

James Tributary Summary:
**A summary of trends in tidal water quality and
associated factors, 1985-2021.**

November 2023

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



This tributary summary updates information released in the James Tributary Summary 1985-2018, which can be found here:

<https://www.chesapeakebay.net/who/projects-archive/integrated-trends-analysis-team>.

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1. Purpose and Scope

The James Tributary Summary outlines change over time for a suite of monitored tidal water quality parameters and associated potential drivers of those trends for the period 1985 – 2021 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), surface water temperature (WTEMP), 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 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 increase in rainfall intensity and volume, and biological factors such as phytoplankton biomass and the presence of submerged aquatic vegetation. Continuing to track water quality response and investigating these influencing factors are important steps to understanding water quality patterns and changes in the James River. The intended audiences for this report include, but are not limited to, 1) technical managers within jurisdictions who are looking at tidal water quality data and trying to understand why patterns are occurring, 2) local watershed organizations that are trying to understand these analyses and working to connect them to their local area(s), and 3) federal, state, and academic researchers. Figure 1 presents a conceptual model highlighting these intended audiences. Our goal is for the Tributary Summary documents to be sources of readily available background for change over time in tidal water quality observed with monitoring data. The intended purpose of the Tributary Summary documents is to help answer questions related to water quality, show how landscape factors drive water quality change over time, provide support for management decisions that may alter water quality trends and living resources conditions, and highlight where there may be information or knowledge gaps.

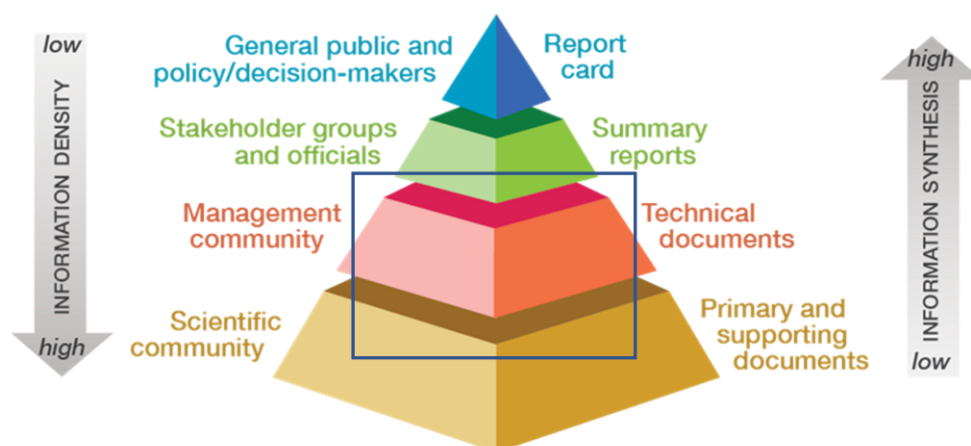


Figure 1: Conceptual model detailing different levels of information density and information synthesis. The intended audiences for the Tributary Summary documents are denoted by the blue box. Figure courtesy of the University of Maryland Center for Environmental Science Integration and Application Network (<https://ian.umces.edu/>).

2. Location

The James River watershed covers approximately 15.7% of the Chesapeake Bay watershed. Its watershed is approximately 25,831 km² (Table 1) and is contained within the state of Virginia (Figure 2).

Tributary Name	Watershed Area km ²
VIRGINIA MAINSTEM	164,197
MARYLAND MAINSTEM	71,967
POTOMAC	36,611
JAMES	25,831
YORK	6,537
RAPPAHANNOCK	6,530
LOWER EASTERN SHORE	4,532
MARYLAND UPPER EASTERN SHORE	2,441
PATUXENT	2,236
CHOPTANK	1,844
PATAPSCO-BACK	1,647
MARYLAND UPPER WESTERN SHORE	1,523
MARYLAND LOWER WESTERN SHORE	439

Table 1. Watershed areas for each of the 13 tributary or tributary groups for which Tributary Summaries have been produced. Each of the tributary summaries can be accessed at the following link:

<https://cast.chesapeakebay.net/Home/TMDLTracking#tributaryRptsSection>.

2.1 Watershed Physiography

The James River watershed stretches across five major physiographic regions, namely, the Valley and Ridge, Blue Ridge, Piedmont, Mesozoic Lowland, and Coastal Plain (Bachman et al., 1998) (Figure 2). The Valley and Ridge physiography covers both carbonate and siliciclastic areas. The Piedmont physiography covers both carbonate and 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.

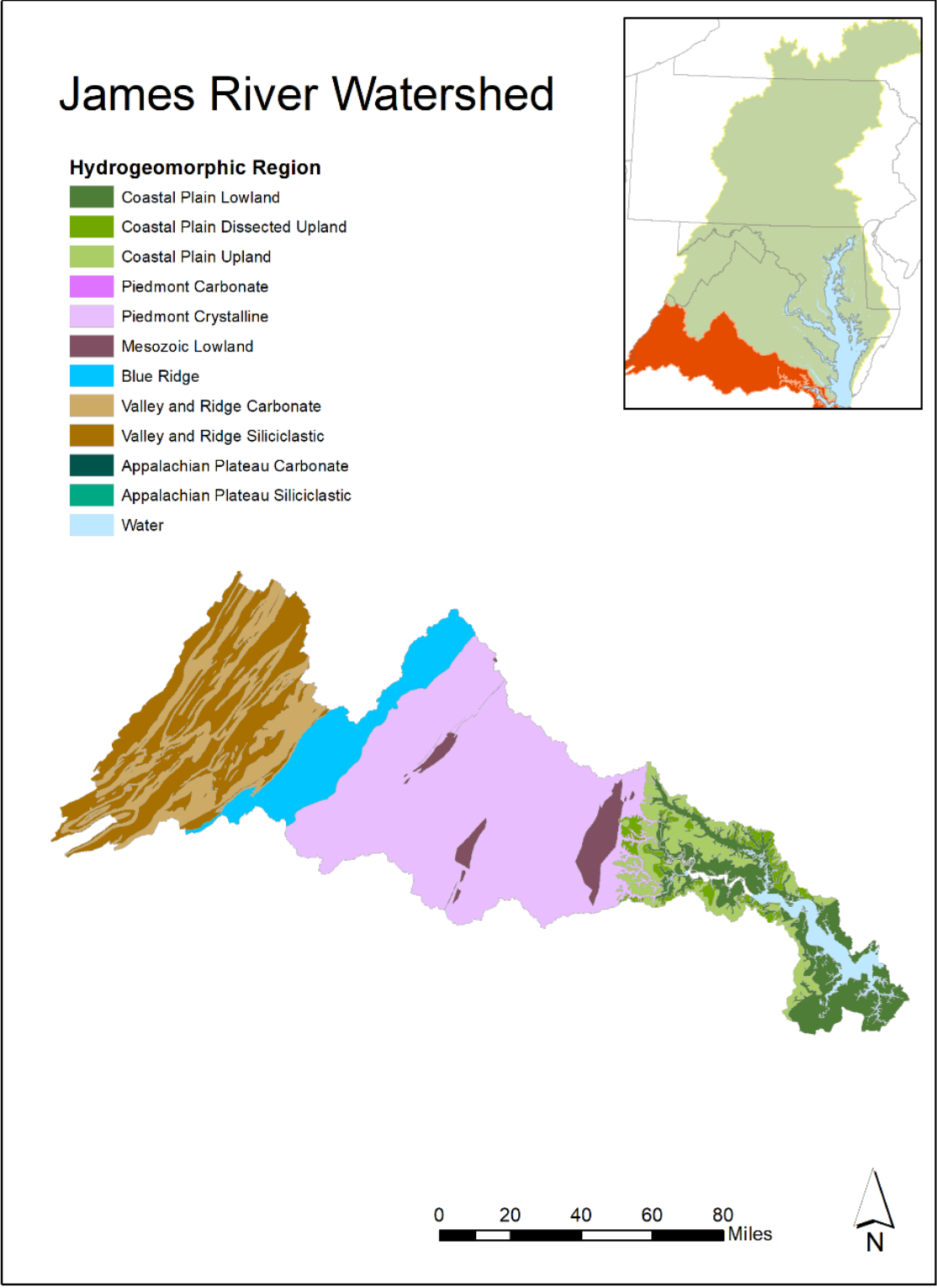


Figure 2. Distribution of physiography in the James River watershed, shown in orange on the inset map. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

2.2 Land Use

Land use in the James watershed is dominated (75%) by natural areas. Urban and suburban land areas have increased by 1,267 km² since 1985, agricultural lands have decreased by 372 km², and natural lands have decreased by 885 km². Correspondingly, the proportion of urban land in this watershed has increased from 7% in 1985 to 12% in 2022 (Figure 3).

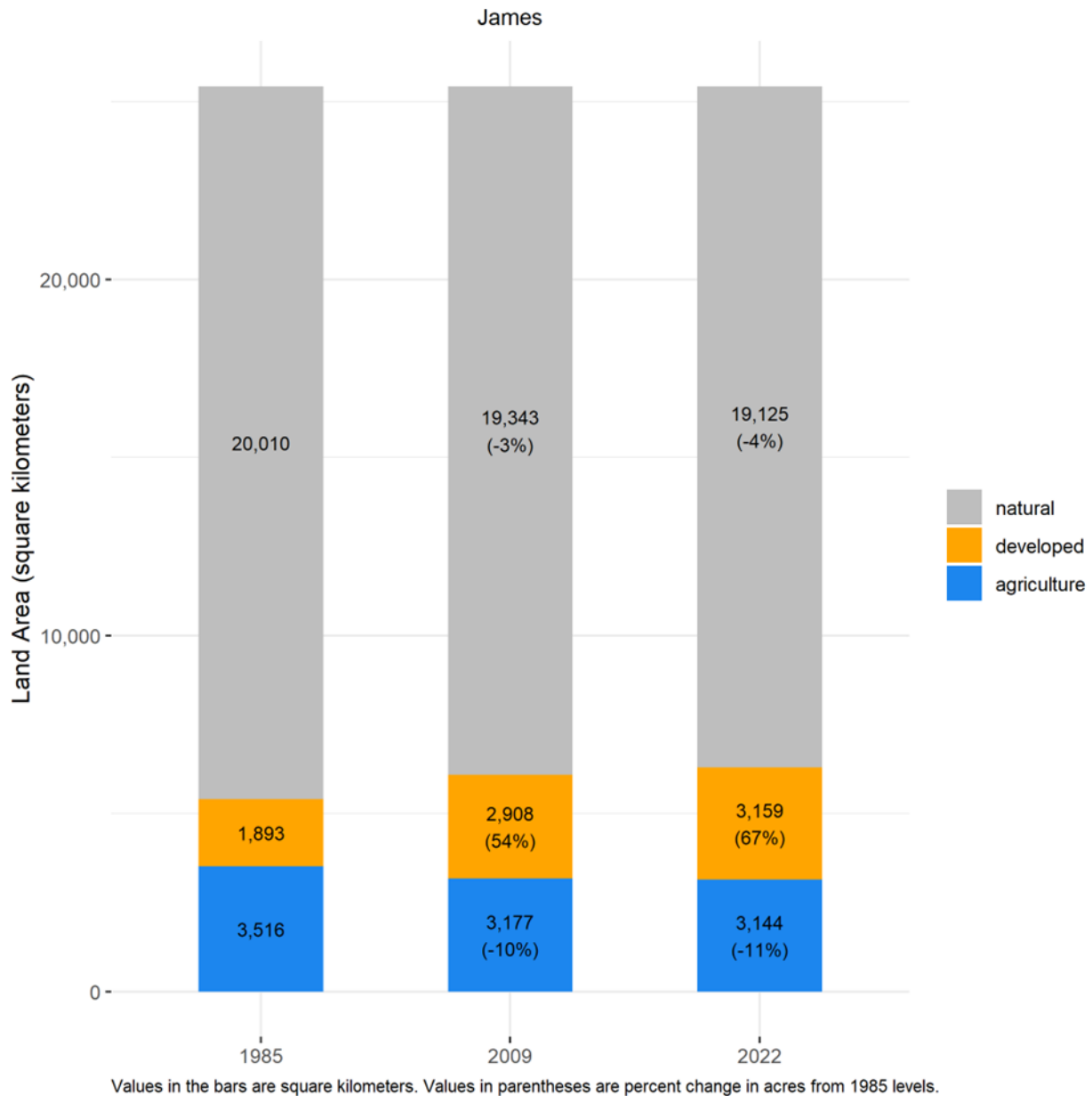


Figure 3. Distribution of land uses in the James watershed. Percentages are the percent change from 1985 for each source sector.

In general, developed lands in 2001 were more concentrated within towns and major metropolitan areas. Since 2001, developed and semi-developed lands have expanded around these urban areas, as

well as extending into previously undeveloped regions. This is demonstrated in Figure 4, which uses impervious surface coverage as a proxy for developed lands (Arnold and Gibbons, 1996). The effects 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 5.1.3.

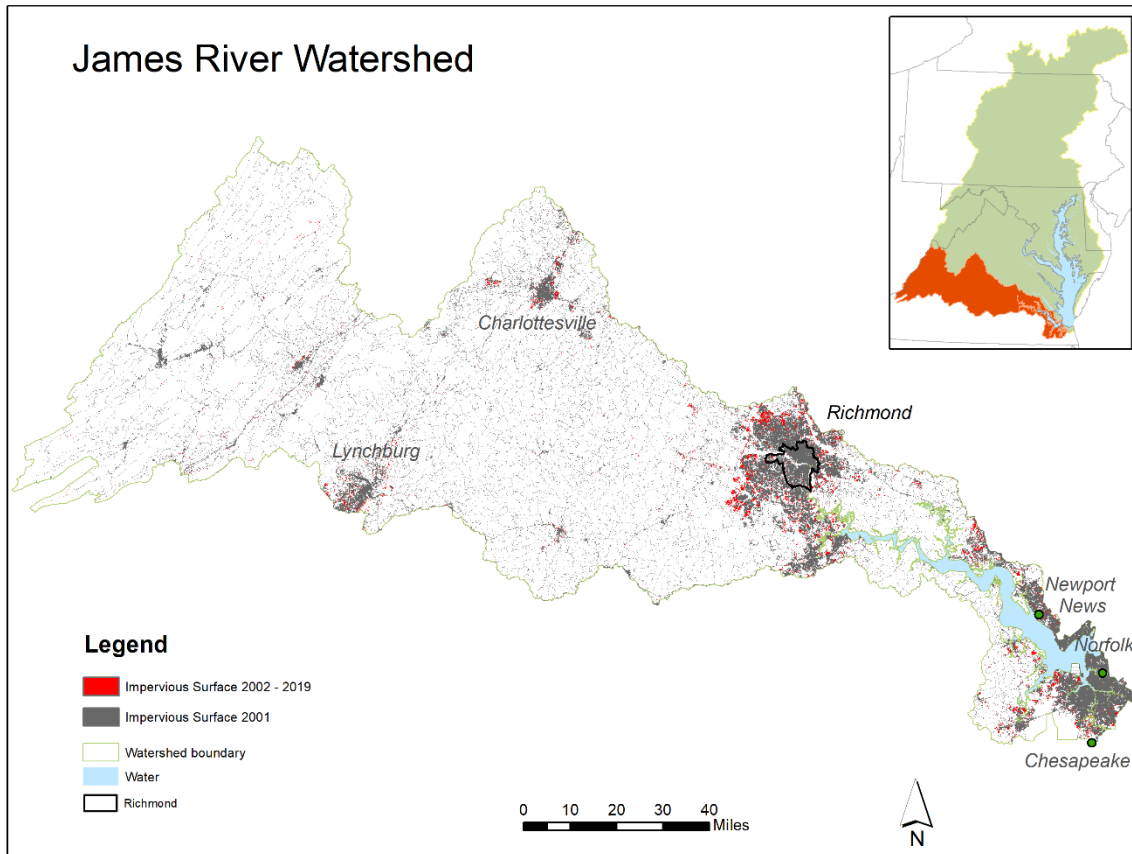


Figure 4. Distribution of impervious surface coverage in the James River watershed, shown in orange on the insert map. Derived from the U.S. Geological Survey (USGS) National Land Cover Database (2019). Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

2.3 Tidal Waters and Stations

For the purposes of water quality standards assessment and reporting, the tidal portion of the James Rivers is split into the following segments (U.S. Environmental Protection Agency, 2004): Tidal Fresh (JMSTF1, JMSTF2), Oligohaline (JMSOH), Mesohaline (JMSMH) and Polyhaline (JMSPH). The Tidal Fresh Appomattox River (APPTF) and Oligohaline Chickahominy (CHKOH) are also included in this group, along with segments in the Elizabeth River and its branches (EBEMH, ELIPH, LAFMH, SBEMH, and WBEMH) (Figure 5).

