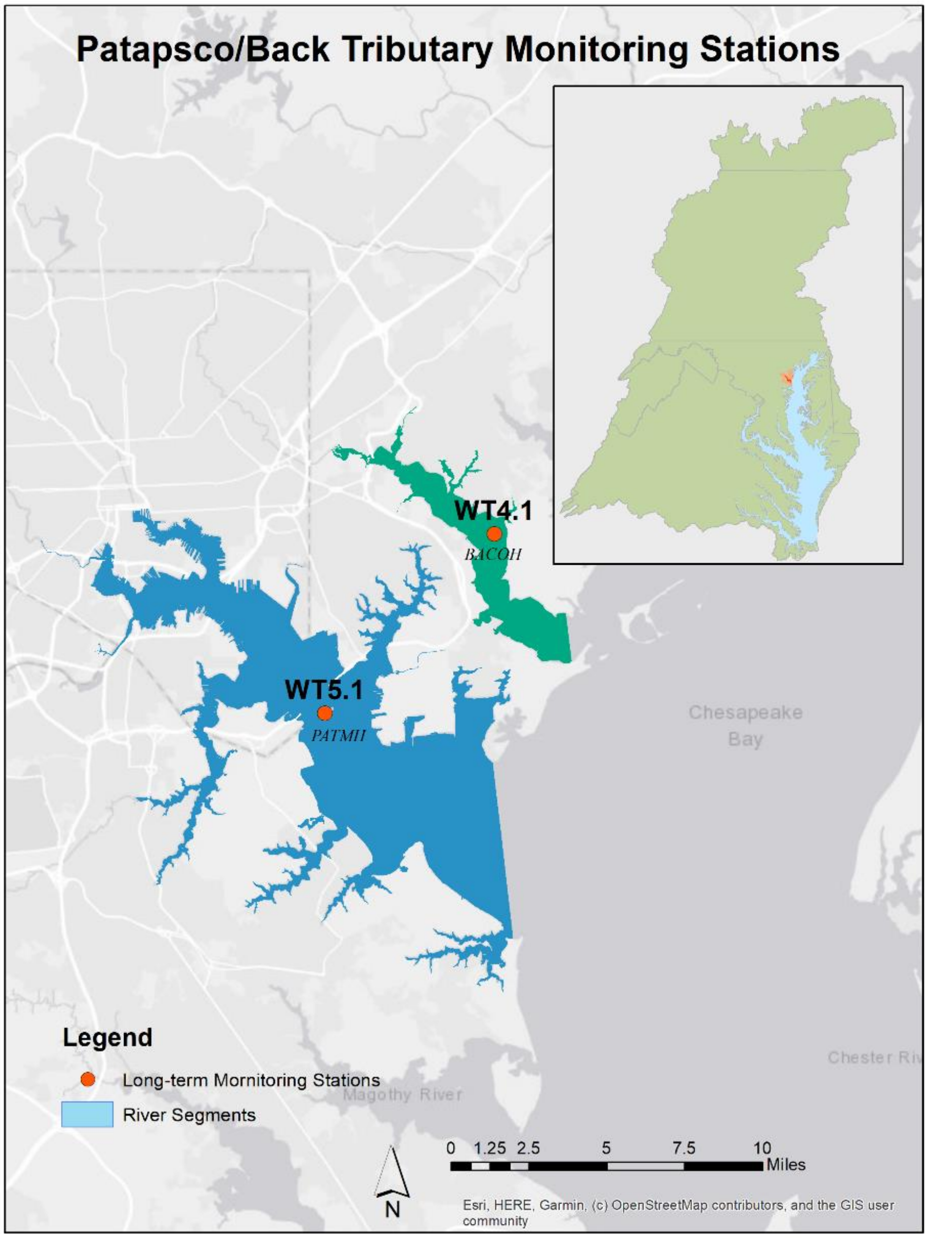

Figure 4. Map of Tidal Patapsco and Back River segments and long-term monitoring stations. Base map credit Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community, World Geodetic System 1984.

Long-term trends in water quality in the Patapsco and Back Rivers are analyzed by MD Department of Natural Resources at two stations, one in the tidal portion of each river (Figure 4). Water quality data at these stations are also used to assess attainment of dissolved oxygen (DO) water quality criteria. All tidal water quality data analyzed for this summary are available from the Chesapeake Bay Program Data Hub (Chesapeake Bay Program, 2018)(Chesapeake Bay Program, 2018)(Chesapeake Bay Program, 2018)(Chesapeake Bay Program, 2018). Other monitoring has been conducted over the years and used for water quality criteria evaluation but is not shown in the long-term trend graphics in subsequent sections because of its shorter duration.

3. Tidal Water Quality Dissolved Oxygen Criteria Attainment

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

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

time period	BACOH	PATMH
1985-1987		
1986-1988		
1987-1989		
1988-1990		
1989-1991		
1990-1992		
1991-1993		
1992-1994		
1993-1995		
1994-1996		
1995-1997		
1996-1998		
1997-1999		
1998-2000		
1999-2001		
2000-2002		

2001-2003		
2002-2004		
2003-2005		
2004-2006		
2005-2007		
2006-2008		
2007-2009		
2008-2010		
2009-2011		
2010-2012		
2011-2013		
2012-2014		
2013-2015		
2014-2016		
2015-2017		
2016-2018		

Table 3. Deep Water summer DO (30-day mean) criteria evaluation results. Green indicates that the criterion was met. White indicates that the criterion was not met. Note: the entire table is white intentionally because these criterion have not been met during this period.

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

2010-2012		
2011-2013		
2012-2014		
2013-2015		
2014-2016		
2015-2017		
2016-2018		

Comparing trends in station-level DO concentrations to the computed DO criterion status for a recent assessment period can reveal valuable information, such as whether progress is being made towards attainment in a segment that is not meeting the water quality criteria, or conversely the possibility that conditions are degrading even if the criteria are currently being met. To illustrate this, the 2016-2018 attainment status for the OW summer and DW summer DO criteria shown in Tables 2 and 3 are overlain with the 1985-2018 change in summer surface DO concentration and the 1985-2018 change in bottom summer DO concentrations, respectively (Figure 5). The bottom depths at each of these stations is different due to varying bathymetry, but the bottom DO trends at these stations are expected to represent water in the DW designated use. The Back River segment is meeting the OW summer criterion in the latest period, and surface DO is possibly improving. The Patapsco segment, however, is not meeting either of the DO criteria shown and has no observed change in surface or bottom DO, indicating lack of progress.

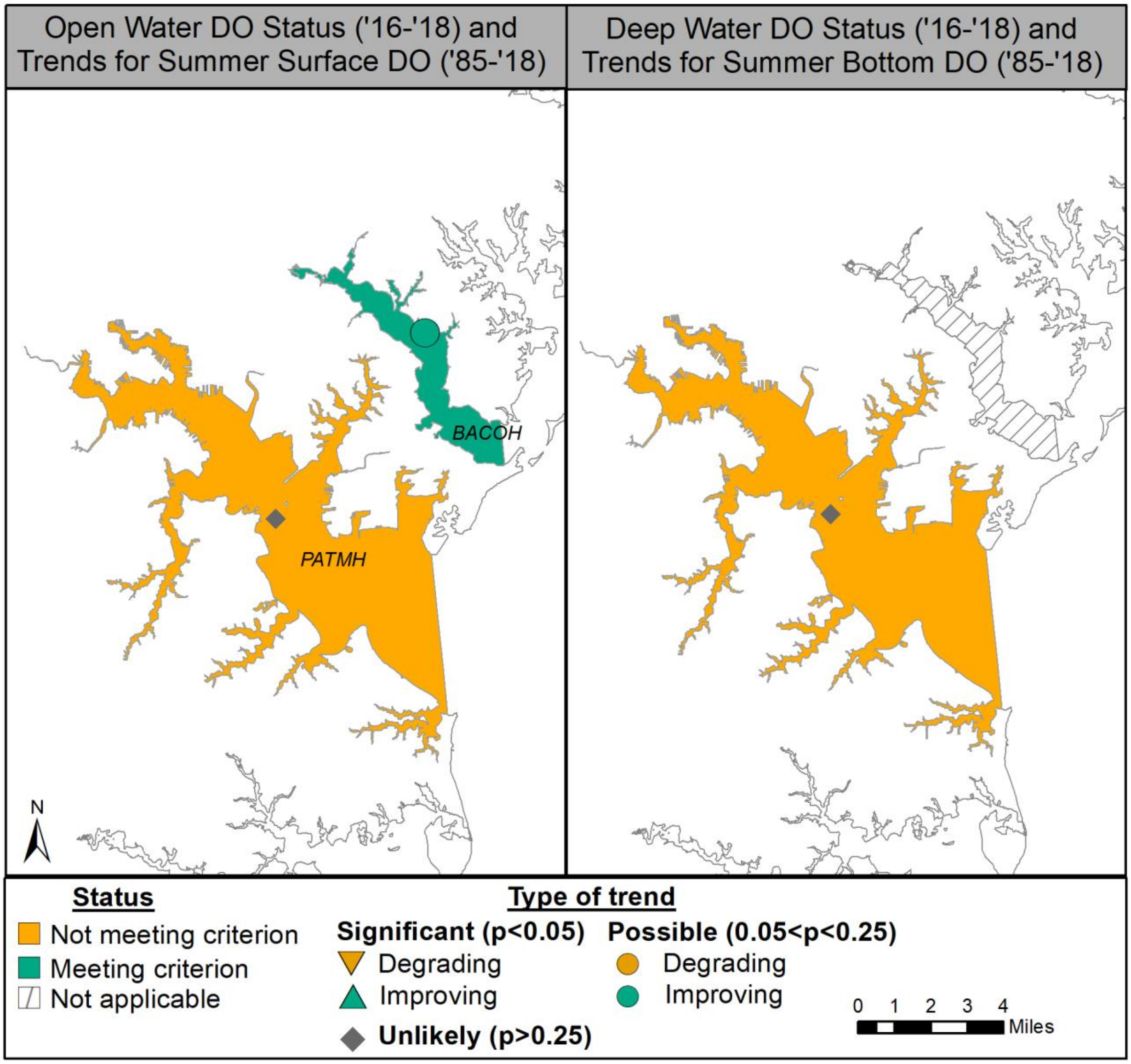

Figure 5. Pass-fail DO criterion status for 30-day OW summer DO and DW summer DO designated uses in Patapsco and Back segments along with long-term trends in DO concentrations. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

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 two 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 the concentrations over time, as observed in the estuary. The second approach involves including monitored river flow or in situ salinity (as an aggregated measure of multiple river flows) in the GAM to explain some of the variation in the water quality parameter. From the results of this second approach, it is possible to estimate the "flow-adjusted" change over time, which gives a mean estimate of what the water quality parameter trend would have been if river flow had been average over the period of record. Note that depending on station and parameter, sometimes gaged river flow is used for this adjustment and sometimes salinity is used, but we refer to all these results as "flow-adjusted" for simplicity.

To determine if there has been a change over time (i.e., a trend) at a particular station for a given parameter, we compute a percent change between the estimates at beginning and end of a period of interest from the GAM fit. For each percent change computation, the level of statistical confidence can be computed as well. Change is called significant if $p < 0.05$ and possible if the p-value is up to 0.25. That upper limit is higher than usually reported for hypothesis tests but allows us to provide a more complete picture of the results, identifying locations where change might be starting to occur and should be investigated (Murphy *et al.*, 2019). In addition to the maps of trends, for each parameter, there is a set of graphs (e.g., Figure 7) that include the raw observations (dots on the graphs) and lines representing the mean annual or seasonal GAM estimates, without flow-adjustment. The flow-adjusted GAM line graphs are not shown.