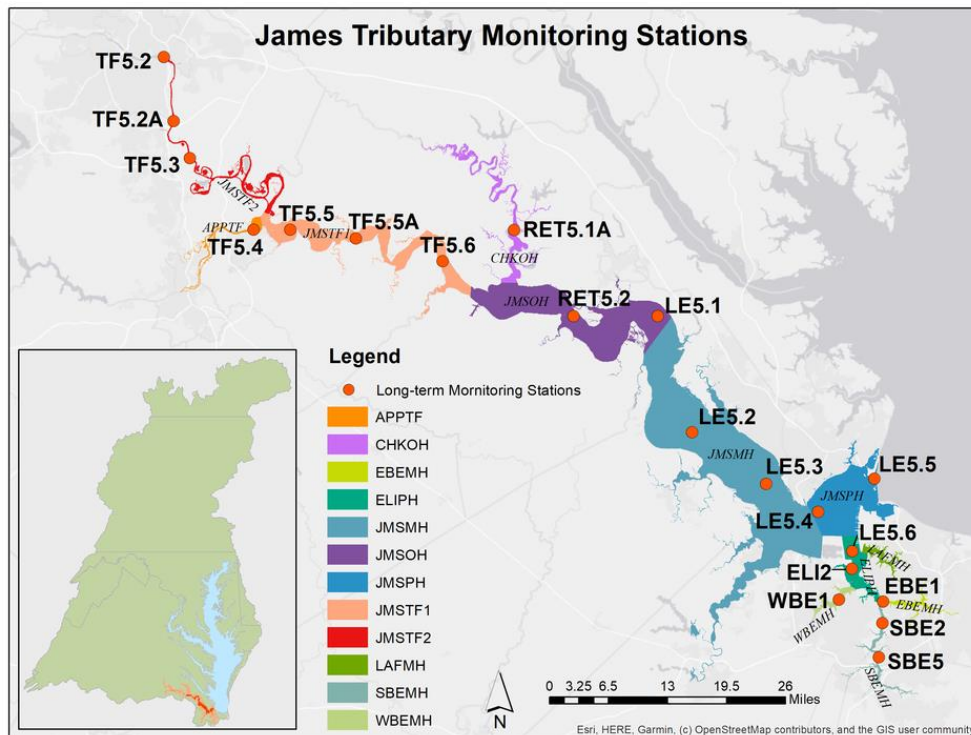


Figure 5. Map of tidal James River segments and long-term monitoring stations. Map of tidal James River segments and long-term monitoring stations. Base map from Esri and its licensors, copyright 2023, HERE, Garmin, GIS User Community, and OpenStreetMap and its contributors (see <https://www.openstreetmap.org/copyright>). World Geodetic System 1984. Any use of trade, firm, logos, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Long-term trends in water quality are analyzed by Virginia Department of Environmental Quality (VA DEQ) at 20 stations stretching from the Appomattox River and Tidal Fresh James to the mouth of the James River, including the Elizabeth River system, flowing into Chesapeake Bay (Figure 5). Water quality data at these stations are also used to assess attainment of DO and chlorophyll *a* water quality criteria (mainstem James stations only). All tidal water quality data analyzed for this summary are available from the Chesapeake Bay Program Data Hub (Chesapeake Bay Program, 2018). Other extensive monitoring has been done in the James and Elizabeth Rivers, especially to analyze the spatial and temporal dynamics of chlorophyll *a*. For additional information please see the Virginia Institute of Marine Science (VIMS) Virginia Estuarine and Coastal Observatory System (VECOS), which serves up much of the extensive monitoring data that has been collected in the James, (Virginia Institute of Marine Science (VIMS), 2023). Those observations are not included in subsequent trend graphics, as the focus here is primarily on the long-term monitoring at fixed stations.

3. Tidal Water Quality Status

Long-term water quality monitoring in the James River is necessary to evaluate the trends needed to measure progress towards the Chesapeake Bay environmental management goals. Multiple water quality standards were developed for the Chesapeake Bay tidal waters to protect aquatic living resources (U.S. Environmental Protection Agency, 2003; Tango and Batiuk, 2013). These standards include specific criteria for DO, chlorophyll a, and water clarity/underwater bay grasses. For the purposes of this report, a record of the evaluation results indicating whether different segments of this system have attained DO criteria over time (Zhang et al., 2018a; Zhang et al., 2018b; Hernandez Cordero et al., 2020) are shown below (Figure 6). Different aquatic organisms have different DO requirements. The different designated use zones (Open Water, Deep Water and Deep Channel) reflect the different needs of the species that inhabit different parts of the water column. The DO criteria results provide important context for understanding water quality trends and their underlying drivers. More specifically, trends in the water quality parameters summarized in this report directly affect environmental management goals implemented by interested stakeholders within the watershed. For more information on water quality standards, criteria, and standards attainment, visit the CBP's "Chesapeake Progress" website at www.chesapeakeprogress.com.

Attainment deficit is an approach used to document whether a particular criterion is met in a certain period, and if not, how far the segment is from meeting it. If the attainment deficit was zero, it means the criterion was fully met; if it was a negative number, it indicates how far the segment and designated use was from meeting the criterion during that period. The graphics in Figure 6 show that the Open Water (OW) criterion was at or near zero from the start of monitoring to the most recent assessment period covered by this report (2019-2021) in five segments, namely, APPTF, JMSMH, JMSOH, JMSPH, and JMSTF2. By contrast, the other segments showed a high degree of variability with four segments (CHKOH, ELIPH, JMSTF1, LAFMH) attaining the criterion in some assessment periods and three segments (EBEMH, SBEMH, WBEMH) never achieving that status. The Deep Water (DW) criterion was applicable to only one segment, i.e., SBEMH, which showed large deficits in the early periods (about -30%) and more frequent occurrences of full attainment in the recent periods. Mann-Kendall trend results indicated two statistically significant trends, i.e., long-term improvements in JMSTF1 OW-DO and SBEMH DW-DO (Figure 6).

Dissolved Oxygen Criterion Attainment Deficit
 (0% = complete attainment; -100% = complete non-attainment)

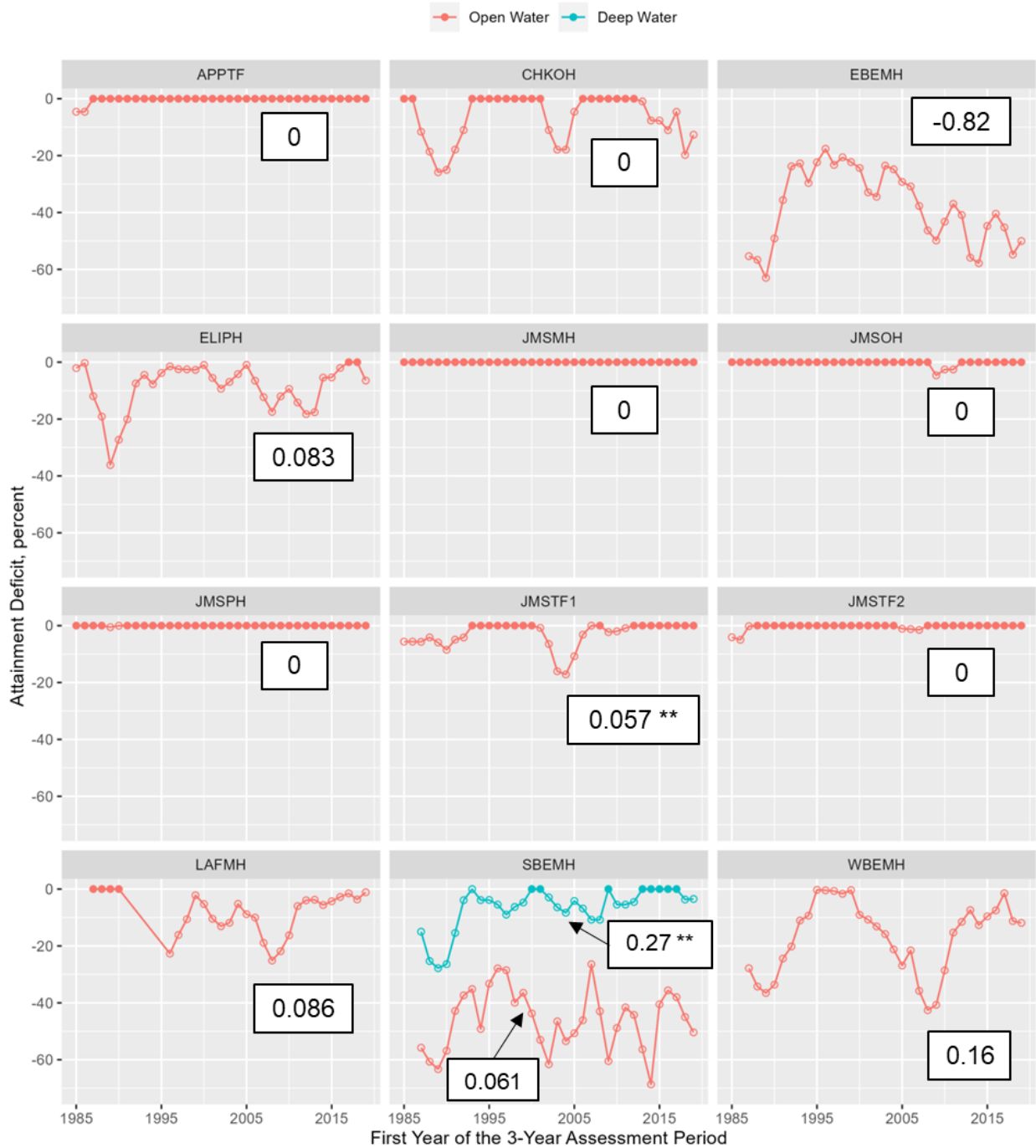


Figure 6. Attainment deficit for Open Water (30-day mean; June-September) and Deep Water (30-day mean; June-September) DO criteria for three-year assessment periods from the start of monitoring through the current (2019-2021) assessment period. A value of 0% indicates full attainment for a given criterion while negative values indicate percent non-attainment (deficit) for the segment and criterion being plotted. Numbers associated with a given line are the Sen Slope estimates. Trends significant at $p < 0.05$ are indicated by **.

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 2019-2021 attainment status for the OW summer and DW summer DO criteria shown in Figure 6 are overlain with the 1985-2021 change in summer surface DO concentration and the 1985-2021 change in bottom summer DO concentrations, respectively (Figure 7). 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. Notably the DO concentrations both in the surface and the bottom are improving at most of the Elizabeth River region stations, suggesting progress even in segments not meeting the DW and OW summer 30-day mean DO criteria.

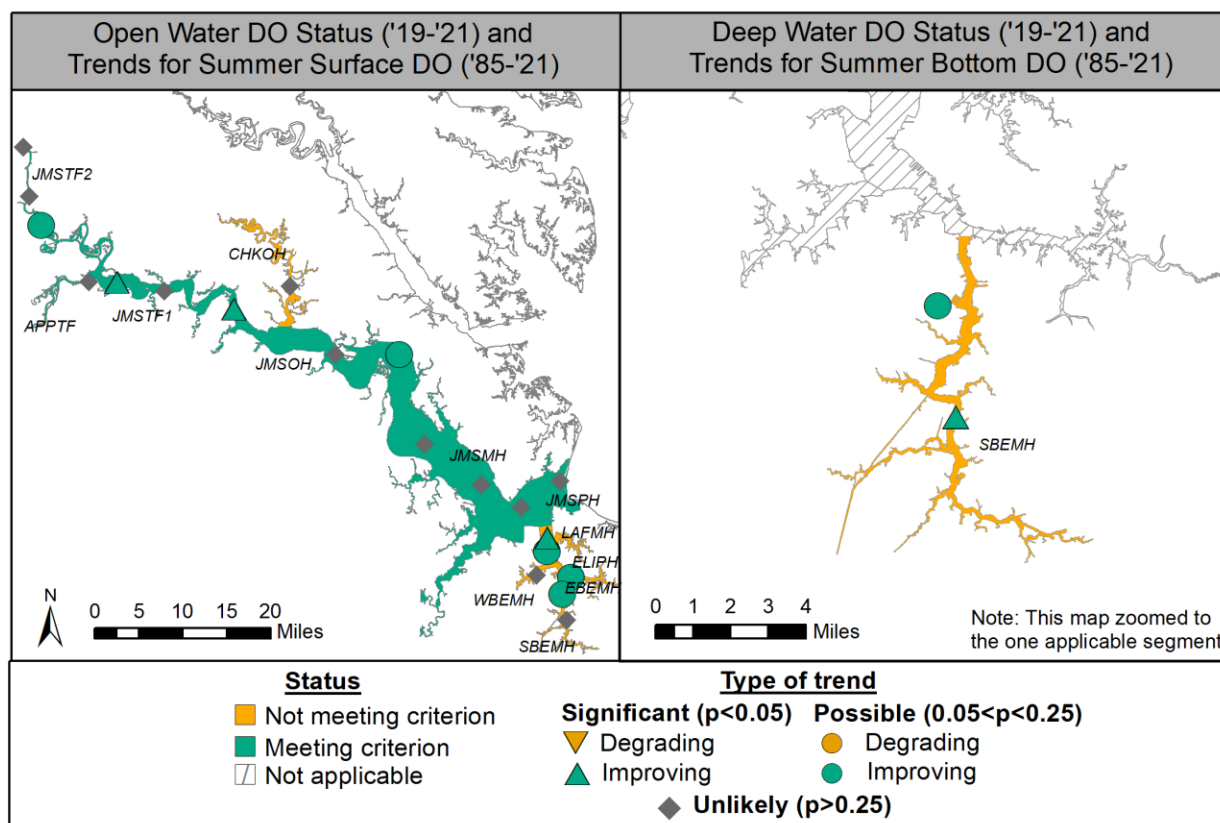


Figure 7. Pass-fail dissolved oxygen (DO) criterion status for 30-day Open Water (OW) summer DO and Deep Water (DW) summer DO designated uses in James River and Elizabeth River segments along with long-term trends in DO concentrations. Note that DW is only applicable in the SBEMH segment of the Elizabeth River, so it is the only segment shown in the right panel. 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 20 tidal stations labeled in Figure 5. For more details on the GAM implementation that is applied each year

by VA DEQ and Old Dominion University for these stations in collaboration with the Chesapeake Bay Program and Maryland analysts, see Murphy et al. (2019).

Results shown below in each set of maps (e.g., Figure 8) include those generated using two different GAM fits to each station-parameter combination. The first approach involves fitting a GAM to the raw observations to generate a mean estimate of the concentrations over time, as observed in the estuary. The second approach involves including monitored river flow or *in situ* salinity (as an aggregated measure of multiple river flows) in the GAM to explain some of the variation in the water quality parameter. From the results of this second approach, it is possible to estimate the “flow-adjusted” change over time, which gives a mean estimate of what the water quality parameter trend would have been if river flow had been average over the period of record. Note that depending on the location in the James, Appomattox, Chickahominy or Elizabeth Rivers, sometimes gaged river flow is used for this adjustment and sometimes salinity is used, but we refer to all of these results as “flow-adjusted” for simplicity.

To determine if there has been a change over time (i.e., a trend) at a particular station for a given parameter, we compute a percent change between the estimates at the 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 9) 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 TN concentrations have improved at all James River and tributary stations over the long-term, using both trends on concentration data alone and adjusting for flow (Figure 8). Over the short-term, more than half of the stations switched to possible trends or no trend, with one possible increase.

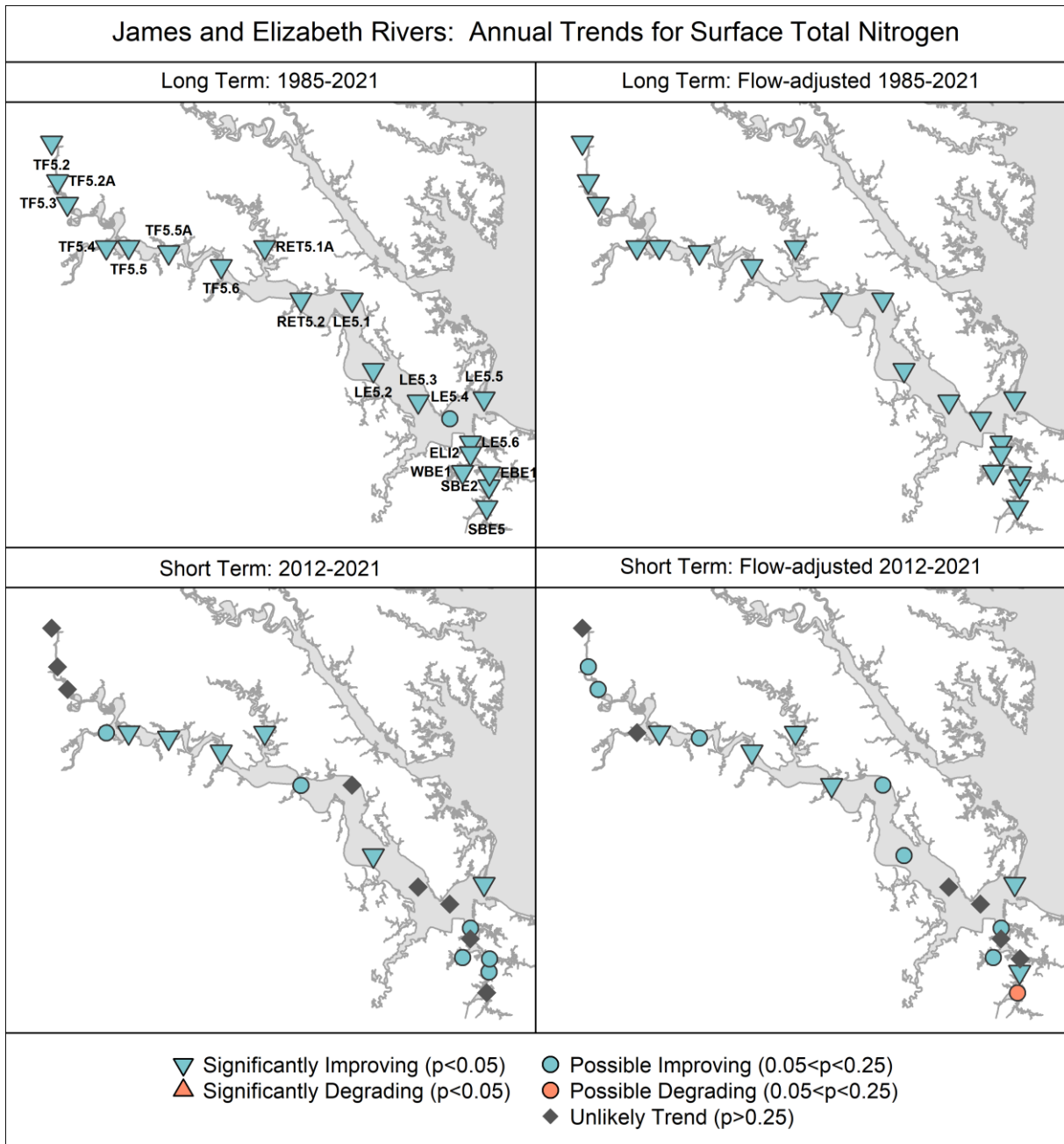


Figure 8. Surface TN trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Decreasing trends are evident in both the data and the non-flow adjusted mean annual GAM estimates presented in Figure 9. The magnitude of the TN concentrations is highest at the lower tidal fresh James and mesohaline Elizabeth branch stations and decreases with distance from those stations. Those stations with the highest initial concentrations also have some of the strongest decreases in TN over time. For TN at most of the VA tributary stations, the records before 1994 contain too many values below the detection limits to accurately model the patterns, therefore, many of the time series start in 1994. All stations in the Elizabeth River began sampling in 1989 (Murphy et al., 2019).

Annual Surface Total Nitrogen Data and Average Predictions

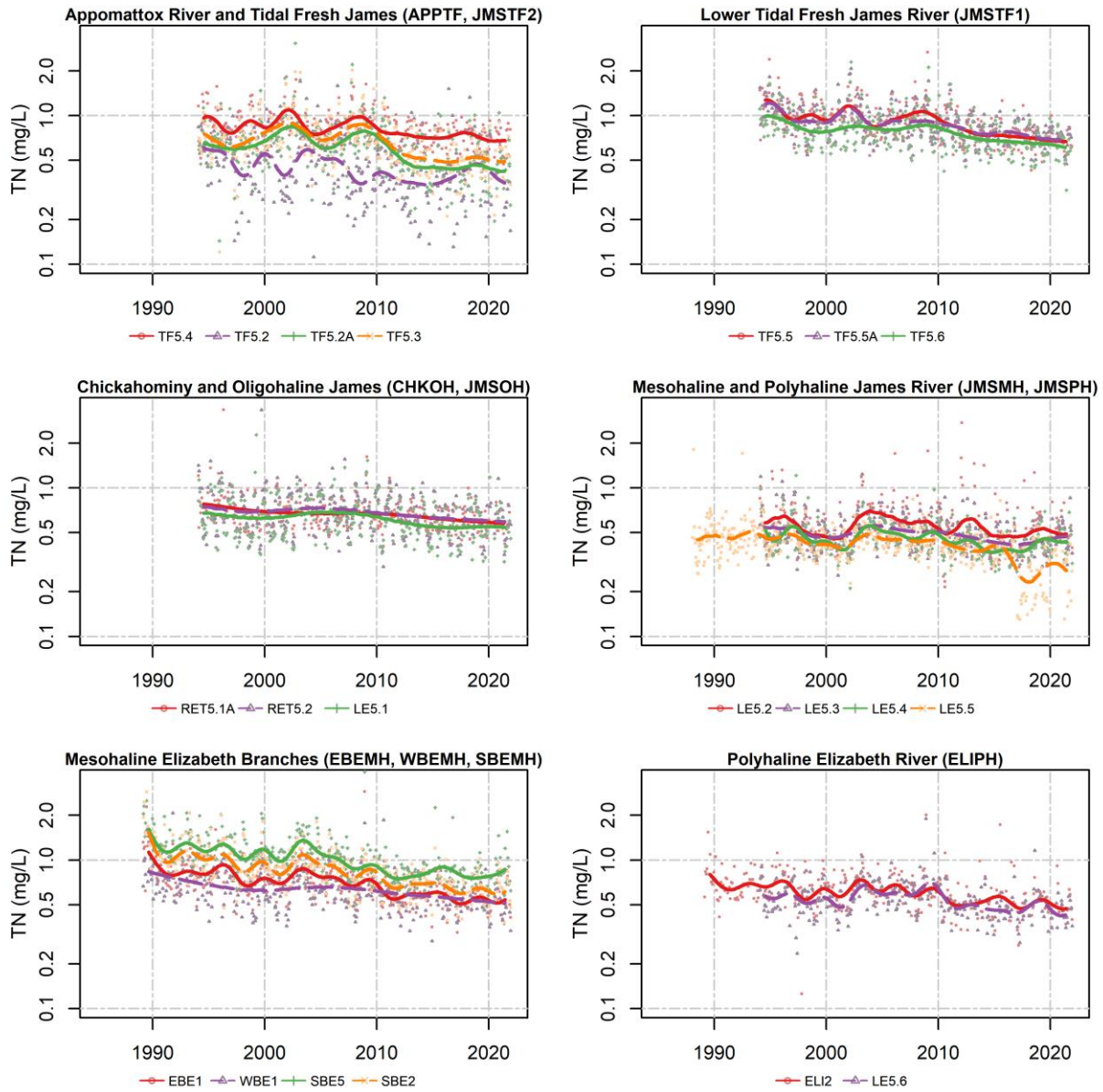


Figure 9. Surface TN data (dots) and average long-term pattern generated from non-flow-adjusted GAMs. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

4.2 Surface Total Phosphorus

Annual TP is also improving at almost all James River and tributary stations over the long-term, using both trends on concentration data alone and adjusting for flow (Figure 10). Over the short-term, the pattern is very different, with almost no short-term trends. Only the station nearest the Chesapeake Bay (LE5.5) has a short-term improving trend.

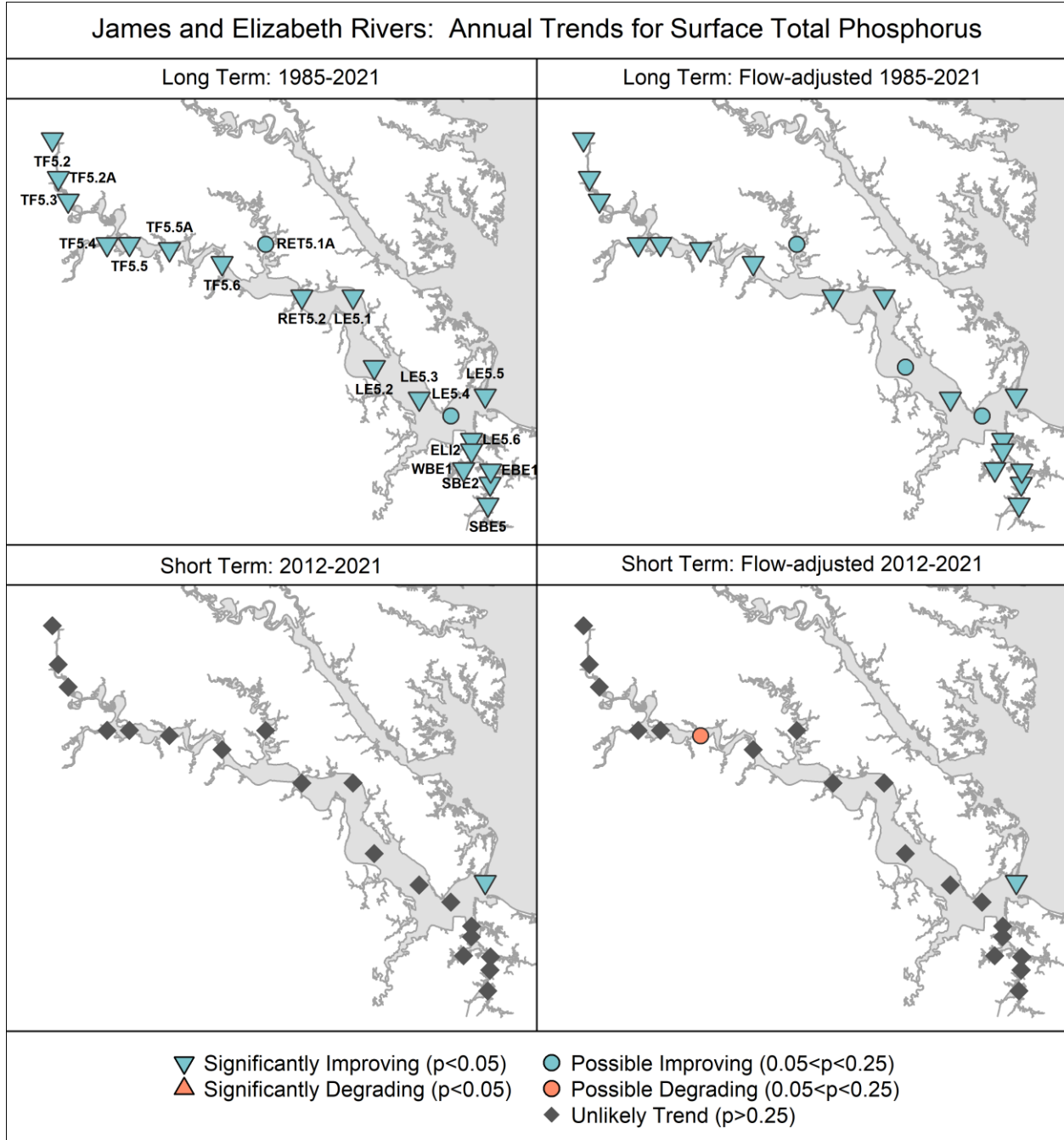


Figure 10. Surface TP trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Long-term decreases are very clear in the Appomattox and tidal fresh James station data and the mean annual GAM estimates presented in Figure 11 (top two panels). Long-term decreases are also apparent at the other stations (bottom four panels), although the magnitude of the decrease is less. At every station, the decreases have leveled out in the second half of the record, resulting in the lack of short-term trends (Figure 10).

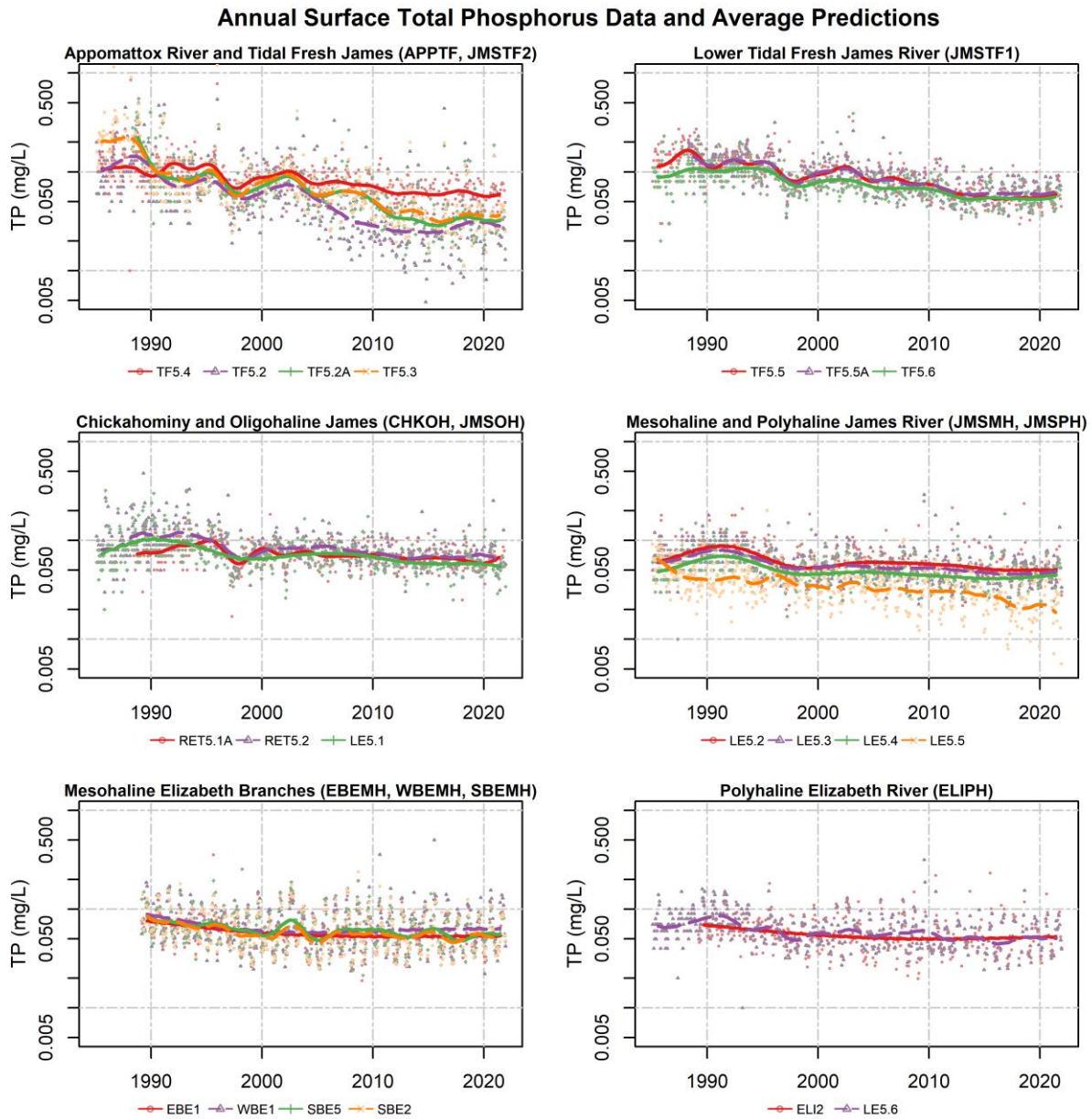


Figure 11. Surface TP data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

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). Long-term spring trends are improving at about half of the James River and tributary stations, with mostly no trend at the remaining stations. Improvements are clustered in the tidal fresh and polyhaline/Elizabeth River regions. Over the short-term, some of the Elizabeth River and polyhaline James River improvements persist, but the lower tidal fresh and oligohaline stations show some possible degradation when flow is adjusted.

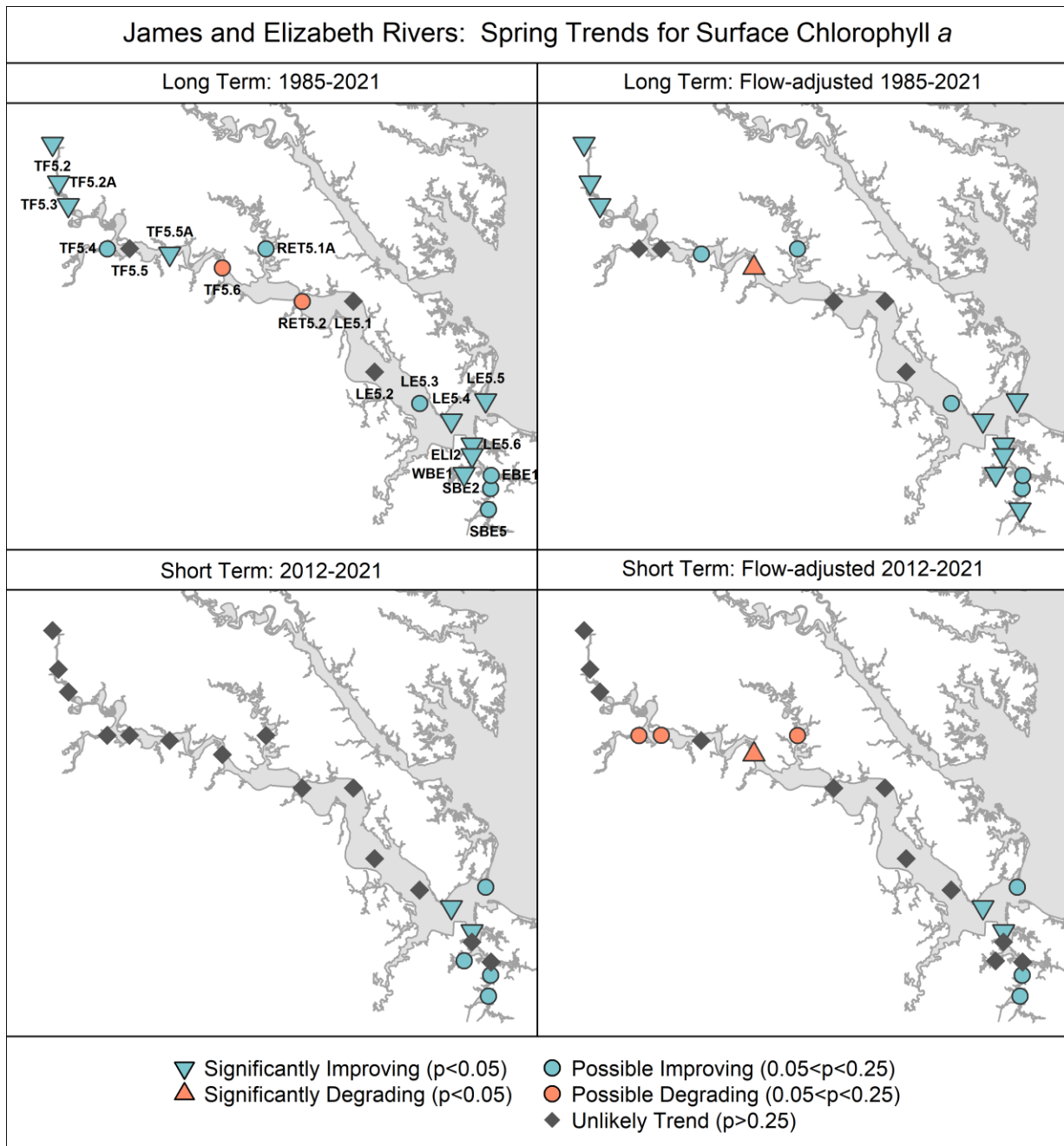


Figure 12. Surface spring (March-May) chlorophyll *a* trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

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 13). Notably, in all graph panels, it is clear that very high spring chlorophyll *a* concentrations that were measured in the 1980s and 1990s have not been observed in recent decades. In the last decade, leveling out of trends or slight increases are apparent in the James River stations while the Elizabeth River trends have decreased continuously through the record.