4.1 Surface Total Nitrogen

Annual total nitrogen (TN) trends have improved at both the Back River (WT4.1) and Patapsco and Back River (WT5.1) stations over the long-term both with and without flow-adjustment. Over the short-term, the improving trend at WT4.1 has continued while no short-term trend has been observed at WT5.1.

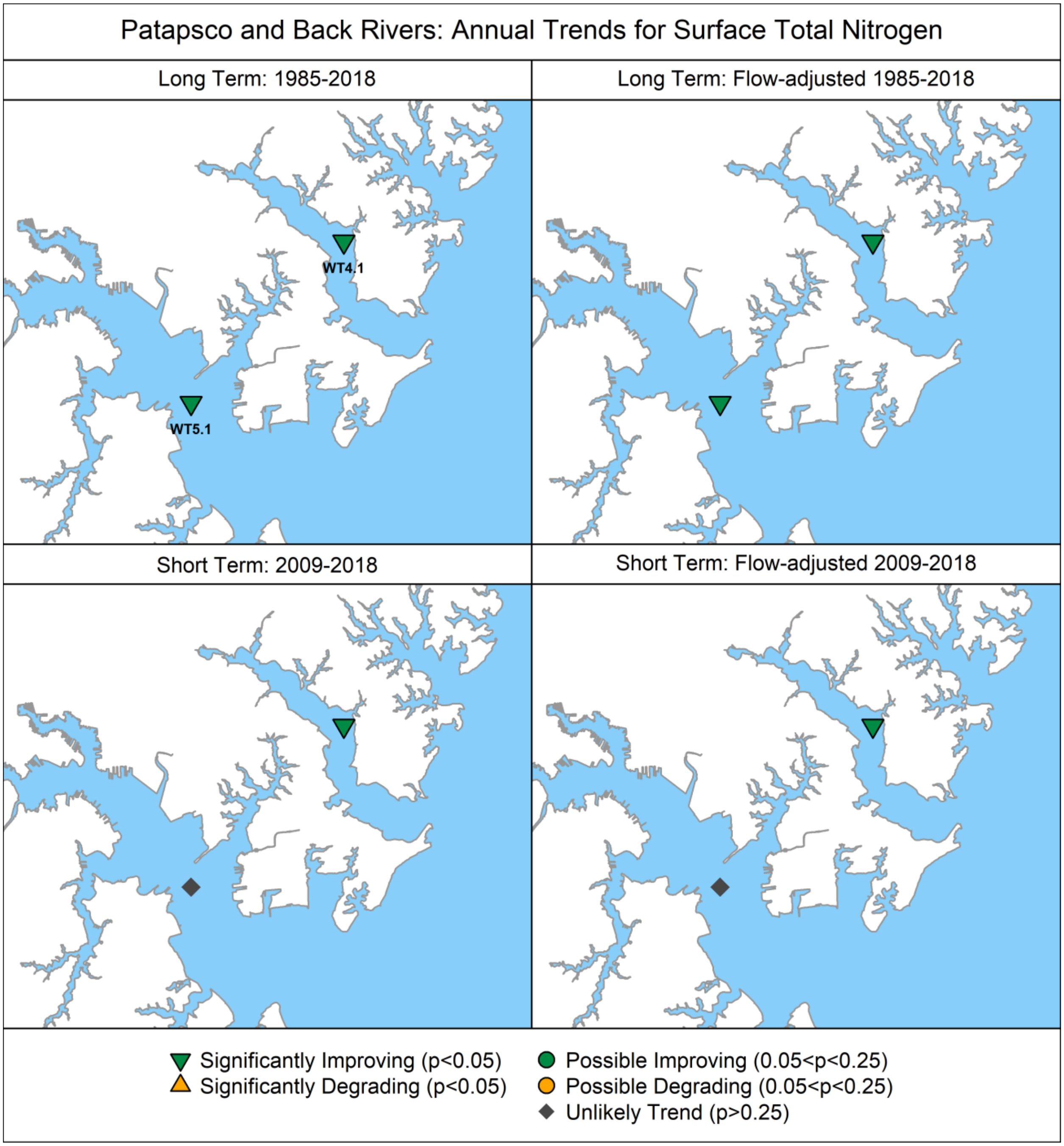

Figure 6. Surface TN trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

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 Back River TN concentrations started very high and have decreased substantially. The TN concentrations in the Patapsco River also decreased from the beginning of the record, but have leveled out in recent decades (Figure 7). 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).

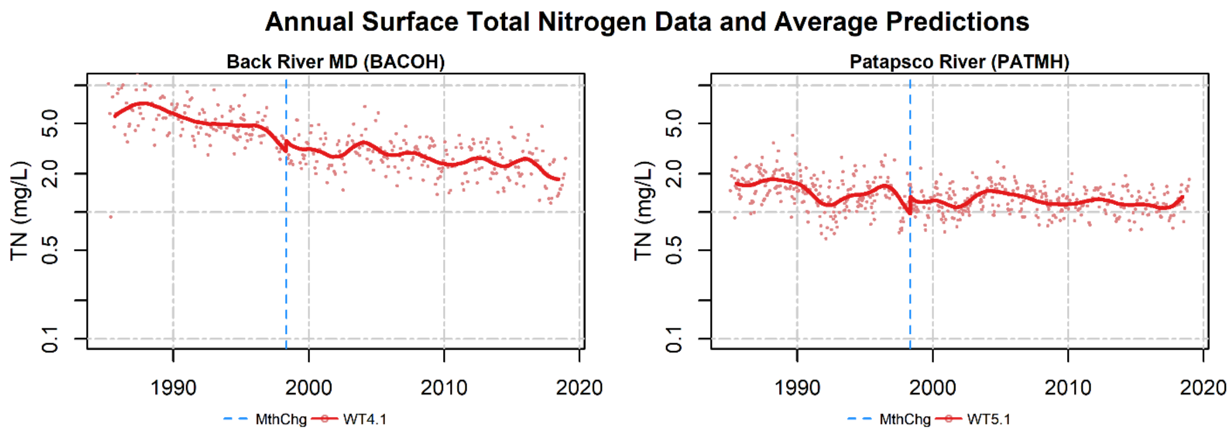

Figure 7. Surface TN data (dots) and average long-term pattern generated from non-flow-adjusted GAMs. Colored dots represent data corresponding to the monitoring station indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations. Vertical blue dotted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

4.2 Surface Total Phosphorus

Surface total phosphorus (TP) is also improving at both stations over the long-term, with and without flow-adjustment (Figure 8). In the short-term, there is possible TP improvement with both techniques at both stations.

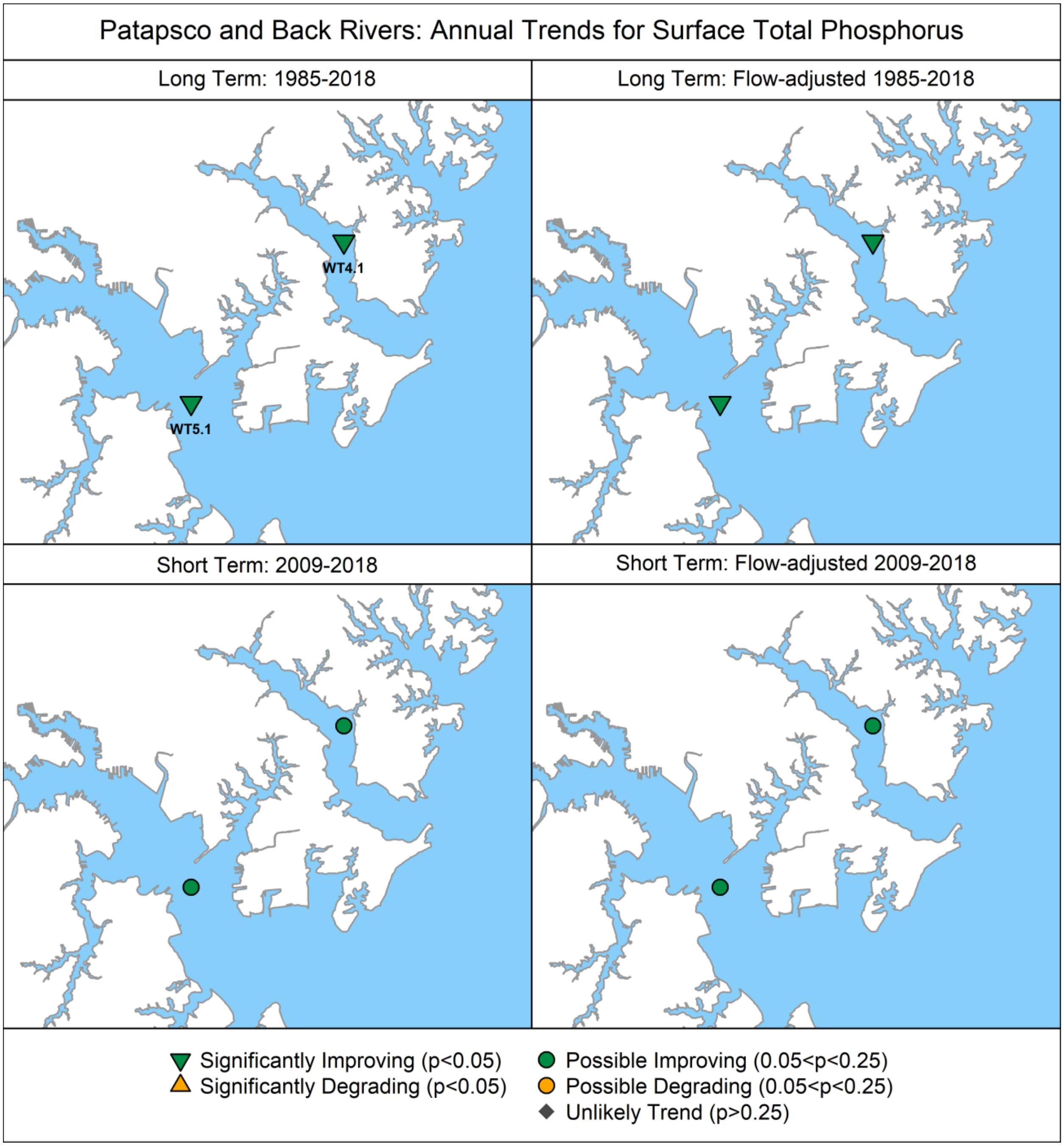

Figure 8. Surface TP trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

The continuous decrease in TP concentrations is evident at both stations in the data values and mean annual GAM estimates (Figure 9). Like for TN, concentrations of TP are higher at the Back River station than the Patapsco station.