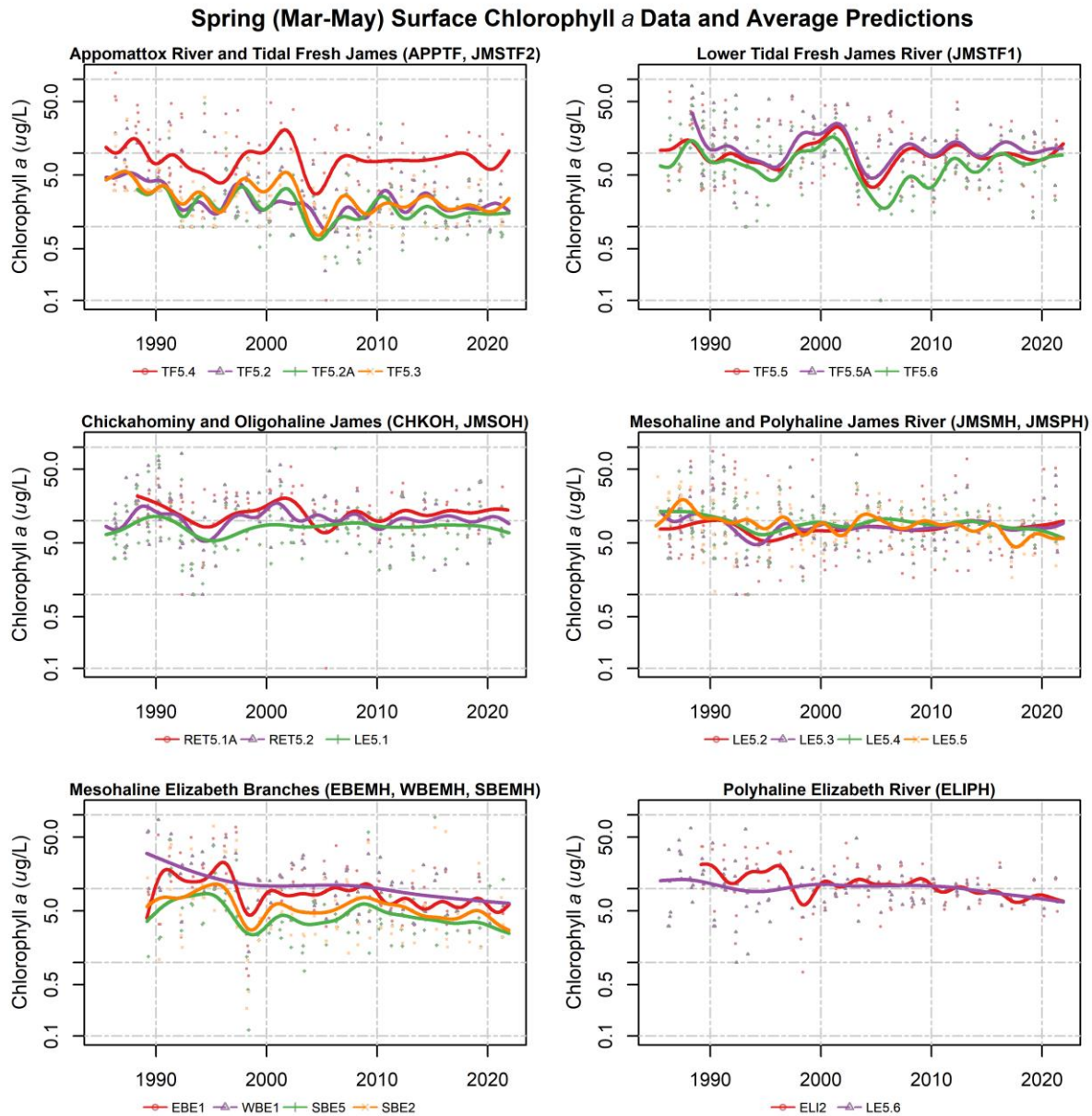


Figure 13. Surface spring chlorophyll *a* data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent March-May data corresponding to the monitoring station

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)

Long-term trends in summer chlorophyll *a* (Figure 14) differ from spring long-term trends (Figure 12) at some of the mesohaline and polyhaline stations. In the summer, there is a mixture of long-term trends in the Elizabeth River and the lower James mesohaline and polyhaline stations, while they were mostly improving in the spring. Other patterns are more similar between the seasons including long-term improvements at tidal fresh stations and the spatial distribution of short-term trends.

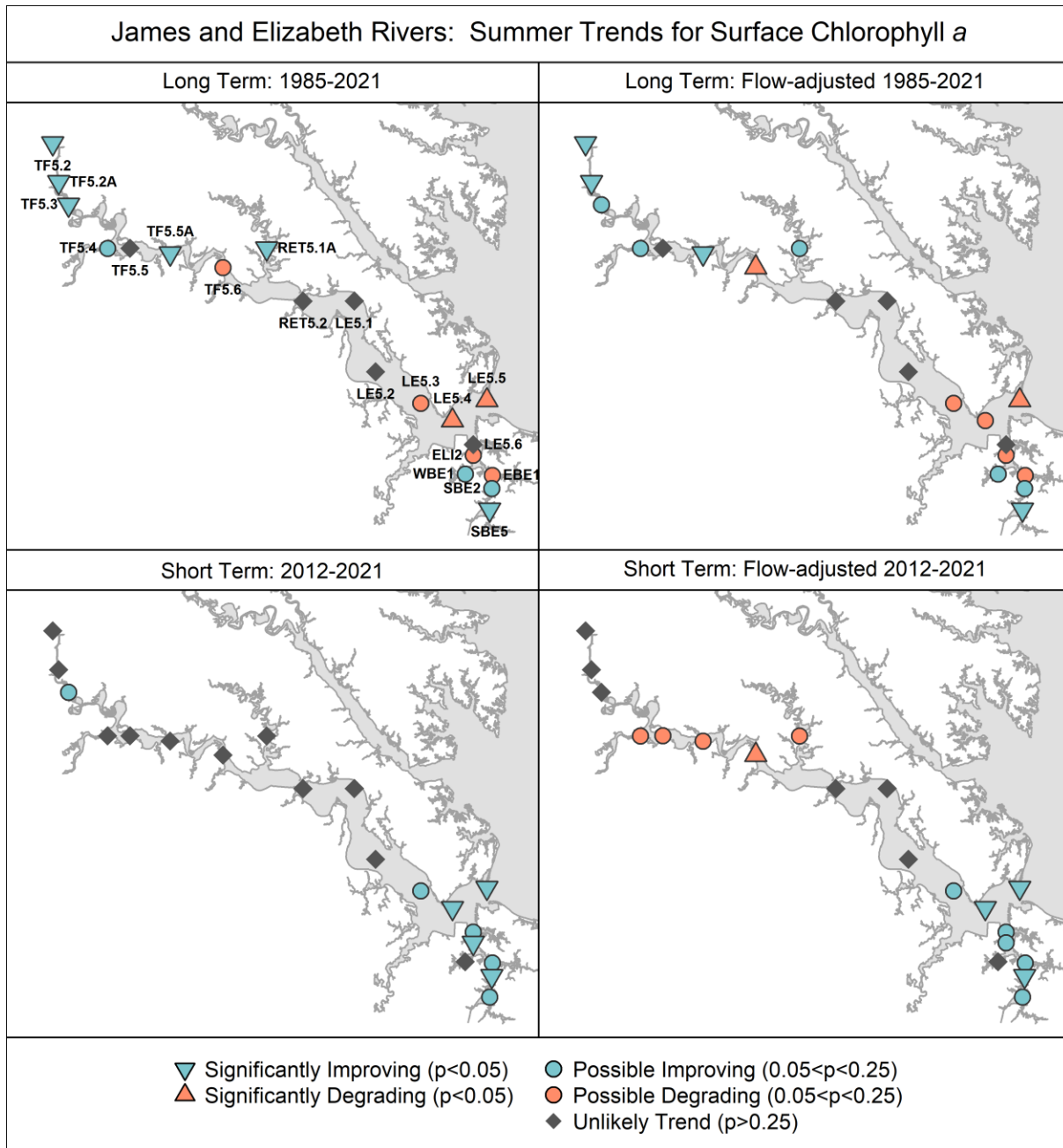


Figure 14. Surface summer (July-September) chlorophyll *a* trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Like the chlorophyll *a* patterns in the spring (Figure 13), summer chlorophyll *a* data and long-term patterns are highly variable, especially at the tidal fresh stations. Slight increases are observed in several of the mesohaline and polyhaline stations' data, resulting in the trend differences between the summer and spring (Figures 14 and 12).

Summer (July-Sept) Surface Chlorophyll *a* Data and Average Predictions

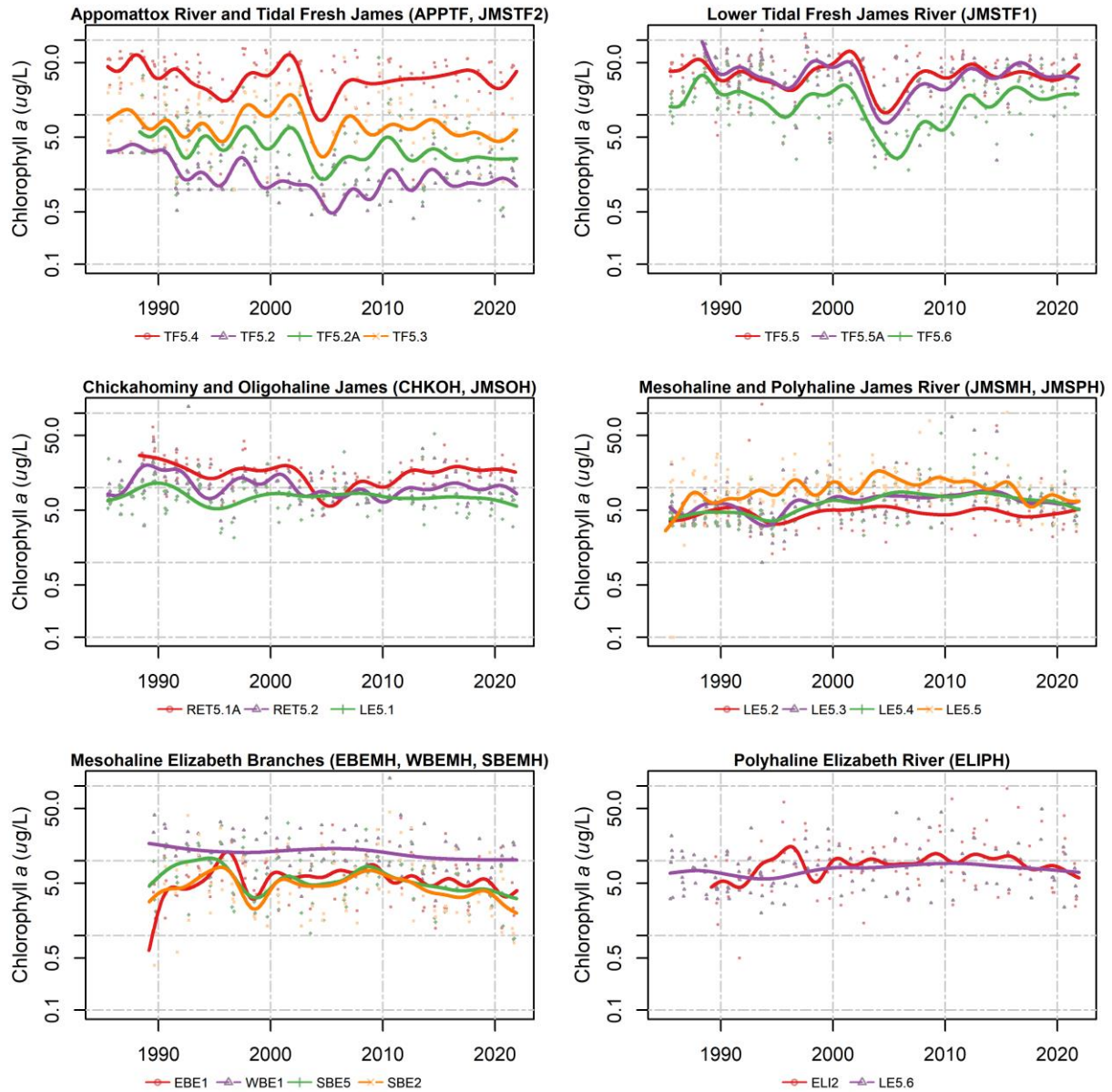


Figure 15. Surface summer chlorophyll *a* data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent July-September data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean summer GAM estimates for the noted monitoring stations.

4.5 Secchi Disk Depth

Trends in Secchi disk depth, a measure of visibility through the water column, are mixed, with half of the stations showing no trend over the long-term, and different stations having improving or degrading trends for the two time periods. Short-term significant and possible improvements reach from the Chickahominy River (RET5.1A) to the Elizabeth River stations for the short-term flow-adjusted analysis. Total Suspended Solids (TSS) data provide another way of examining factors that impact water clarity. Trends in TSS from 1999 forward are presented in the appendix and, unlike Secchi, show improvements at almost all James River tidal stations during this time period.

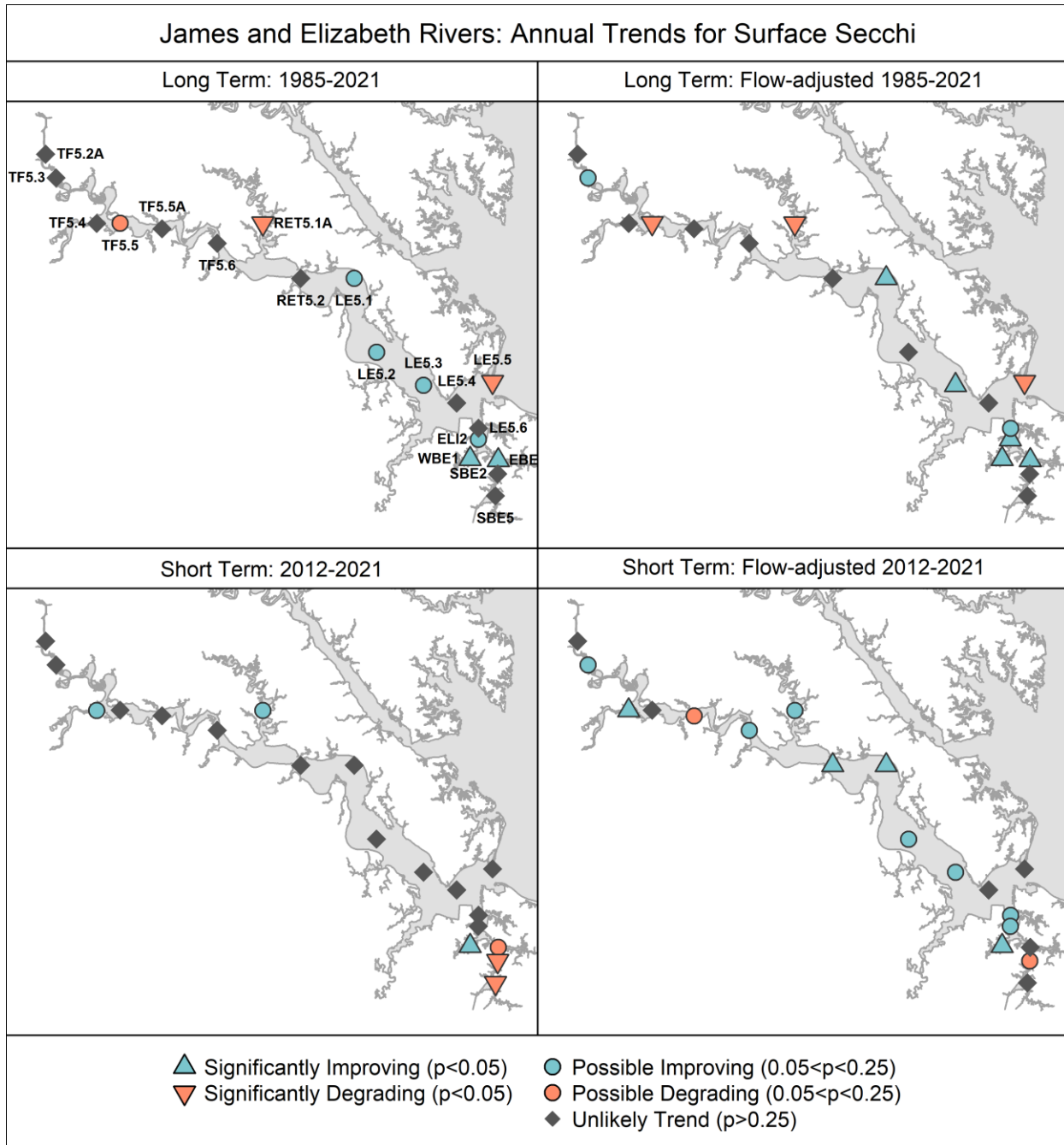


Figure 16. Annual Secchi depth trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Shallow Secchi depths make it hard to decipher trends at these stations in the data values and mean annual GAM estimates (Figure 17). Year-to-year fluctuations and some slight increases near the end of the record are consistent with the mixed trends observed in Figure 16.

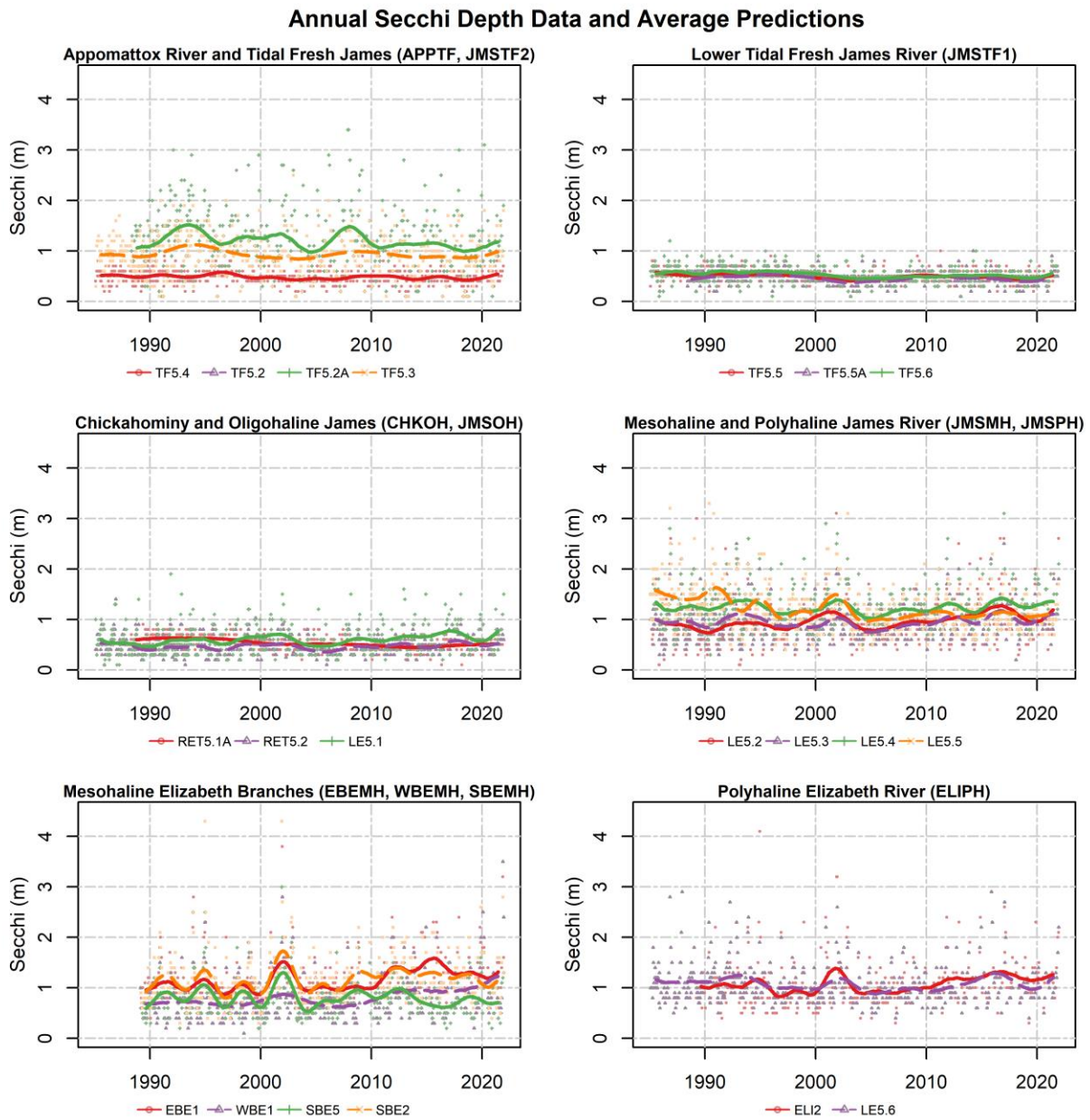


Figure 17. Annual Secchi depth data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

4.6 Summer Bottom Dissolved Oxygen (June-September)

James River and tributary summer bottom oxygen trends are fairly mixed, with more than half of the stations showing no-trend over the long and short-term (Figure 18).

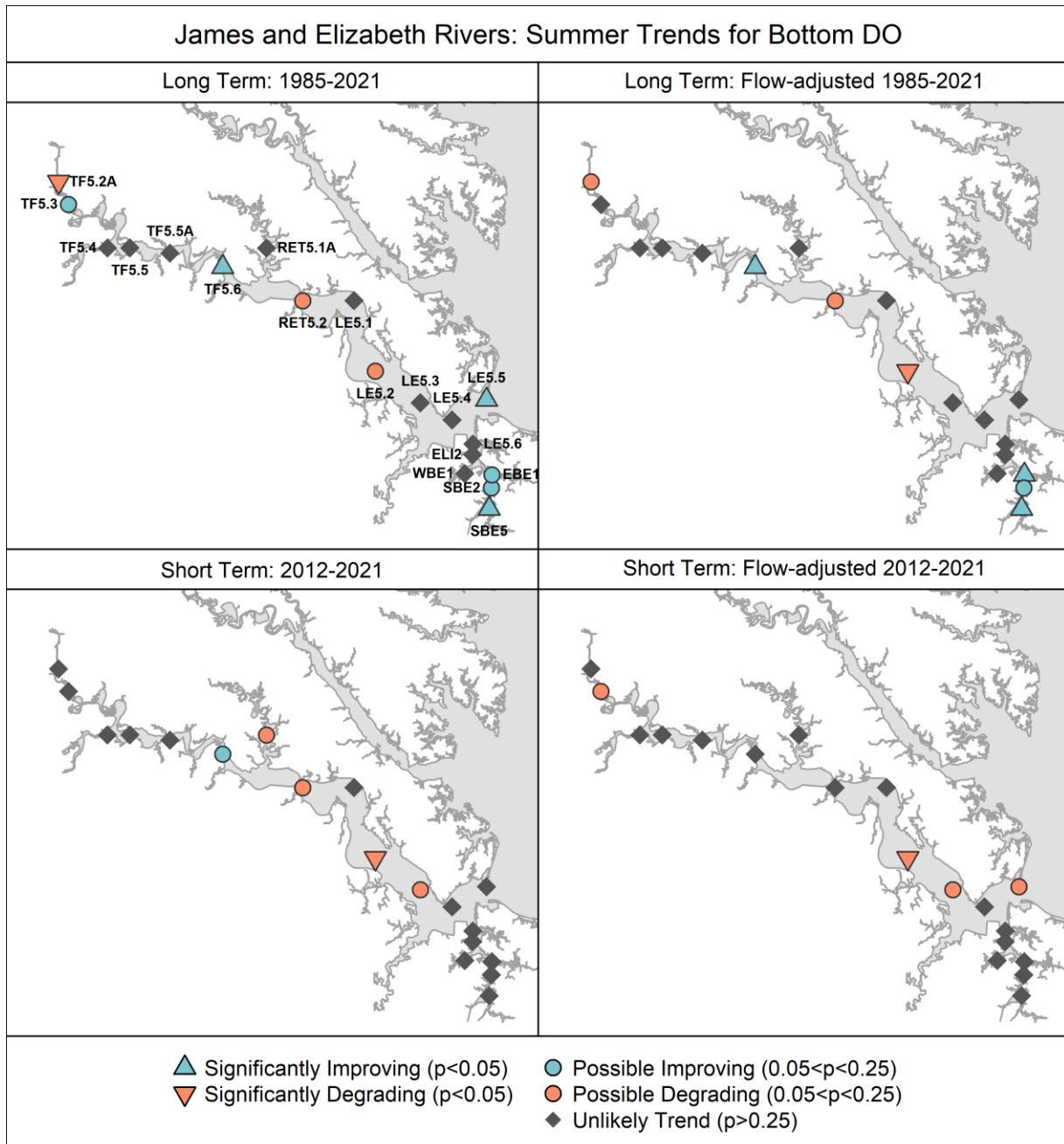


Figure 18. Summer (June-September) bottom DO trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Summer bottom DO concentrations do not generally fall as low in the James River as some other regions in Chesapeake Bay, due to relatively shallow bathymetry and mixing from the Atlantic. Observations and mean summer GAM estimates are mostly above the 5 mg/L Open Water 30-day mean criterion that apply to the James segments (Figure 19). One of the Elizabeth River segments (SBEMH) has the deep

water designated use. Those stations (SBE5, SBE2) show an increase over time in both observed DO and mean summer GAM estimates, which is due to an increase in concentrations in the early 1990s (Figure 19, bottom two panels).

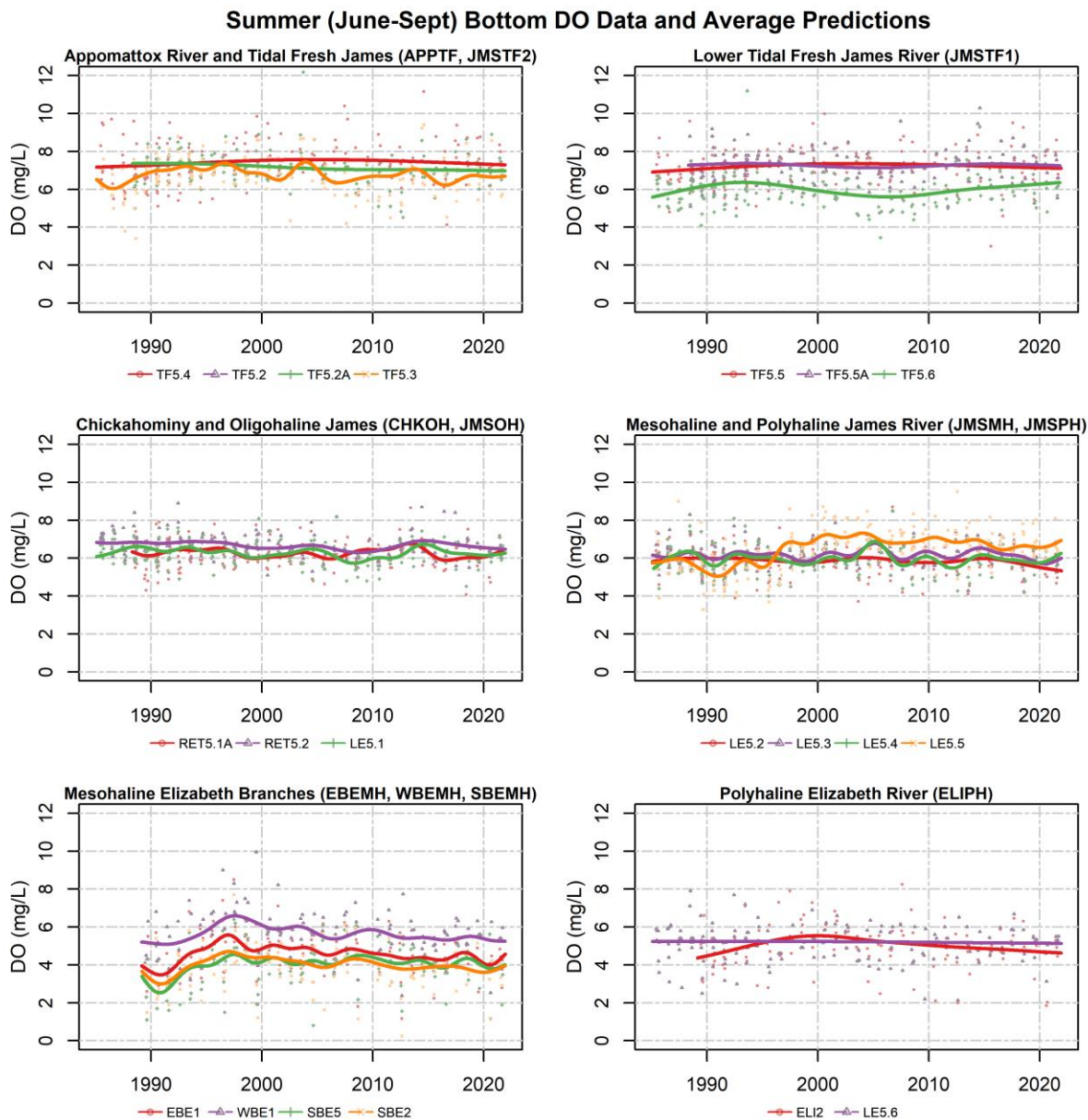


Figure 19. Summer (June-September) bottom DO data (dots) and average summer long-term pattern generated from non-flow adjusted GAMs. Colored dots represent June-September data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean summer GAM estimates for the noted monitoring stations.

4.7 Surface Water Temperature

James River and tributary surface water temperatures are increasing at most stations over the long- and short-term (Figure 20). This is consistent with other studies in Chesapeake Bay that document long-term

increases in tidal water temperatures (Hinson et al., 2022; Ding and Elmore, 2015). One station in the Elizabeth River system has decreasing water temperatures across all analysis periods. These differing trends in water temperature could be a result of the shifts in industrial operations along the Deep Creek Southern Branch of the Elizabeth River, but more analysis could be done to investigate this different pattern.

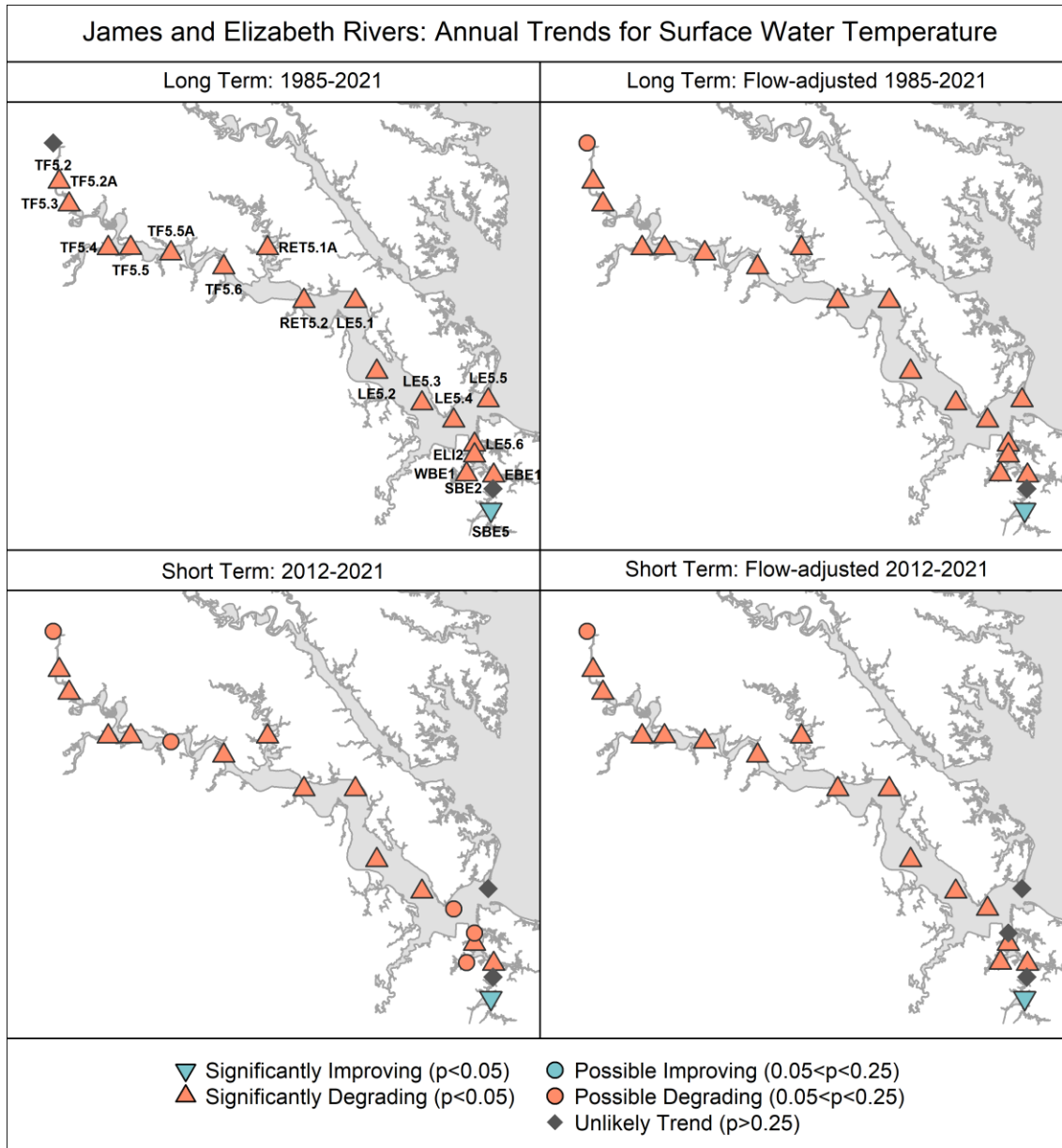


Figure 20. Annual surface water temperature trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Water temperature varies seasonally in the tidal Chesapeake Bay waters, which is evident in the range of data values from almost 0 to 35 degrees Celsius (Figure 21). The mostly increasing long term trends (Figure 20) are clear from the long-term averages of the data, even with the large seasonal variability.

The decrease at SBE5 is clear in the bottom left panel of Figure 21 with the green line that drops down after 2010.

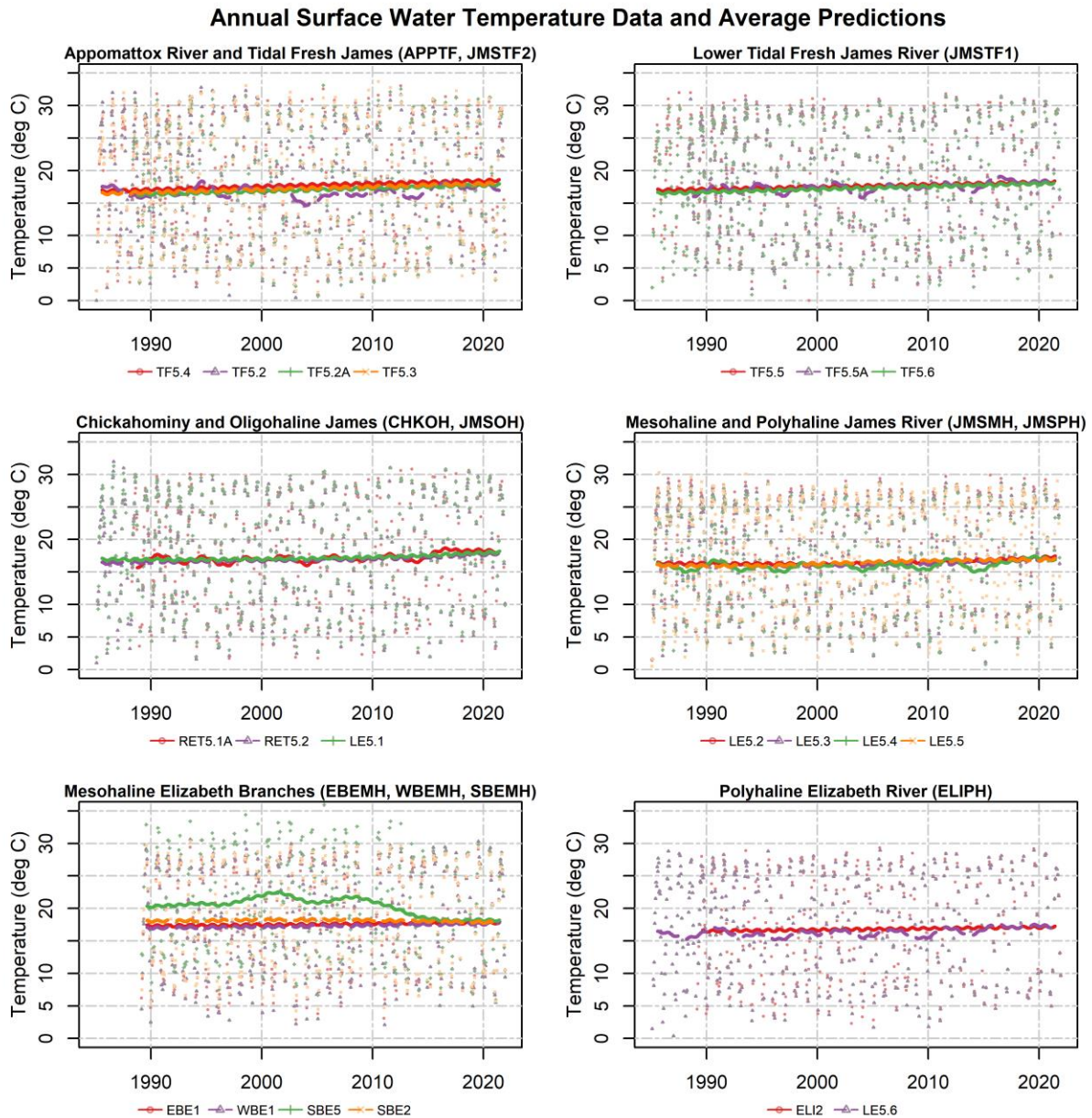


Figure 21. Annual surface water temperature data (dots) and average long-term pattern generated from non-flow adjusted GAMs. Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

5. Factors Affecting Trends

5.1 Watershed Factors

5.1.1 Effects of Physical Setting

The geology of the James River watershed and its associated land use affects the quantity and transmissivity of nitrogen, phosphorus, and sediment delivered to non-tidal and tidal streams (Figure 22) (Brakebill et al., 2010; Ator et al., 2011; Ator et al., 2019; Ator et al., 2020; Noe et al., 2020).