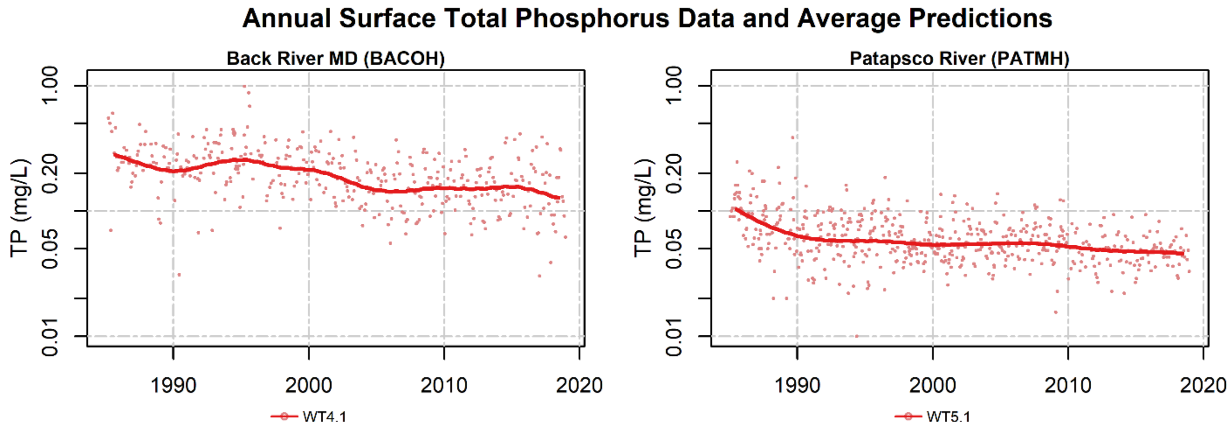

Figure 9. Surface TP data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

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). Over the long-term, spring chlorophyll *a* trends are improving at the Back River station (WT4.1), while there is no trend at the Patapsco River station (WT5.1) (Figure 10). Over the short-term, both stations are showing possible or significant improvement.

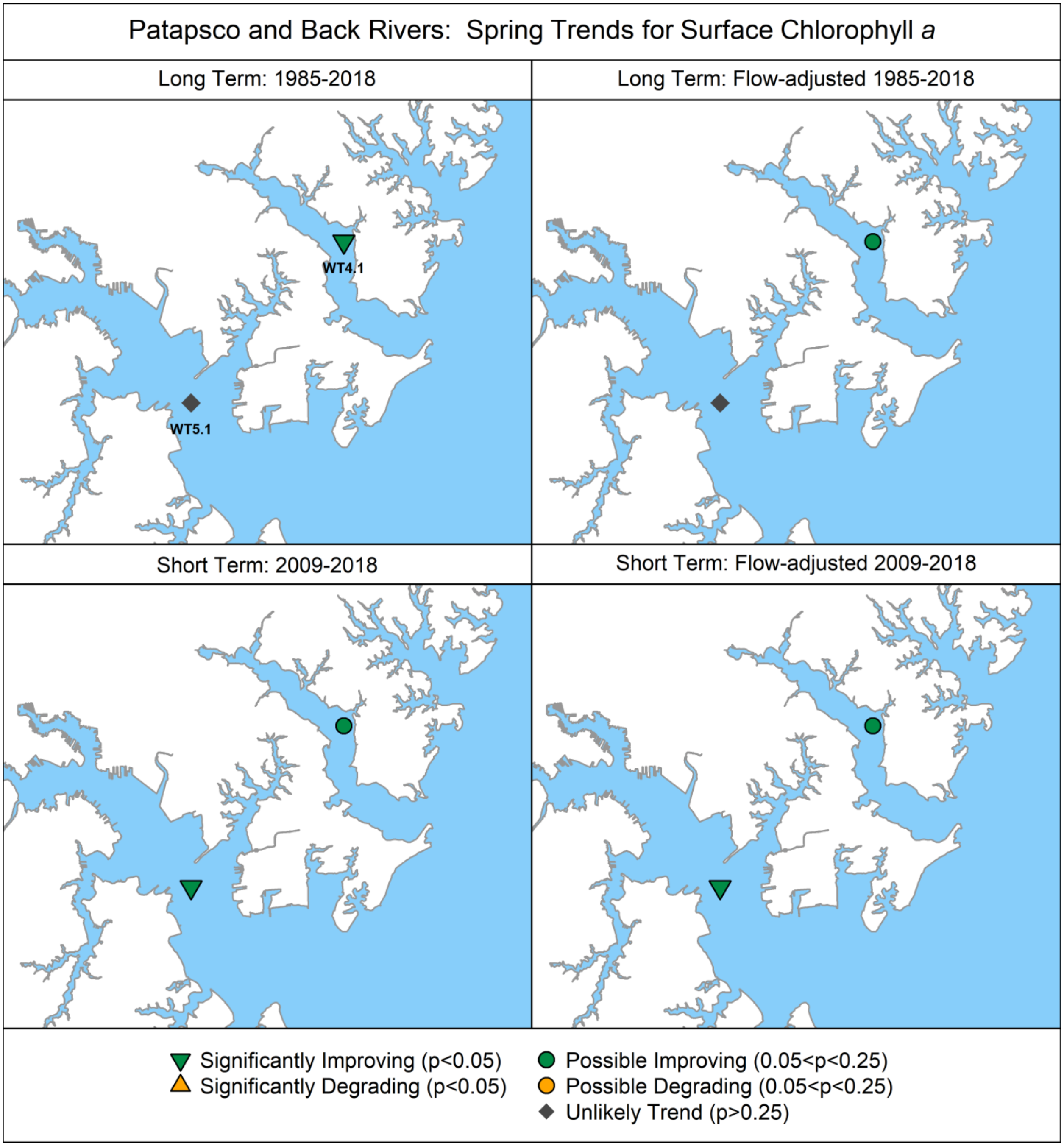

Figure 10. Surface spring (March-May) chlorophyll *a* trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

The spring chlorophyll *a* data and mean seasonal GAM estimates (Figure 11) show a clear decrease in the last few years at the Back River station. In addition, in the Back River, the maximum concentrations on the plot are all in the first half of the record, and then there appears to be a step-down in those extreme values during the second half of the record. At the Patapsco River station, a decrease at the very end of the time period also leads to the short-term improving trend noted above (Figure 11).

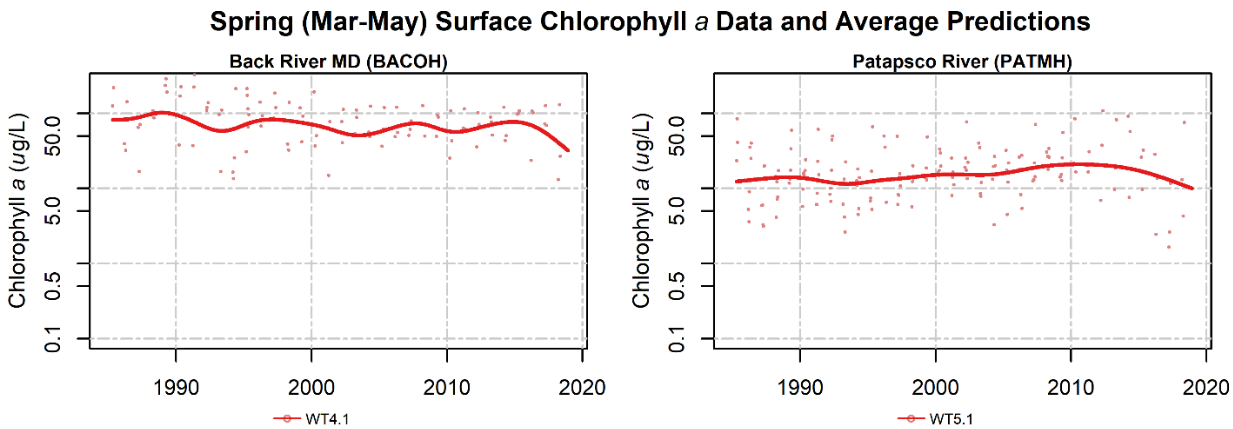

Figure 11. Surface spring chlorophyll *a* data (dots) and average long-term pattern generated from non-flow adjusted GAM. Colored dots represent March-May data corresponding to the monitoring station indicated in the legend; colored lines represent mean spring GAM estimates for the noted monitoring stations.

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

Summer long-term chlorophyll *a* trends are improving over the long-term at both stations, with and without flow-adjustment (Figure 12). The short-term trends are also possibly improving at both stations.

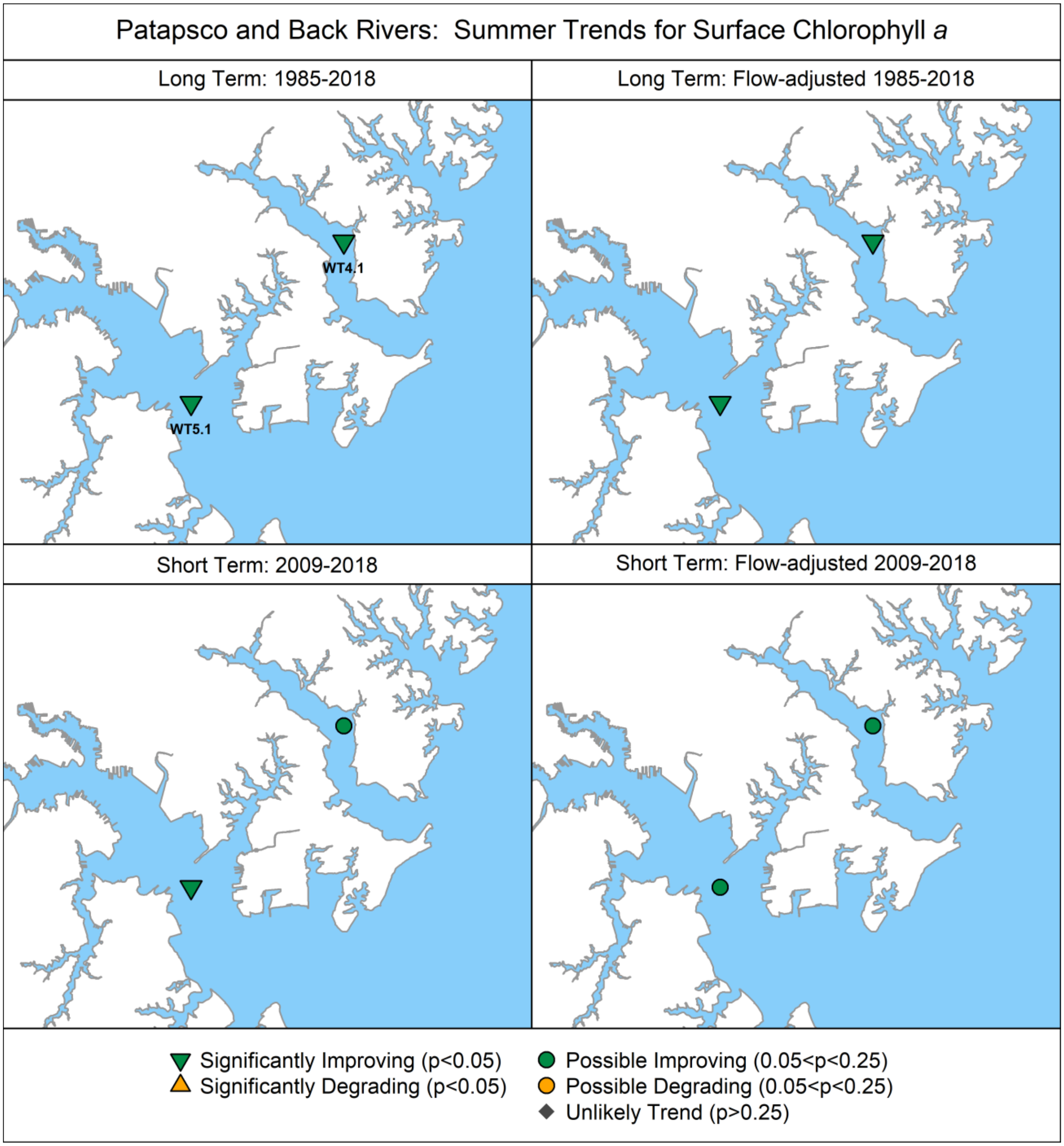

Figure 12. Surface summer (July-September) chlorophyll *a* trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Summer chlorophyll *a* concentrations and mean seasonal GAM estimates (Figure 13) are fairly steady over time but show gradual decreases which account for the long-term trends (Figure 12). Observations at both stations drop at the very end of the record at both stations, as the short-term trends suggest.

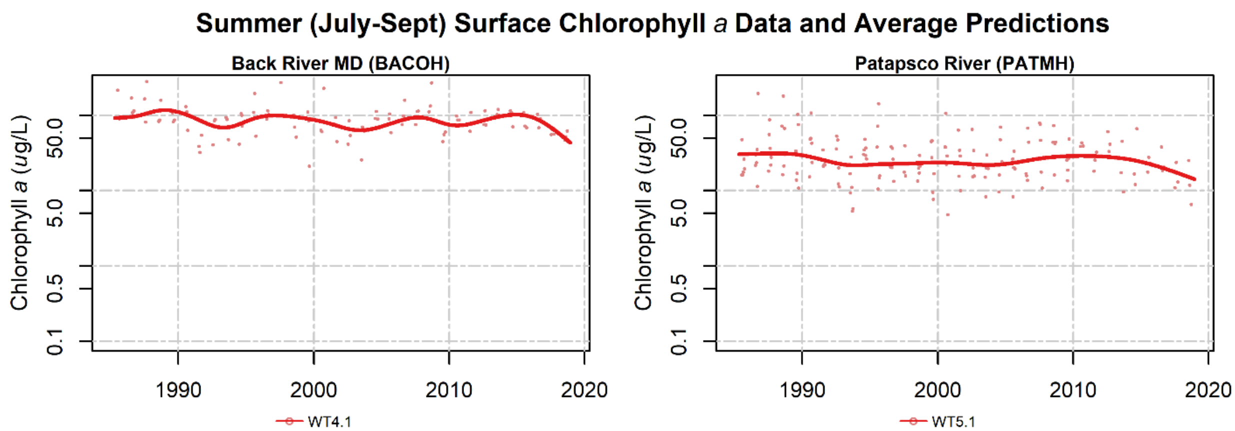

Figure 13. Surface summer chlorophyll *a* data (dots) and average long-term pattern generated from non-flow adjusted GAM. Colored dots represent July-September data corresponding to the monitoring station indicated in the legend; colored lines represent mean summer GAM estimates for the noted monitoring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

4.5 Secchi Disk Depth

Results for Secchi disk depth, a measure of visibility through the water column, indicate only a possible degrading trend at station WT4.1 (Back River) without flow adjustment (Figure 14). Otherwise there are no long-term trends in Secchi at these stations. There is indication of short-term improvement in Secchi at WT5.1 (Patapsco River) and possibly after flow-adjustment at WT4.1.

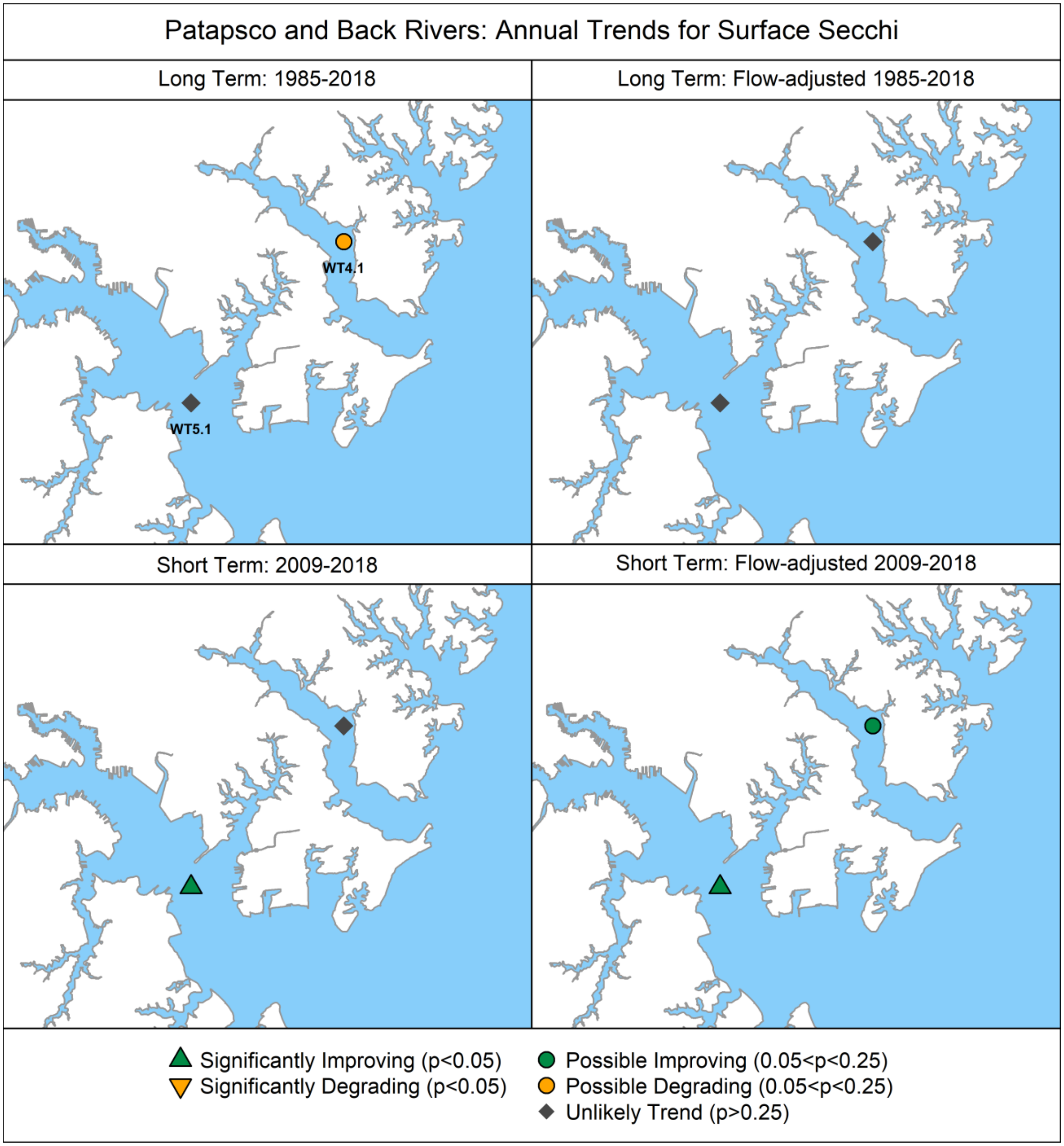

Figure 14. Annual Secchi depth trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Secchi depth is much shallower at the Back River station than the Patapsco River station (Figure 15). There is a slight long-term decrease in the Back River mean annual GAM estimates consistent with the long-term possible degrading trend (Figure 14). The Patapsco River Secchi pattern is more variable, and the short-term increase looks similar to other fluctuations in the data over time (Figure 15).

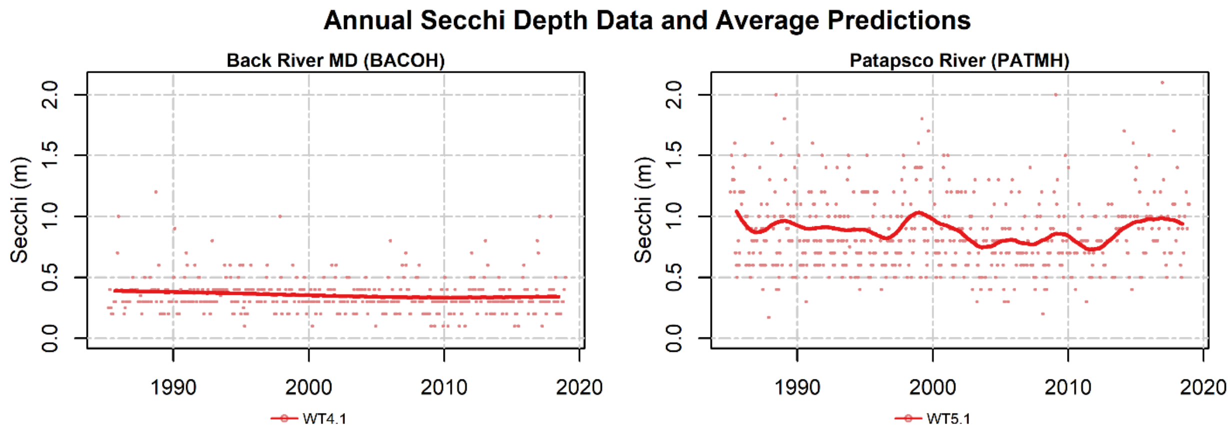

Figure 15. Annual Secchi depth data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

4.6 Summer Bottom Dissolved Oxygen (June-September)

Summer bottom water oxygen concentrations are not trending in a significant way at these stations either in the long- or short-term (Figure 16). There is only a possible improving trend over the long-term after flow adjustment at WT4.1.