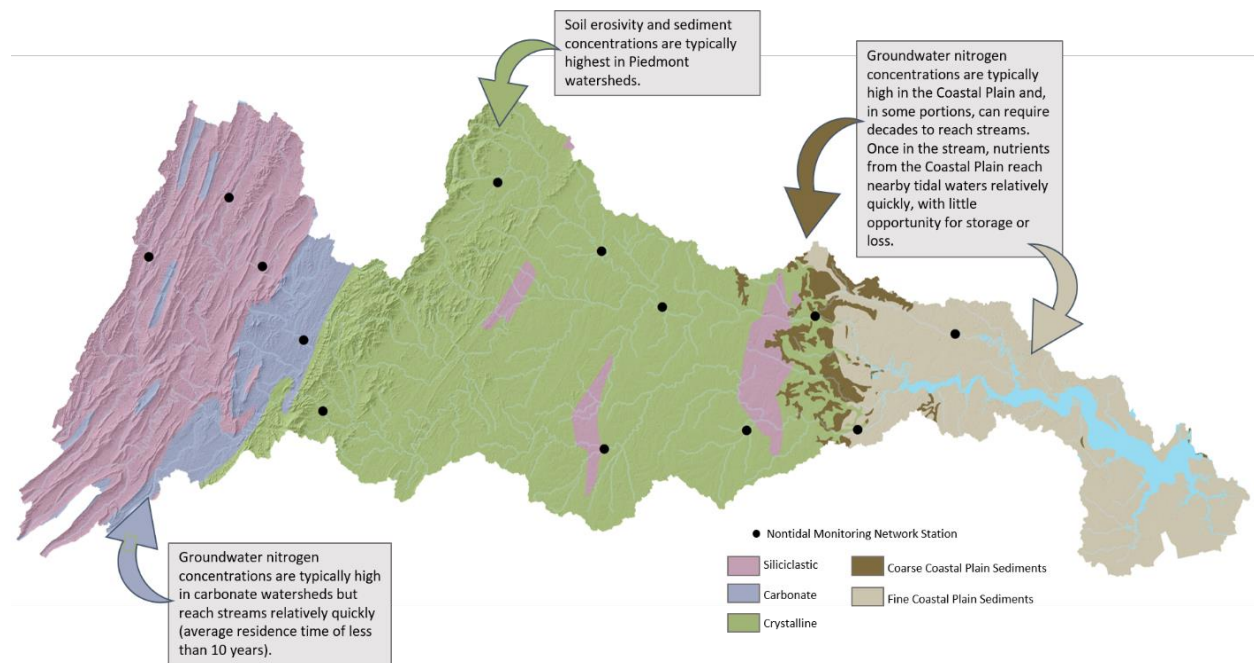


Figure 22. Effects of watershed hydrogeomorphology on nutrient transport to freshwater streams and tidal waters. Base map modified from (King et al., 1974) and (Ator et al., 2005), North American Datum 1983.

Nitrogen

Groundwater is an important delivery pathway for nitrogen, as nitrate, to most streams in the Chesapeake Bay watershed (Ator and Denver, 2012; Lizarraga, 1997). Concentrations of groundwater nitrogen, as nitrate, are typically highest in headwater portions of the James River watershed where carbonate rocks underlie some of the Valley and Ridge physiographic province (Greene et al., 2005; Terziotti et al., 2017). The geology of these areas provides suitable land for agriculture, but little potential for denitrification (Böhlke and Denver, 1995; Lizarraga, 1997; Miller et al., 2007; Sanford and Pope, 2013), so nitrogen that is not removed by plants or exported in agricultural products can move relatively efficiently to groundwater. Carbonate rocks only compose a small area of the James River watershed, with most streams underlain by Piedmont crystalline rocks or Coastal Plain sediments. The

typical residence time of groundwater delivered to streams in the Chesapeake Bay watershed is about 10 years, but ages vary from less than one year to greater than 50 years based on bedrock structure, groundwater flow paths, and aquifer depths (Lindsey et al., 2003). 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 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 James River watershed where inputs of manure and fertilizer applied to agricultural fields exceed crop needs. Reducing soil phosphorus concentrations can take a decade or more (Kleinman et al., 2011) and, until this occurs, watershed phosphorus loads may be unresponsive to management practices (Jarvie et al., 2013; Sharpley et al., 2013).

Sediment

The delivery of sediment from upland soil erosion, streambank erosion, and tributary loading varies throughout the James River watershed, but in-stream concentrations are typically highest in streams above the fall line that drain Piedmont geology (Brakebill et al., 2010). The erosivity of Piedmont soils results from its unique topography and from the prevalence of agricultural and urban land uses in these areas (Trimble, 1975; Gellis et al., 2005; Brakebill et al., 2010). Factors affecting streambank erosion are highly variable throughout this watershed and include drainage area (Gellis and Noe, 2013; Gellis et al., 2015; Gillespie et al., 2018; Hopkins et al., 2018), bank sediment density (Wynn and Mostaghimi, 2006), vegetation (Wynn and Mostaghimi, 2006), stream valley geomorphology (Hopkins et al., 2018), and developed land uses (Brakebill et al., 2010).

Delivery to tidal waters from the non-tidal watershed

The delivery of nitrogen, phosphorus, and sediment in non-tidal streams to tidal waters in the James River watershed varies based on physical and chemical factors that affect in-stream retention, loss, or storage. In general, nutrient and sediment loads in tidal waters are most strongly influenced by conditions in proximal non-tidal streams that have less opportunity for denitrification and floodplain trapping of sediment associated phosphorus. In-stream denitrification rates vary spatially with soil moisture and temperature (Pilegaard, 2013) and are typically higher in portions of the James River watershed than in more northern Bay regions because of a warmer climate. More than half of the nitrogen in the uppermost reaches of the James River is removed via denitrification before reaching tidal waters (Ator et al., 2011). There are no natural chemical processes that remove phosphorus from streams, but sediment, and associated phosphorus, can be trapped in floodplains before reaching tidal waters (Noe et al., 2022). 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., 2013). The average age of sediment stored in-channel is typically assumed to be less than a year (Gellis et al., 2017), but delivery to tidal waters can be exponentially longer as sediment moves in and out of different storage zones during downstream transport.

5.1.2 Estimated Nutrient and Sediment Loads

Estimated nutrient and sediment loads to the James River are a combination of monitored loads from its U.S. Geological Survey (USGS) River Input Monitoring (RIM) station located at the nontidal-tidal interface and below-RIM simulated loads from the Chesapeake Bay Program Watershed Model. Nitrogen loads to the tidal James were primarily from the below-RIM areas, whereas phosphorus and suspended sediment loads were primarily from the RIM areas (Figure 23). Over the period of 1985-2021, 0.54, 0.068, and 43 million tons of nitrogen, phosphorus, and suspended sediment loads were exported through the James River watershed, with 34%, 55%, and 60% of those loads coming from the RIM areas, respectively. Mann-Kendall trends and Sen's slope estimates are summarized for each loading source in Table 2.

Estimated TN loads showed an overall decline of 240 ton/yr in the period between 1985 and 2021, which is statistically significant ($p < 0.01$). This reduction is largely driven by reductions in below-RIM loads (-230 ton/yr; $p < 0.01$), with a much smaller contribution by the RIM loads (-1.7 ton/yr; $p = 0.84$). The below-RIM decline is largely driven by below-RIM point sources (-230 ton/yr; $p < 0.01$), and to a much lesser extent, atmospheric deposition to tidal waters (-3.1 ton/yr; $p < 0.01$). The significant reduction in below-RIM point sources is a result of substantial efforts to reduce nitrogen loads from major wastewater treatment facilities by implementing biological nutrient removal (Lyerly et al., 2014). The significant decline in atmospheric deposition of TN to the tidal waters is consistent with findings that atmospheric deposition of nitrogen has decreased due to benefits from the Clean Air Act implementation (Eshleman et al., 2013; Lyerly et al., 2014).

Estimated TP loads showed an overall decline of 30 ton/yr in the period between 1985 and 2021, which is statistically significant ($p < 0.01$). This reduction reflects a combination of reductions in below-RIM loads (-16 ton/yr; $p < 0.01$) and RIM loads (-11 ton/yr; $p = 0.18$). The below-RIM decline is entirely driven by below-RIM point sources (-18 ton/yr; $p < 0.01$). The 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). By contrast, the below-RIM nonpoint sources showed a long-term increase in this period (5.4 ton/yr; $p < 0.01$).

Estimated suspended sediment (SS) loads showed an overall decline of 970 ton/yr in the period between 1985 and 2021, although it is not statistically significant ($p = 0.89$). Both the RIM and below-RIM loads showed long-term declines, but neither is statistically significant. Like TP and TN, the below-RIM point source load of SS showed a statistically significant decline in this period (-190 ton/yr; $p < 0.01$).

James River

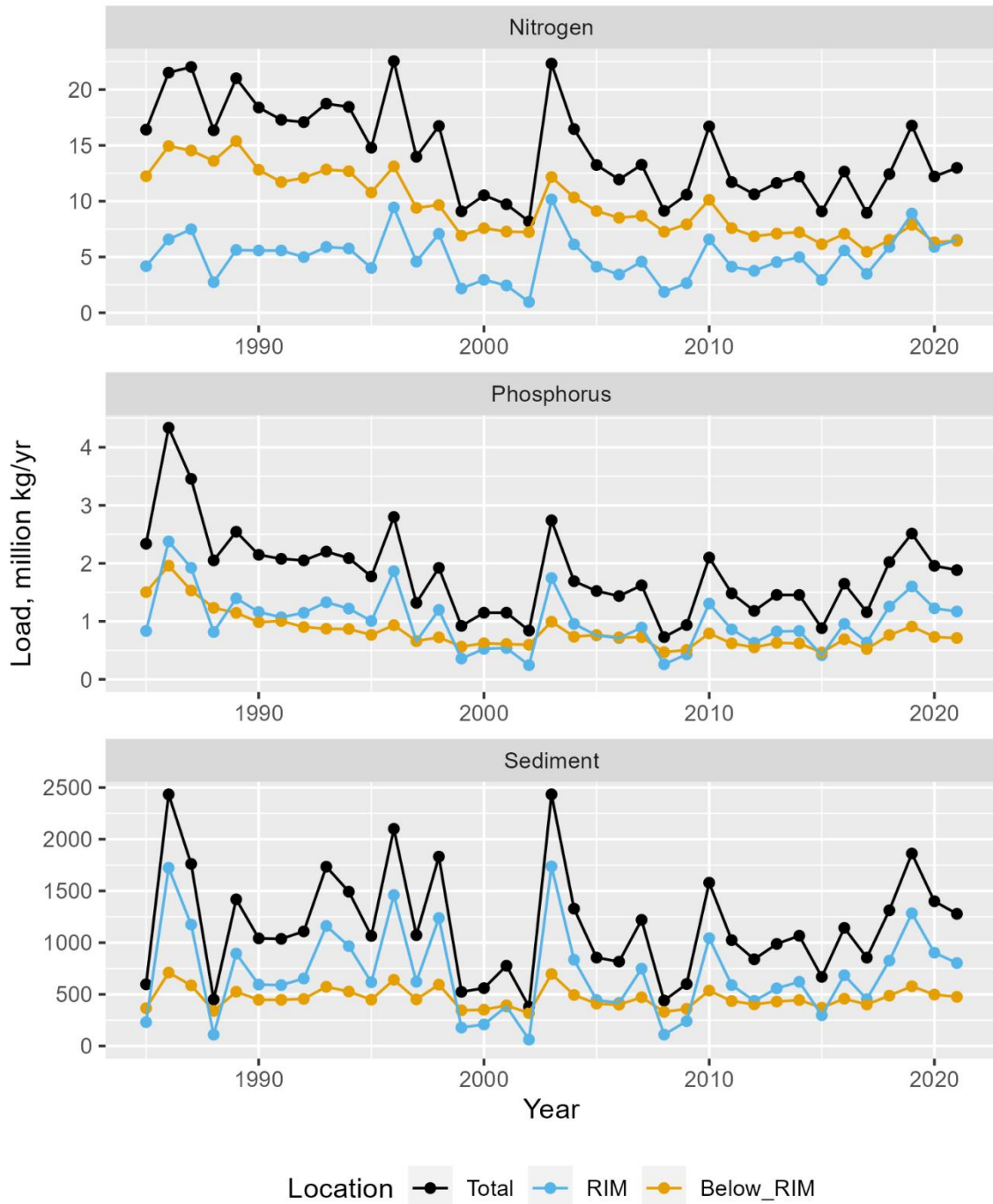


Figure 23. Estimated total loads of nitrogen (TN), phosphorus (TP), and suspended sediment (SS) from the RIM and below-RIM areas of the James River. RIM refers to the USGS River Input Monitoring site located just above the head of tide of this tributary, which includes upstream point source loads. Below-RIM estimates are a combination of simulated non-point source, atmospheric deposition, and reported point-source loads.

Table 2. Summary of Mann-Kendall trends for the period of 1985-2021 for total nitrogen (TN), total phosphorus (TP), and suspended sediment (SS) loads to the James River. Significant p-values are shown in green. TP and SS for Below-River Input Monitoring tidal deposition is not applicable, so it is represented as a dash in the table.

Categories	TN		TP		SS	
	Trend, metric ton/yr	p-value	Trend, metric ton/yr	p-value	Trend, metric ton/yr	p-value
Total watershed	-240	< 0.01	-30	< 0.01	-970	0.89
RIM watershed ¹	-1.7	0.84	-11	0.18	-430	0.97
Below-RIM watershed ²	-230	< 0.01	-16	< 0.01	-730	0.72
<i>Below-RIM point source</i>	-230	< 0.01	-18	< 0.01	-190	< 0.01
<i>Below-RIM nonpoint source</i> ³	9.2	0.67	5.4	< 0.01	-450	0.82
<i>Below-RIM tidal deposition</i>	-3.1	< 0.01	-	-	-	-

¹ Loads for the RIM watershed were estimated loads at the USGS RIM station 02035000 (James River at Cartersville, Va.; <https://www.usgs.gov/CB-wq-loads-trends>).

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 2021, which were adjusted to reflect actual hydrology using the method of the Chesapeake Bay Program's Loads to the Bay indicator (see <https://www.chesapeakeprogress.com/clean-water/water-quality>).

5.1.3 Expected Effects of Changing Watershed Conditions

According to the Chesapeake Bay Program's Watershed Model known as the Chesapeake Assessment Scenario Tool (CAST; <https://cast.chesapeakebay.net/About/UpgradeHistory>, version Phase 6 - 7.6.0), changes in population size, land use, and pollution management controls between 1985 and 2022 would be expected to change long-term average nitrogen, phosphorus, and sediment loads to the tidal James River by -44%, -71%, and -4%, respectively (Figure 24). 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 Best Management Practices (BMPs) becoming fully effective after installation. In 1985, wastewater and agriculture were the two largest sources of nitrogen loads. By 2022, wastewater remained the largest nitrogen source; however, agriculture nitrogen loads had changed by -28%, and the developed sector had taken its place as the second largest nitrogen source. Overall, decreasing nitrogen loads from agriculture (-28%), natural (-9%), stream bed and bank (-6%), and wastewater (-70%) sources were partially counteracted by increases from developed (55%) and septic (58%) sources.

The two largest sources of phosphorus loads as of 2022 were the wastewater and stream bed and bank sectors. Overall, expected declines from agriculture (-44%), natural (-8%), stream bed and bank (-25%), and wastewater (-90%) sources were partially counteracted by increases from developed (67%) sources.

For sediment, the largest sources are stream bed and bank and shoreline areas: these two sources changed by -3% and -1%, respectively between 1985 and 2022. Sediment loads from the agriculture sector changed by -45%, whereas sediment load from developed areas changed by 28%.

Overall, changing watershed conditions are expected to result in the agriculture, natural, stream bed and bank, and wastewater sectors achieving reductions in nitrogen, phosphorus, and sediment loads between 1985 and 2022, whereas the developed sectors are expected to increase in nitrogen, phosphorus, and sediment loads.