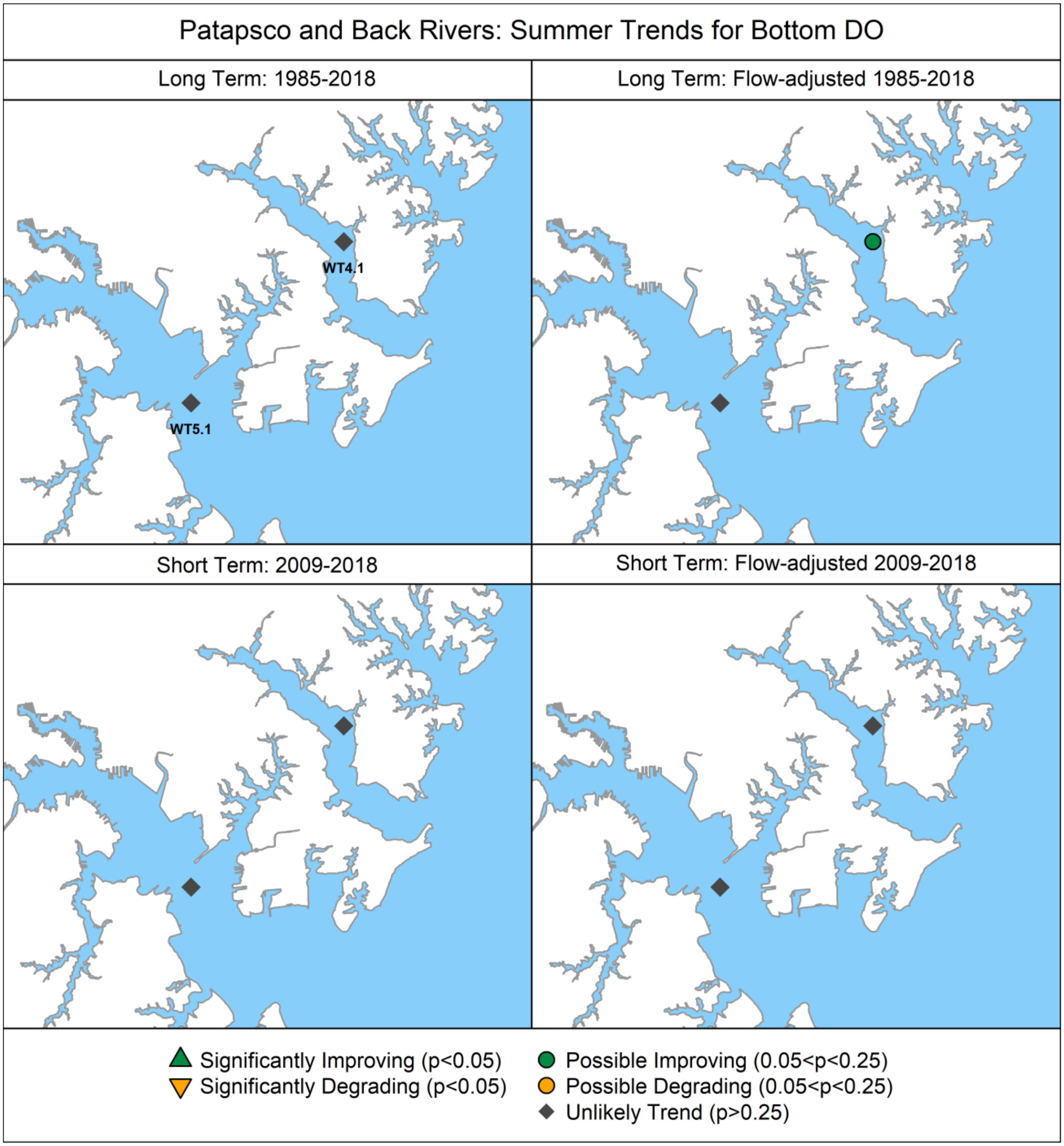

Figure 16. Summer (June-September) bottom DO trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Plots of the summer DO data and mean seasonal GAM estimates show that much higher bottom oxygen concentrations persist at the Back River station than the Patapsco River station (Figure 17). At the Back River station, DO concentrations have less frequently gone below the 5 mg/L summer open water 30-day mean criterion in recent years. In the Patapsco River where deeper water DO criteria apply, the DO concentrations and mean summer estimates are well below the appliable criteria and not trending.

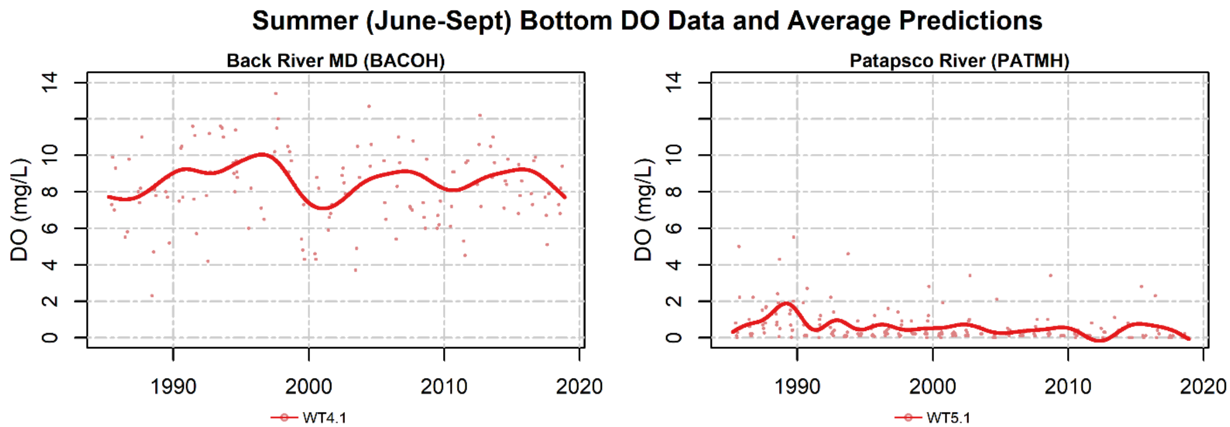

Figure 17. Summer (June-September) bottom DO data (dots) and mean summer long-term pattern generated from non-flow adjusted GAM. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring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

5. Factors Affecting Trends

5.1 Watershed Factors

5.1.1 Effects of Physical Setting

The geology of the Patapsco and Back River watersheds and their associated land use affects the quantity and transmissivity of nitrogen, phosphorus, and sediment delivered to non-tidal and tidal streams (Figure 18) (Lizarraga, 1997; Bachman *et al.*, 1998; Ator and Denver, 2012).

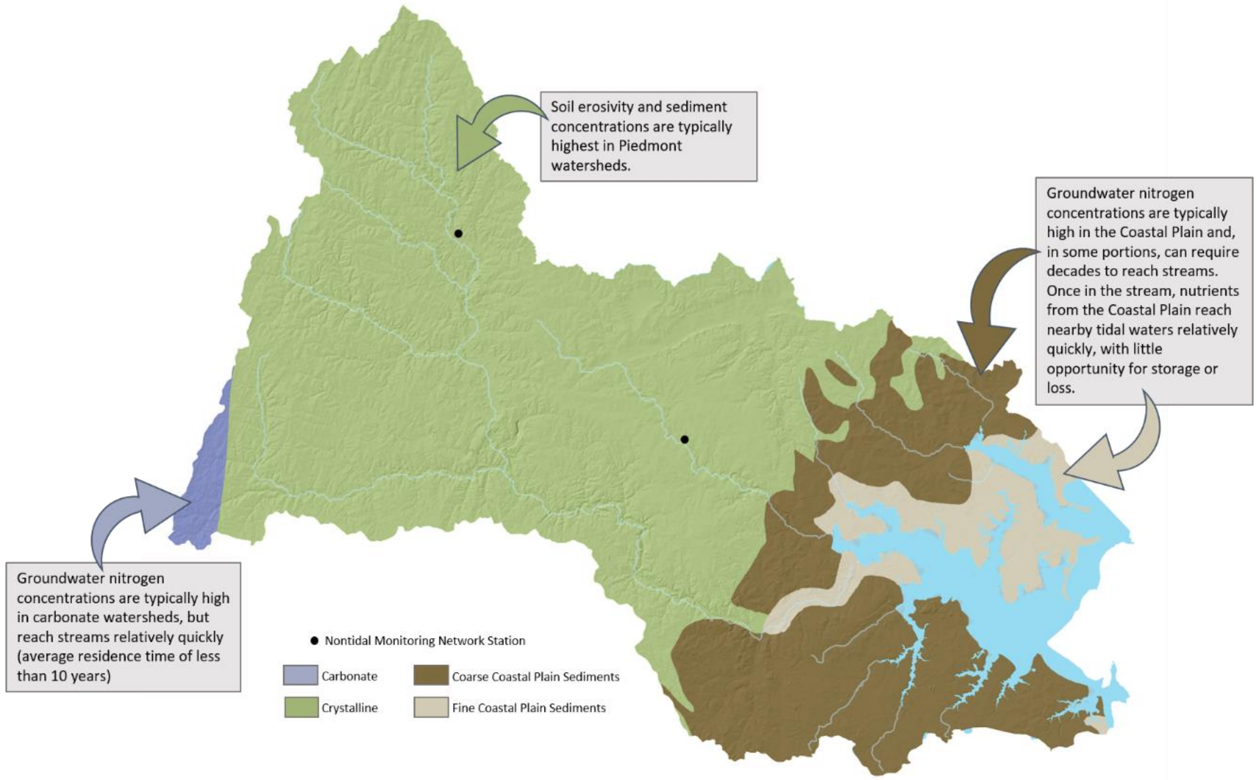

Figure 18. Effects of watershed hydrogeomorphology on nutrient transport to freshwater streams and tidal waters. Base map modified from King *et al.* (1974) and Ator *et al.* (2005), North American Datum 1983.

Nitrogen

Groundwater is an important delivery pathway of nitrogen, as nitrate, to most streams in the Chesapeake Bay watershed (Ator and Denver, 2012; Lizarraga, 1997). Groundwater nitrate concentrations in the Patapsco River and Back River watersheds are highest in streams above the fall line that drain Piedmont soils, but are lower than other regions of Maryland's western shore (Greene and others, 2005; Terziotti and others, 2017). Crystalline rocks in the upper portion of the Patapsco river watershed contain large amounts of oxic groundwater, which promotes nitrate transport (Tesoriero and others, 2015), but their low porosity and the large amounts of impervious land use in this region limits the amount of surface water infiltration (Lindsey and others, 2003). The typical residence time of groundwater delivered to streams in the Chesapeake Bay watershed is about 10 years, but ages vary from less than one year to greater than 50 years based on bedrock structure, groundwater flow paths, and aquifer depths (Lindsey and others, 2003). A similar range of water ages has been measured from Piedmont crystalline springs (0 – 33 years, Phillips and others, 1999). Groundwater represents about 50% of streamflow in most Chesapeake Bay streams, with the other half composed of soil moisture and runoff, which have residence times of months to days (Phillips, 2007).

Phosphorus

Phosphorus binds to soil particles and most phosphorus delivered to the Bay is attached to sediment (Zhang *et al.*, 2015); however, once fully phosphorus saturated, soils will not retain new applications and export of dissolved phosphorus to streams, from shallow soils and groundwater, will increase (Staver and Brinsfield, 2001). Phosphorus sorption capacity varies based on soil particle chemical composition and physical structure with clays typically having the greatest number of sorption sites and highest average phosphorus concentrations (Sharpley, 1980). The highest soil phosphorus concentrations occur in the headwaters of the Patapsco 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).

<u>Sediment</u>

The delivery of sediment from upland soil erosion, streambank erosion, and tributary loading varies throughout the Patapsco and Back River watersheds, but in-stream concentrations are typically highest in the upper portion of watershed that drains 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 (Trimble 1975, Gellis et al. 2005, Brakebill et al. 2010), bank sediment density (Wynn and Mostaghimi, 2006), vegetation (Wynn and Mostaghimi, 2006), stream valley geomorphology (Hopkins *et al.*, 2018), and developed land uses (Brakebill *et al.*, 2010).

<u>Delivery to tidal waters</u>

The delivery of nitrogen, phosphorus, and sediment in non-tidal streams to tidal waters in the Patapsco and Back River watersheds 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. There are no natural chemical processes that remove phosphorus from streams, but sediment, and associated phosphorus, can be trapped in floodplains before reaching tidal waters. High rates of sediment trapping by Coastal Plain nontidal floodplains and head-of-tide tidal freshwater wetlands creates a sediment shadow in many tidal rivers and limits sediment delivery to the bay (Noe and Hupp, 2009; Ensign *et al.*, 2014). Shoreline erosion contributes more fine-grained sediment to estuarine waters in Maryland's western shore than is delivered from the watershed (Langland and Cronin, 2003), likely as a result of such trapping.

5.1.2 Estimated Nutrient and Sediment Loads

Estimated loads to tidal portions of the Patapsco and Back Rivers are a combination of simulated non-point source, atmospheric deposition, and reported point-source loads. These loads were obtained from the Chesapeake Bay Program Watershed Model's progress runs specific to each year from 1985 and 2018 (https://cast.chesapeakebay.net/). Nonpoint source loads 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). Over the period of 1985-2018, 0.20, 0.010, and 5.5 million tons of nitrogen, phosphorus, and suspended sediment loads were exported from this watershed, respectively (Figure 19).

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 113 ton/yr in the period between 1985 and 2018, which is statistically significant ($p < 0.01$). This reduction is largely driven by point sources (-101 ton/yr, $p < 0.01$), and to a much lesser extent, by atmospheric deposition to the tidal waters (-0.66 ton/yr, $p < 0.01$). In addition, nonpoint sources also showed a decrease in this period (-2.2 ton/yr), although it is not statistically significant ($p = 0.55$). The significant point source reductions in TN are a result of substantial efforts to reduce nitrogen loads from major wastewater treatment facilities by implementing biological nutrient removal (Boynton *et al.*, 2008; 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 decrease of 6.7 ton/yr in the period between 1985 and 2018, which is statistically significant ($p < 0.01$). This reduction is entirely driven by point sources (-6.7 ton/yr, $p < 0.01$). By contrast, nonpoint sources showed a long-term increase (0.86 ton/yr, $p = 0.10$). 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 (Boynton *et al.*, 2008; Lyerly *et al.*, 2014).

Sediment

Estimated suspended sediment (SS) loads showed an overall increase of 1,347 ton/yr in the period between 1985 and 2018, although it is not statistically significant ($p = 0.06$). This increase is entirely driven by nonpoint sources (1,578 ton/yr, $p < 0.05$). Like TP and TN, point source load of SS showed a statistically significant decline in this period (-220 ton/yr; $p < 0.01$).

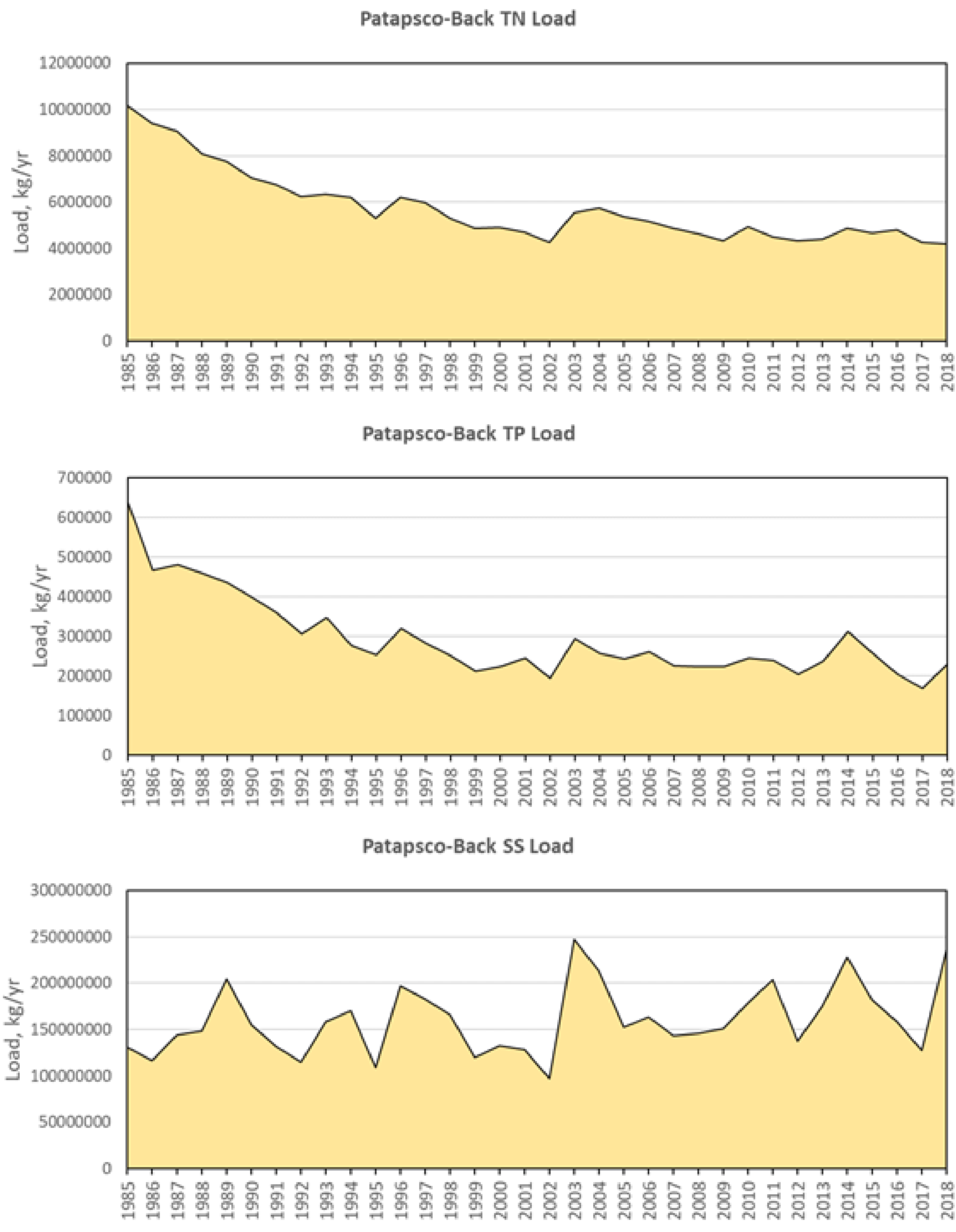

Figure 19. Simulated loads of nitrogen, phosphorus, and sediment to the tidal Patapsco-Back River.

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 Patapsco-Back River watershed.

Variable	Trend, metric ton/yr	Trend p-value
TN		
Total watershed[1]	-113	< 0.01
Point source	-101	< 0.01
Nonpoint source[2]	-2.2	0.55
Tidal deposition	-0.66	< 0.01
TP		
Total watershed	-6.7	< 0.01
Point source	-6.7	< 0.01
Nonpoint source	0.86	0.10
SS		
Total watershed	1,347	0.06
Point source	-220	< 0.01
Nonpoint source	1,578	< 0.05

[1] Loads from the different sources were obtained from the Chesapeake Bay Program Watershed Model progress runs specific to each year from 1985 and 2018, (https://cast.chesapeakebay.net/).
[2] Nonpoint source loads 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). The adjustment factor for each year is defined as the ratio between monitored load and watershed model simulated load for an applicable USGS River Input Monitoring (RIM) station. Because the Patapsco and Back Rivers do not have RIM stations, adjustment factors need to be transferred from a different tributary that has a RIM station. In this regard, the Patuxent River was selected for two reasons: (1) it is geographically proximate to the Patapsco and Back Rivers, and (2) it is hydrologically similar to the Patapsco and Back Rivers based on an analysis of annual riverflow anomalies.

5.1.3 Expected Effects of Changing Watershed Conditions

According to the Chesapeake Bay Program's Watershed Model known as the Chesapeake Assessment Scenario Tool (CAST; https://cast.chesapeakebay.net, version CAST-2019), changes in population size, land use, and pollution management controls between 1985 and 2019 would be expected to change long-term average nitrogen, phosphorus, and sediment loads to the tidal Patapsco River by -73%, -70%, and -7%, respectively (Figure 20). In contrast to the annual loads analysis above, CAST loads are based on changes in management only and do not include annual fluctuations in weather. CAST loads are calculated without lag times for delivery of pollutants or lags related to BMPs becoming fully effective after installation. In 1985, wastewater and developed were the two largest sources of nitrogen loads. By 2019, wastewater and developed remained the two largest sources of nitrogen loads. Overall, decreasing nitrogen loads from agriculture (-53%), natural (-25%), stream bed and bank (-8%), and wastewater (-80%) sources were partially counteracted by increases from developed (21%) and septic (33%) sources.

The two largest sources of phosphorus loads as of 2019 were the wastewater and developed sectors. Overall, expected declines from agriculture (-81%), developed (-2%), natural (-29%), stream bed and bank (-39%), and wastewater (-78%) sources were partially counteracted by increases from sources.

For sediment, the largest sources are shoreline and stream bed and bank areas: these two sources changed by 0% and 1%, respectively between 1985 and 2019. Sediment loads from the agriculture sector changed by -71%, whereas sediment load from developed areas changed by 14%.

Overall, changing watershed conditions are expected to result in the agriculture, natural, and wastewater sectors achieving reductions in nitrogen, phosphorus, and sediment loads between 1985 and 2019, whereas the sectors are expected to increase in nitrogen, phosphorus, and sediment loads.

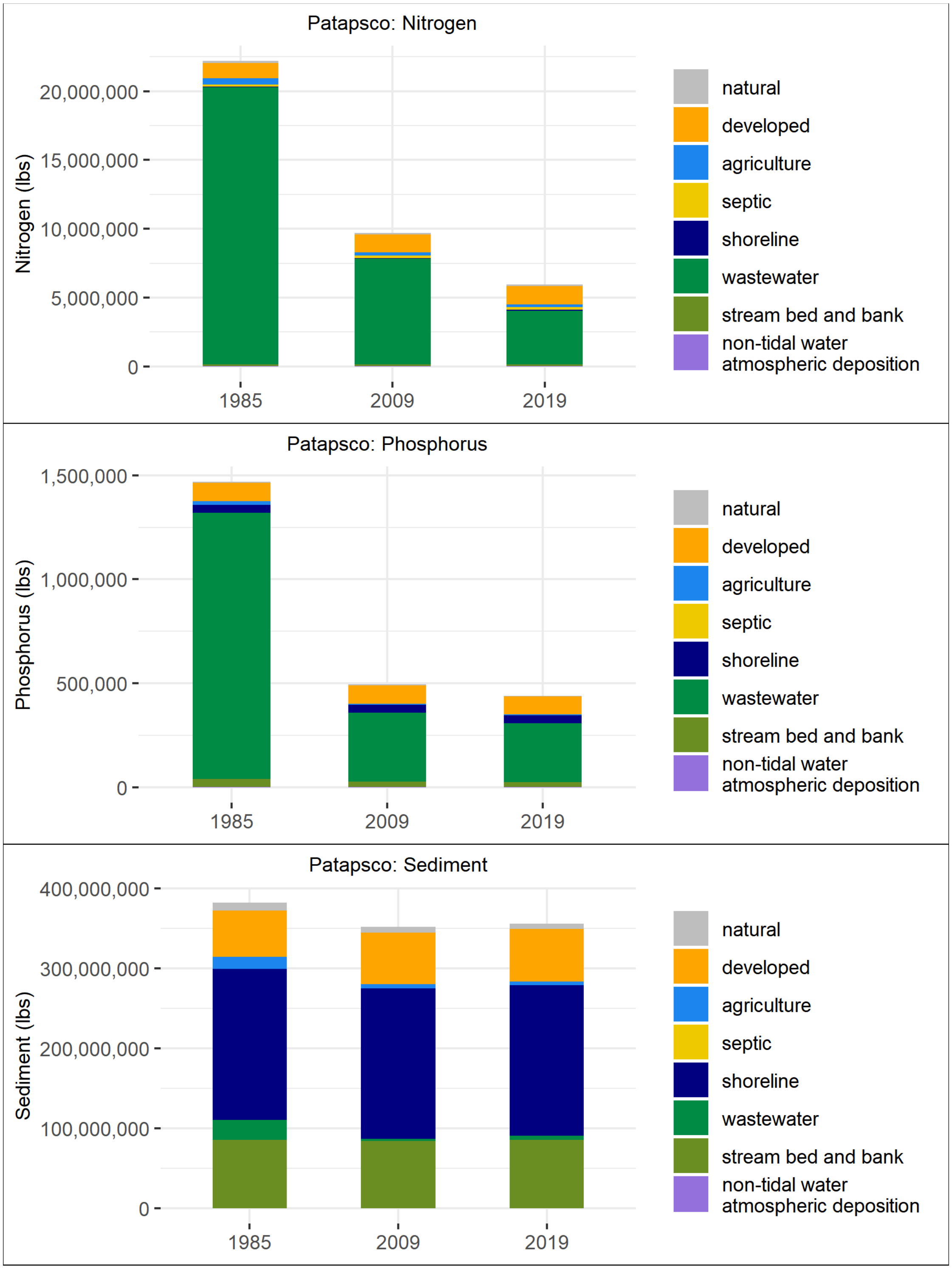

Figure 20. Expected long-term average loads of nitrogen, phosphorus, and sediment from different sources to the tidal Patapsco and Back, as obtained from the Chesapeake Assessment Scenario Tool

(CAST). Data shown are time-average delivered loads over the average hydrology of 1991-2000, once the steady state is reached for the conditions on the ground, as obtained from the 1985, 2009, and 2018 progress (management) scenarios.