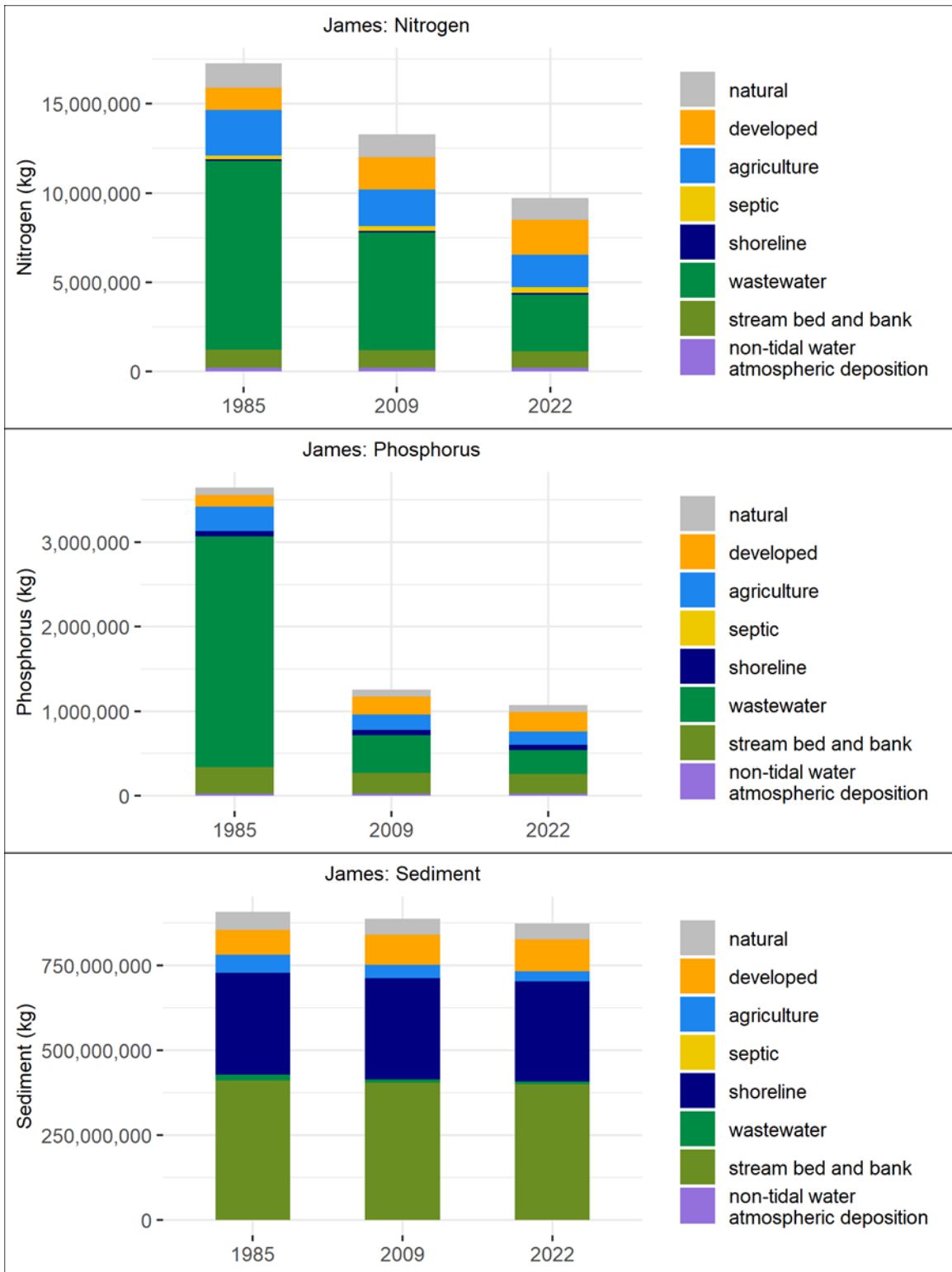


Figure 24. Expected long-term average loads of nitrogen, phosphorus, and sediment from different sources to the tidal James, based on watershed conditions in 1985, 2009, and 2022.

5.1.4 Best Management Practices (BMPs) Implementation

Data on reported BMP implementation are available for download from CAST (<https://cast.chesapeakebay.net/About/UpgradeHistory>, version Phase 6 - 7.6.0). Reported BMP implementations on the ground as of 1985, 2009, and 2022 are compared to planned 2025 implementation levels in Figure 25 for a subset of major BMP groups measured in km². As of 2022, tillage, cover crops, pasture management, forest buffer and tree planting, stormwater management, agricultural nutrient management, and urban nutrient management were credited for 568, 314, 819, 12, 360, 1,551, and 119 km², respectively. Implementation levels for some practices are already close to achieving their planned 2025 levels: for example, 101% of planned acres for tillage had been achieved as of 2022. In contrast, about 13% of planned urban nutrient management implementation had been achieved as of 2022.

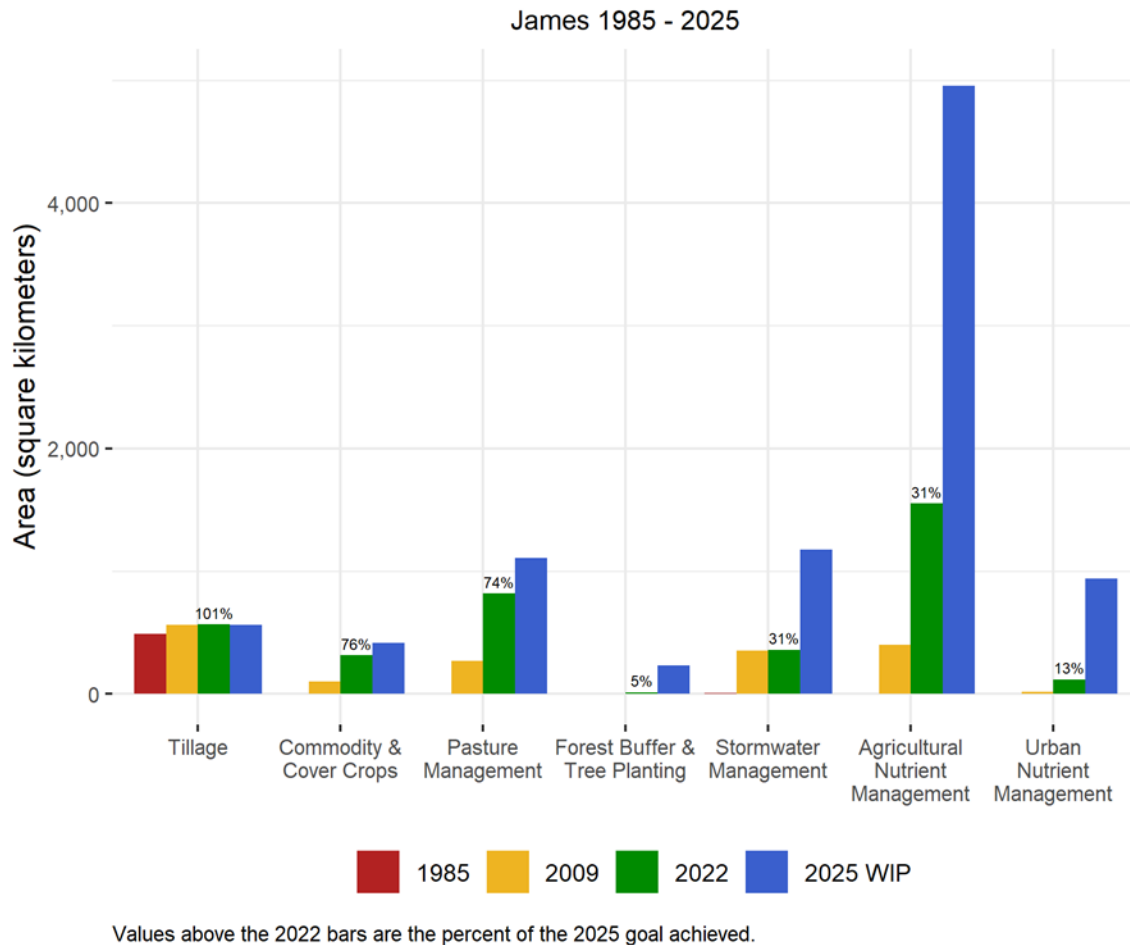


Figure 25. Best Management Practices (BMPs) implementation in the James watershed from 1985, 2009, 2022, and 2025 Watershed Implementation Plans.

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 0 m in 1985 to 6,483 m in 2022. Over the same period, animal waste management systems treated 68 animal units in 1985 and 54,891 animal units in 2022 (one animal unit represents

1,000 pounds of live animal). These implementation levels represent 4% and 14% 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 (1985-2020) and short term (2011-2020) at nontidal network stations throughout the watershed and can be found at the USGS water data for the Nation: U.S. Geological Survey National Water Information System (Mason et al., 2023; USGS NWIS, 2022) (Table 3). 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 3. Long-term (1985 - 2020) and short-term trends (2011 - 2020) of flow-normalized total nitrogen (TN), total phosphorus (TP), and suspended sediment (SS) loads for nontidal network monitoring locations in the James 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://www.usgs.gov/CB-wq-loads-trends>.

USGS Station ID	USGS Station Name	Trend start water year	Percent change in FN load, through water year 2020		
			TN	TP	SS
02011500	BACK CREEK NEAR MOUNTAIN GROVE, VA	1985	6.95	-	-
		2011	16.9	-	-
02015700	BULLPASTURE RIVER AT WILLIAMSVILLE, VA	1985	15.1	-	-
		2011	3.06	-	-
02020500	CALFPASTURE RIVER ABV MILL CREEK AT GOSHEN, VA	2011	24.8	-	-
02024000	MAURY RIVER NEAR BUENA VISTA, VA	1985	31.9	-	-
		2011	1.55	-	-
02024752	JAMES RIVER AT BLUE RIDGE PKWY NR BIG ISLAND, VA	2011	-2.53	-10.5	-12.6
02031000	MECHUMS RIVER NEAR WHITE HALL, VA	1985	-14.9	-	-
		2011	1.7	-	-
02034000	RIVANNA RIVER AT PALMYRA, VA	1985	-23	-	-
		2011	-21	-18.8	-22.1
02035000	JAMES RIVER AT CARTERSVILLE, VA	1985	-17.2	-39.2	15.9
		2011	-6.17	-14.2	-11
02037500	JAMES RIVER NEAR RICHMOND, VA	1985	-22.7	-	-
		2011	-19.2	-4.01	4.49
02039500	APPOMATTOX RIVER AT FARMVILLE, VA	1985	-2.12	-	-
		2011	-7.66	-	-
02041000	DEEP CREEK NEAR MANNBORO, VA	2011	-3.22	-	-

02041650	APPOMATTOX RIVER AT MATOACA, VA	1985	9.32	86.6	19.7
		2011	17.1	24.5	29.7
02042500	CHICKAHOMINY RIVER NEAR PROVIDENCE FORGE, VA	1985	-16.4	-	-
		2011	-0.175	8.75	25.5

Decreasing trends listed in bold green, increasing trends listed in bold 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 (Figure 26) (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 (Bukaveckas et al., 2011; Keisman et al., 2019; Testa et al., 2019). DO 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).

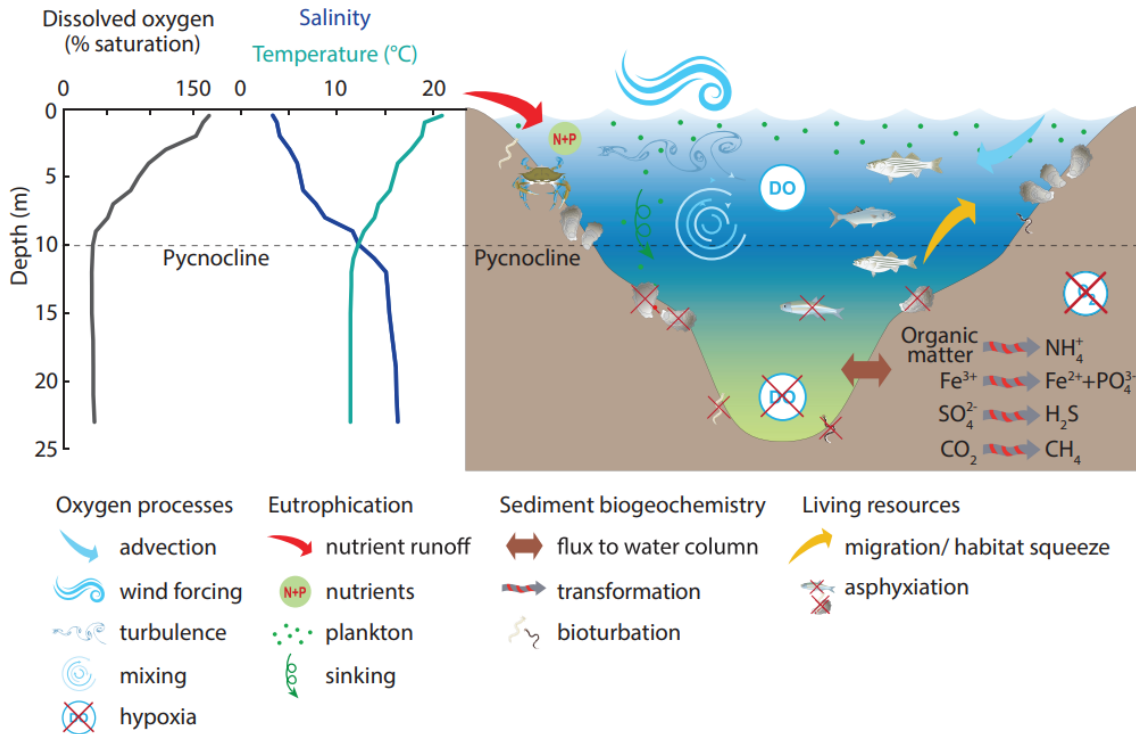


Figure 26. Conceptual diagram illustrating how hypoxia is driven by eutrophication and physical forcing, while affecting sediment biogeochemistry and living resources. From (Testa et al., 2017).

5.2.1 Watershed and Estuarine Volume

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 27 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 28 and 29 are comparisons of estimated annual average nitrogen and phosphorus loads, respectively, for the 2021 progress scenario in CAST versus the estuarine volume for the same set of estuaries and sub-estuaries.

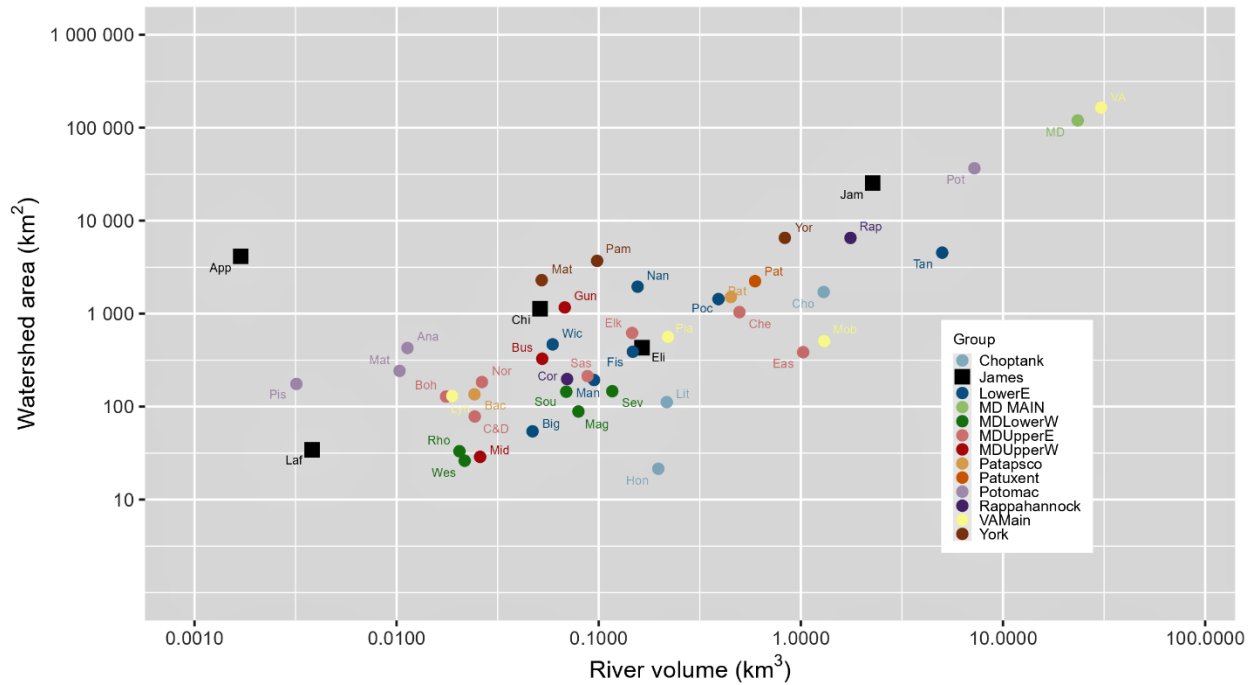


Figure 27. A comparison of watershed area (km²) vs estuarine volume (km³) for each tributary. The table of tributary names and their abbreviations can be found below.