5.1.4 Best Management Practices (BMPs) Implementation

Data on reported BMP implementation are available for download from CAST (https://cast.chesapeakebay.net, version CAST-2019). Reported BMP implementations on the ground as of 1985, 2009, and 2019 are compared to planned 2025 implementation levels in Figure 21 for a subset of major BMP groups measured in acres. As of 2019, tillage, cover crops, pasture management, forest buffer and tree planting, stormwater management, agricultural nutrient management, and urban nutrient management were credited for 23, 10, 2.7, 0.1, 36, 68, and 104 thousand acres, respectively. Implementation levels for some practices are already close to achieving their planned 2025 levels: for example, 178% of planned acres for pasture management had been achieved as of 2019. In contrast, about 68% of planned stormwater management implementation had been achieved as of 2019.

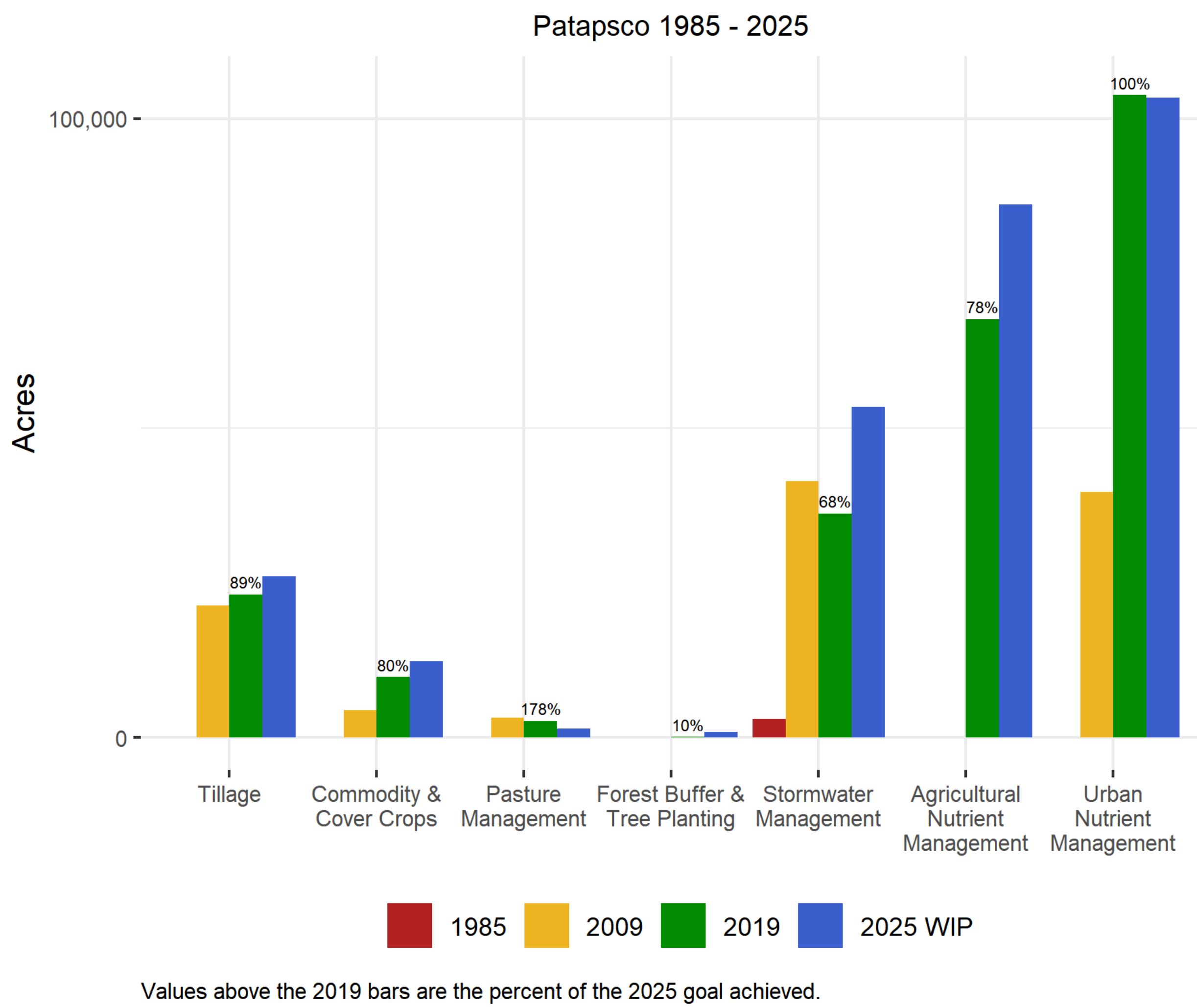

Figure 21. BMP implementation in the Patapsco watershed

Stream restoration and animal waste management system systems are two important BMPs that cannot be compared directly with those above because they are measured in different units. However, progress towards implementation goals can still be documented. Stream restoration (agricultural and urban) had increased from 0 feet in 1985 to 20,994 feet in 2019. Over the same period, animal waste management systems treated 63 animal units in 1985 and 5,295 animal units in 2019 (one animal unit represents 1,000 pounds of live animal). These implementation levels represent 5% and 73% of their planned 2025 implementation levels, respectively.

5.1.5 Flow-Normalized Watershed Nutrient and Sediment Loads

Flow normalization can better reveal temporal trends in river water quality by removing the effect of inter-annual variability in streamflow. Flow-normalized trends help scientists evaluate changes in load resulting from changing sources, delays associated with storage or transport of historical inputs, and/or implemented management actions. Flow-normalized nitrogen, phosphorus, and sediment trends have been reported for the long term (1985-2019) and short term (2009-2018) at nontidal network stations throughout the watershed (Moyer and Langland, 2020) (Table 5). These trends result from variability in nutrient applications, the delivery of nutrients and sediment from the landscape to streams, and from processes that affect in-stream loss or retention of nutrients and sediment.

Table 5. Long-term (1985 - 2018) and short-term trends (2009 - 2018) of flow-normalized total nitrogen (TN), total phosphorus (TP), and suspended sediment (SS) loads for nontidal network monitoring locations in the Patapsco River watershed. A more detailed summary of flow-normalized loads and trends measured at all USGS Chesapeake Bay Nontidal Network stations can be found at https://cbrim.er.usgs.gov/summary.html.

USGS Station ID	USGS Station Name	Trend start water year	Percent change in FN load, through water year 2018		
			TN	TP	SS
01586000	NORTH BRANCH PATAPSCO RIVER AT CEDARHURST, MD	1985	2.2	-	-
		2009	-7.7	-15.4	-7.5
01589300	GWYNNS FALLS AT VILLA NOVA, MD	2009	-11.9	-26.3	-9.8

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

5.2 Tidal Factors

Once pollutants reach tidal waters, a complex set of environmental factors interact with them to affect key habitat indicators like algal biomass, DO concentrations, water clarity, submerged aquatic vegetation (SAV) abundance, and fish populations (Kemp *et al.*, 2005; Testa *et al.*, 2017) (Figure 22). For example, phytoplankton growth depends not just on nitrogen and phosphorus (Fisher *et al.*, 1992; Kemp *et al.*, 2005; Zhang *et al.*, 2021), but also on light and water temperature (Buchanan *et al.*, 2005; Buchanan, 2020). In general, the saline waters of the lower Bay tend to be more transparent than tidal-fresh regions, and waters adjacent to nutrient input points are more affected by these inputs than more distant regions (Keisman *et al.*, 2019; Testa *et al.*, 2019). Dissolved oxygen concentrations are affected by salinity- and temperature-driven stratification of the water column, and conversely by wind-driven mixing, in addition to phytoplankton respiration and decomposition (Scully, 2010; Murphy *et al.*, 2011). When anoxia occurs at the water-sediment interface, nitrogen and phosphorus stored in the sediments can be released through anaerobic chemical reactions (Testa and Kemp, 2012). When low-oxygen water and sediment burial suffocate benthic plant and animal communities, their nutrient consumption and water filtration services are lost. Conversely, when conditions improve enough to support abundant SAV and benthic communities, their functions can sustain and even advance progress towards a healthier ecosystem (Cloern, 1982; Phelps, 1994; Ruhl and Rybicki, 2010; Gurbisz and Kemp, 2014).

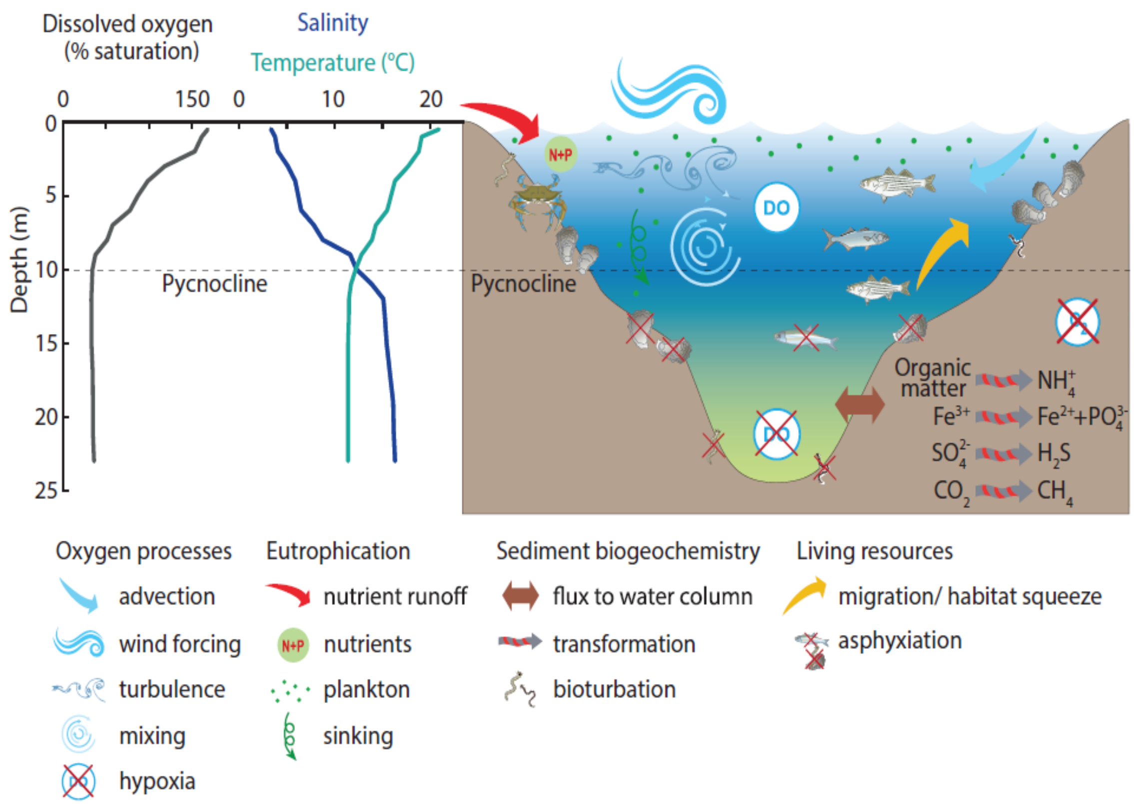

Figure 22. Conceptual diagram illustrating how hypoxia is driven by eutrophication and physical forcing, while affecting sediment biogeochemistry and living resources. From Testa *et al.* (2017).

High nutrient loads relative to tidal river size are indicative of areas that are more susceptible to eutrophication (Bricker *et al.*, 2003; Ferreira *et al.*, 2007). The relationship between watershed area and tidal river size may also be an important indicator of eutrophication potential, however there are competing effects. A large watershed relative to the volume of receiving water would likely correlate with higher nutrient loads, however it would also correlate with a higher flow rate and decreased flushing time (Bricker *et al.*, 2008). Figure 23 is a comparison of watershed area versus estuarine volume for all estuaries and sub-estuaries identified in the CBP monitoring segment scheme. Larger estuaries will contain multiple monitoring segments and, in many cases, sub-estuaries. For example, the Potomac River contains monitoring segments in the tidal fresh, oligohaline, and mesohaline sections of the river as well as the entire Anacostia River and other sub-estuaries. Figures 24 and 25 are comparisons of estimated annual average nitrogen and phosphorus loads, respectively, for the 2018 progress scenario in CAST versus the estuarine volume for the same set of estuaries and sub-estuaries.

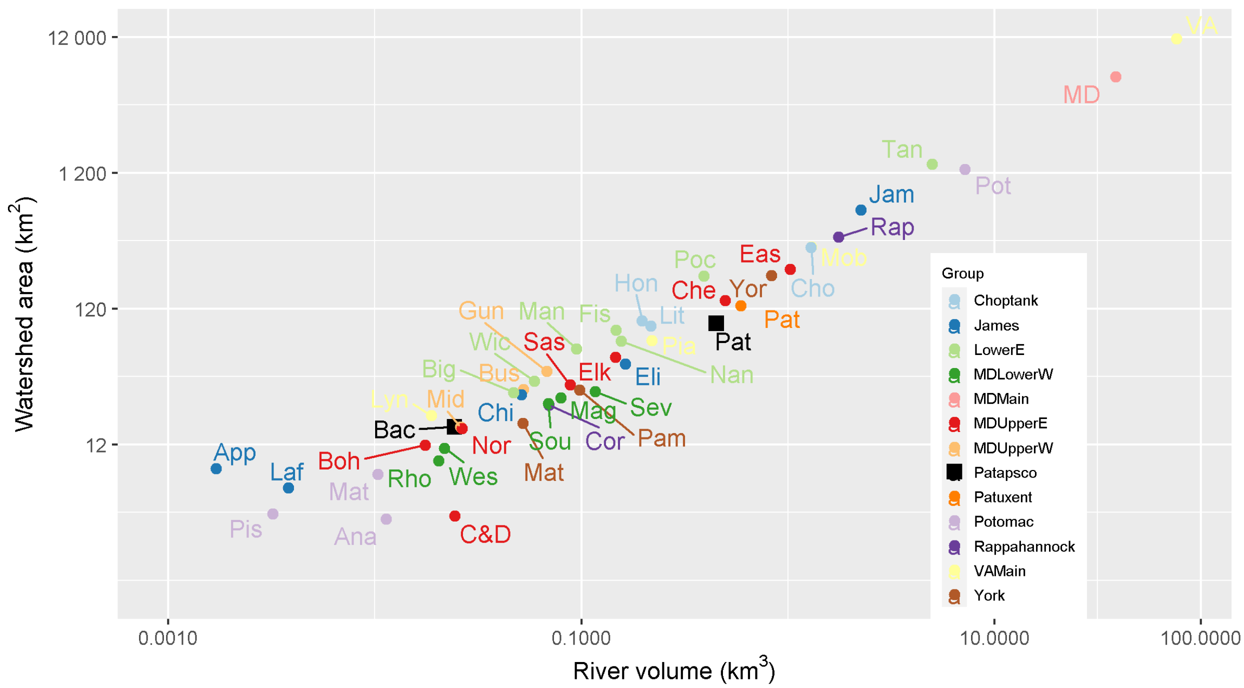

Figure 23. Watershed area vs estuarine volume.

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

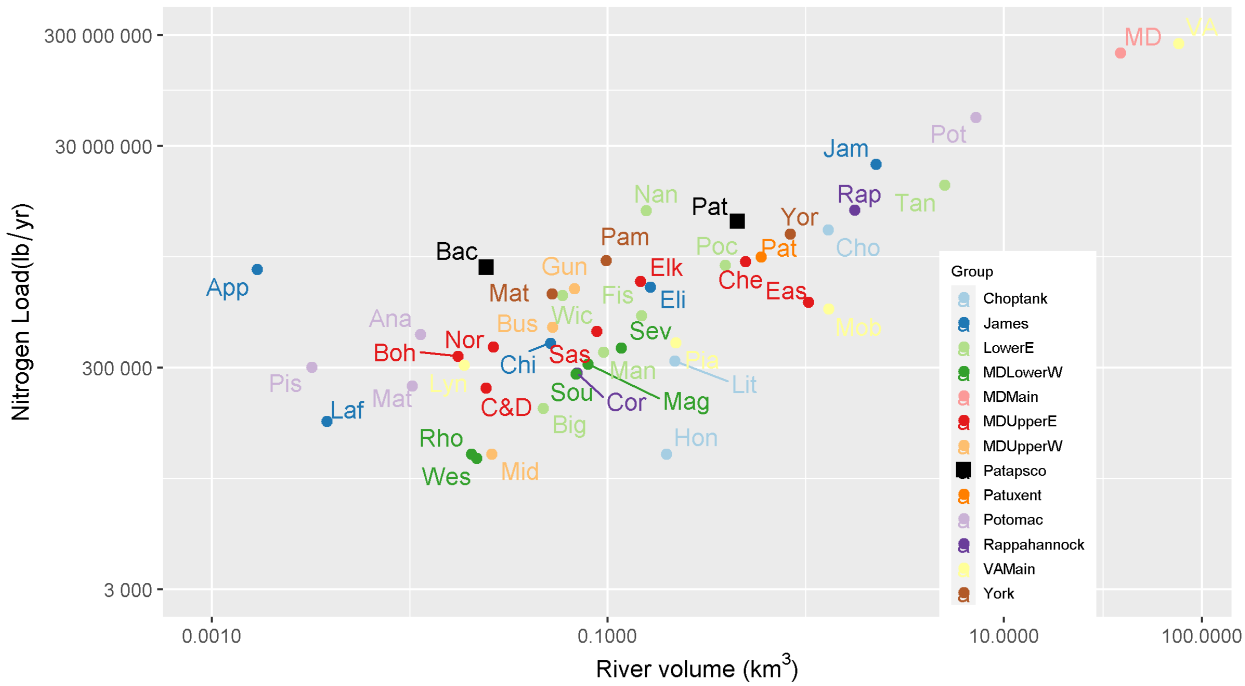

Figure 24. Annual average expected nitrogen loads versus estuarine volume. Nitrogen loads are from the 2018 progress scenarios in CAST (Chesapeake Bay Program, 2020), which is an estimate of nitrogen loads under long-term average hydrology given land use and reported management as of 2018.

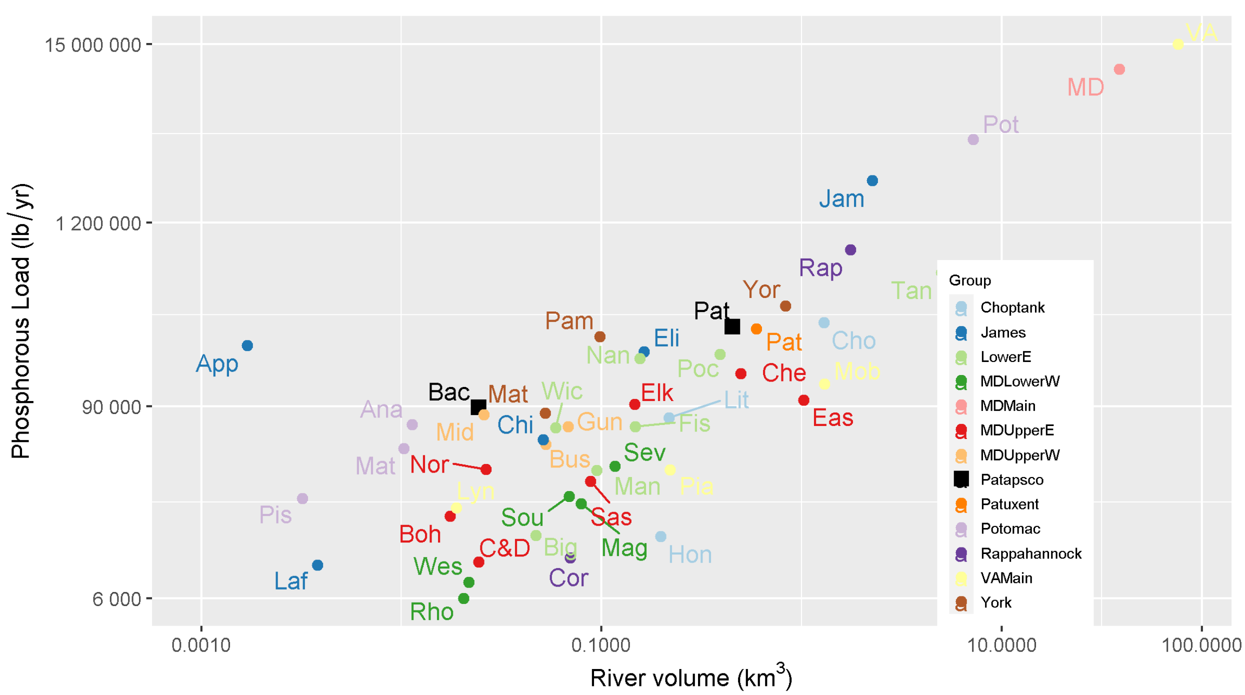

Figure 25. Annual average expected phosphorus loads versus estuarine volume. Phosphorus loads are from the 2018 progress scenarios in CAST (Chesapeake Bay Program, 2020), which is an estimate of

phosphorus loads under long-term average hydrology given land use and reported management as of 2018.

The Patapsco river estuary volume and watershed contain approximately 0.6 and 1% of the total volume and watershed of the Chesapeake Bay. This ranks the James as the 11th largest volume and 11th largest watershed area aggregated tributary in this summary (Figures 23, 24, and 25). The ratios of watershed area, nitrogen loading, and phosphorus loading to estuarine volume are consistent with other estuaries in the Chesapeake system, indicating a moderate level of susceptibility to eutrophication. The smaller tributary within the Patapsco system, Back river follows this trend indicating moderate susceptibility to eutrophication. Back river has a slightly higher phosphorus load relative to estuarine volume. The Patapsco river and Back river both have slightly elevated nitrogen loads relative to estuarine volume.

5.3 Insights on Changes in the Patapsco and Back Rivers

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

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

6. Summary

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

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Appendix

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

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