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

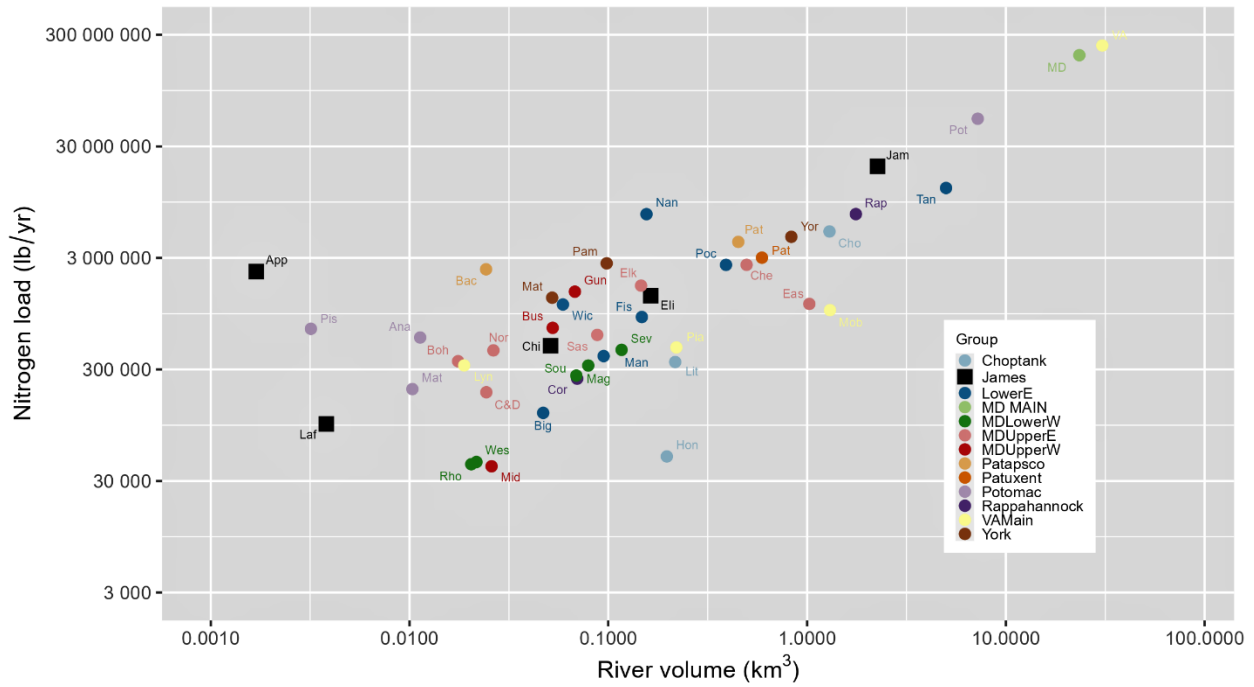


Figure 28. Annual average expected nitrogen loads versus estuarine volume. Nitrogen loads are from the 2021 progress scenarios in CAST (Chesapeake Bay Program, 2020), which is an estimate of nitrogen loads under long-term average hydrology given land use and reported management as of 2021.

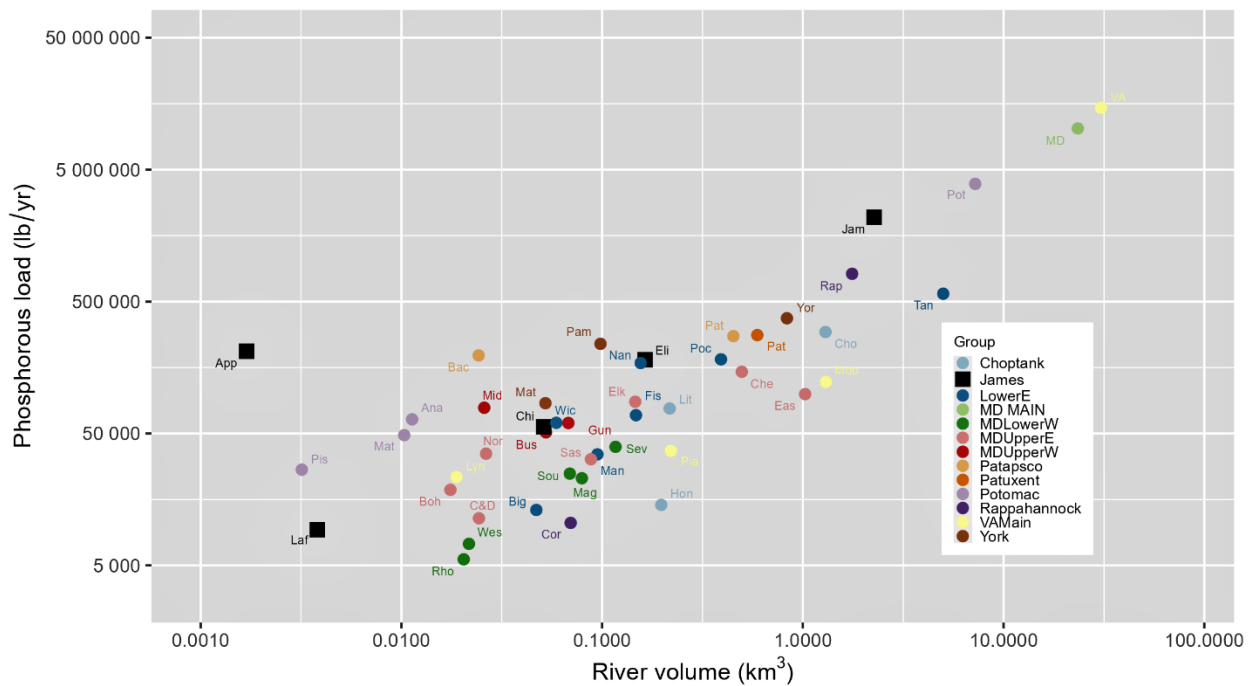


Figure 29. Annual average expected phosphorus loads versus estuarine volume. Phosphorus loads are from the 2021 progress scenarios in CAST (Chesapeake Bay Program, 2020), which is an estimate of

phosphorus loads under long-term average hydrology given land use and reported management as of 2021.

The James River estuary volume and watershed contain approximately 3 and 16% of the total volume and watershed of the Chesapeake Bay. This ranks the James mainstem as the 5th largest volume and 4th largest watershed area aggregated tributary in this summary (Figures 27, 28, and 29). Several of the smaller tributaries within the James system, the Elizabeth River, Chickahominy River, and Lafayette River, all follow the same trend as the main James River. However, the Appomattox River has a higher watershed area relative to its estuarine volume, indicating potentially high susceptibility to eutrophication. The Appomattox River also has elevated loads of phosphorus and nitrogen relative to its estuarine volume, while phosphorus and nitrogen loads in the Elizabeth River, Chickahominy River, and Lafayette River are more moderate. The ratios of watershed area, nitrogen loading, and phosphorus loading to estuarine volume in the James watershed are generally consistent with other estuaries in the Chesapeake system. This indicates a moderate level of susceptibility to eutrophication, apart from the Appomattox.

5.2.2 Long-term Changes in Water Quality Longitudinal Profiles

This section presents a series of longitudinal profiles of five water quality parameters across all James River stations. The water quality parameters include TN, TP, chlorophyll a , water clarity as measured by Secchi depth (Secchi), and bottom DO. The profiles are generated from the results of GAM models estimated for each station. Cluster analysis is used to group years according to similarity of longitudinal profiles. The profiles of the same color represent years with similar upstream to downstream trends across all the stations in the James River. Comparing these groups allow for assessment of both spatial and temporal patterns for a given parameter, and comparisons among parameters allows for assessment of associations of parameters.

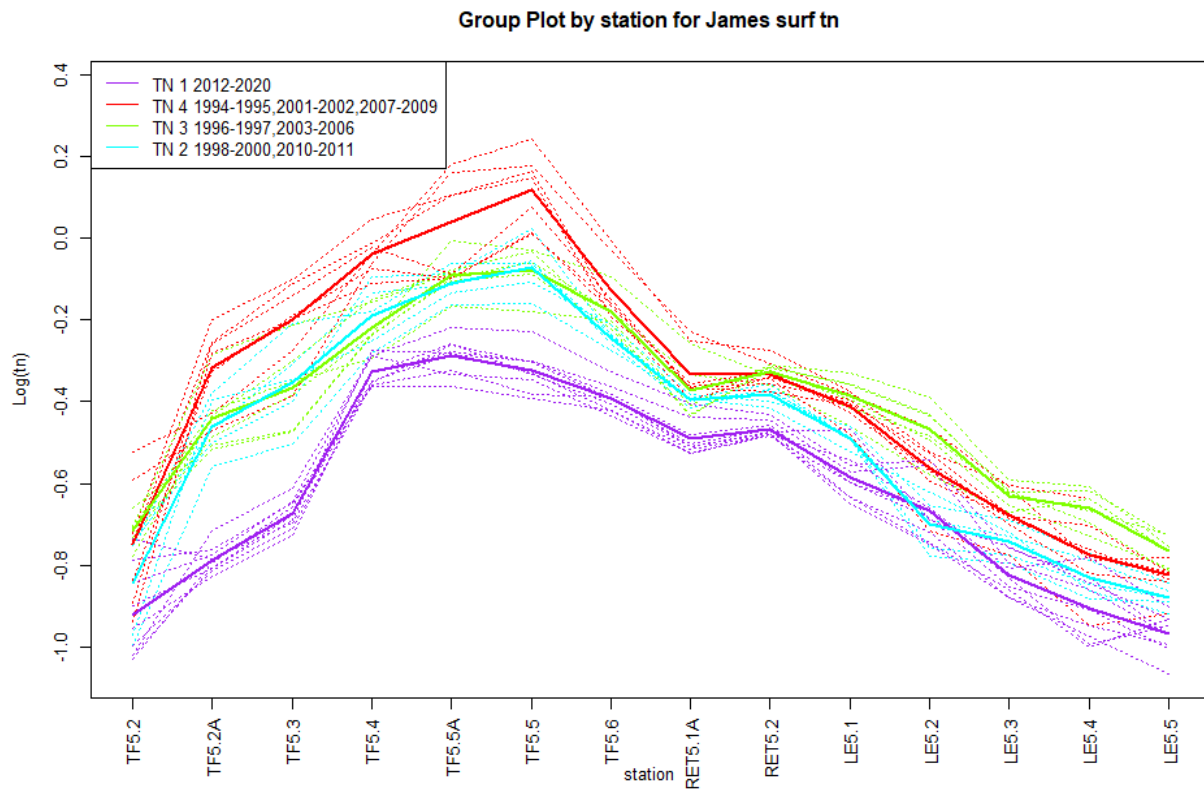


Figure 30. Station means of TN from upstream to downstream plotted with year groups segregated by color. Multiple dashed line traces within group show variability among years within groups.

In the James River, TN shows a spatial pattern of increasing TN down to the lower tidal fresh (TF5.5, TF5.5A) and then decreasing from this zenith toward the estuary mouth. It should be noted that this increasing and then decreasing trend is not typical of western shore tributaries to the Chesapeake Bay. In most tributaries the longitudinal profile of TN is monotonically decreasing from the fall line to the estuary mouth. This pattern in the James suggests that TN may have a local source in the lower tidal fresh.

Over time, the most recent years (2012-2020, purple) have lower TN than prior years over the entire estuary. The greatest improvements in TN occur in the lower tidal fresh, and the degree of improvement is somewhat less in the lower estuary and the upper tidal fresh.

A comparison of the high flow years shown in green versus the low flow years shown in red and cyan suggests that increased flow results in high export of TN into the lower estuary.

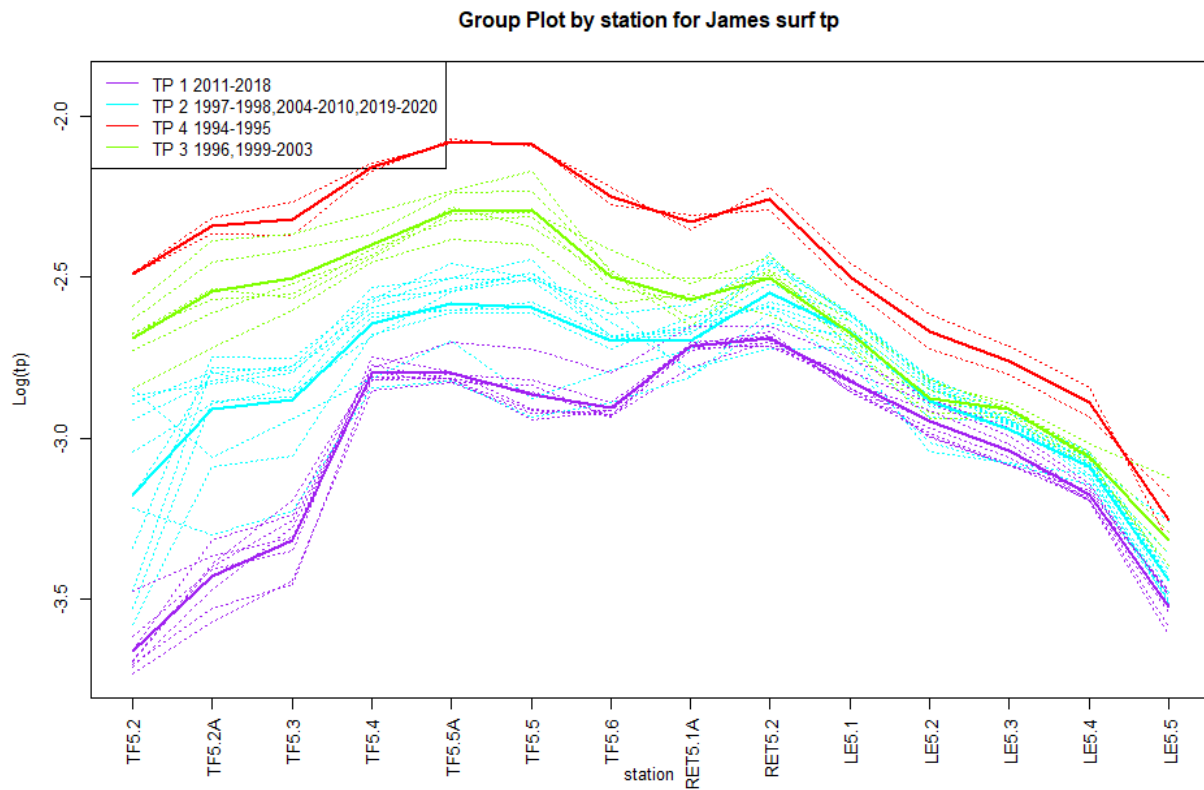


Figure 31. Station means of TP from upstream to downstream plotted with year groups segregated by color. Multiple dashed line traces within group show variability among years within groups.

In the James River, TP shows a spatial pattern of increasing TP down to the RET stations (RET5.1A, RET5.2) and then decreasing from this zenith toward the estuary mouth. This pattern of reaching a zenith in the turbidity maximum zone of the estuary is typical of the western shore tributaries to the Chesapeake Bay. It is attributed to the close association of TP and suspended particles. The estuarine mixing that occurs in the RET section of the estuary keeps particulate matter suspended in the water column.

Over time, the recent period from 2011-2018 (purple) have lower TP than prior years over the entire estuary. The greatest improvements in TP occur in the lower tidal fresh. The two most recent years, 2019-2020 are grouped with the cyan years which are slightly higher in TP than 2011-2018. This is likely due to 2019 and 2020 being high flow years. The years 1994- and 1995 (red) are above average flow years and stand out as having high levels of TP estuary wide.

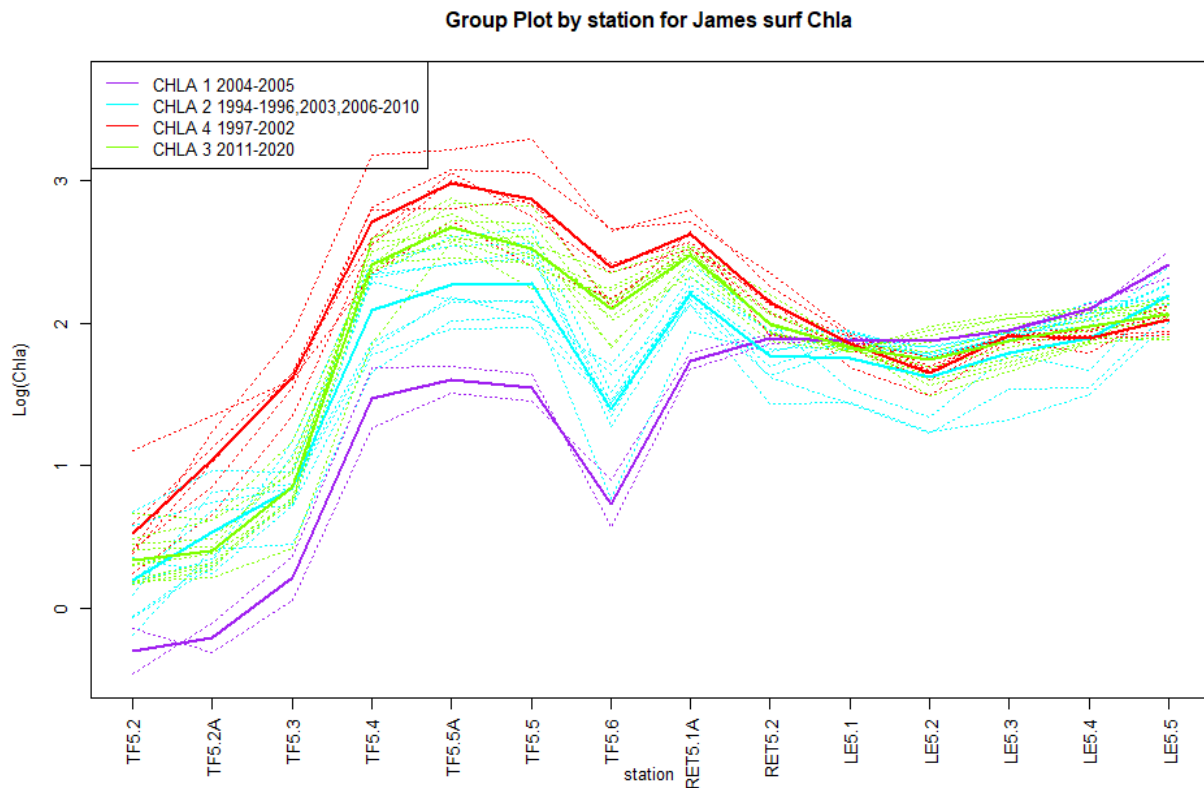


Figure 32. Station means of chlorophyll *a* plotted from upstream to downstream with year groups segregated by color. Multiple dashed line traces within groups show variability among years within groups.

The highest levels of chlorophyll *a* are typically observed in the lower tidal fresh down through the RET stations. An exception occurs in 2004-2005 (purple) where the highest levels are in the lower estuary. Station TF5.6 has depressed levels of chlorophyll *a* compared to its neighbors.

Over time, chlorophyll *a* does not exhibit the consistent improvement that is shown by the nutrients TN and TP. In the tidal fresh, the highest levels of chlorophyll *a* occur in 1997-2002 which are mostly low flow years. In the lower estuary, the highest levels of chlorophyll *a* occur in 2011-2020 (green) which are mostly high flow years. The years 2004-2005 have the longitudinal profile that is least similar to other years: 2004 is a high flow year while 2005 is a below average flow year. There is no ready explanation for similarity between these two years or the disparity between these years and others.

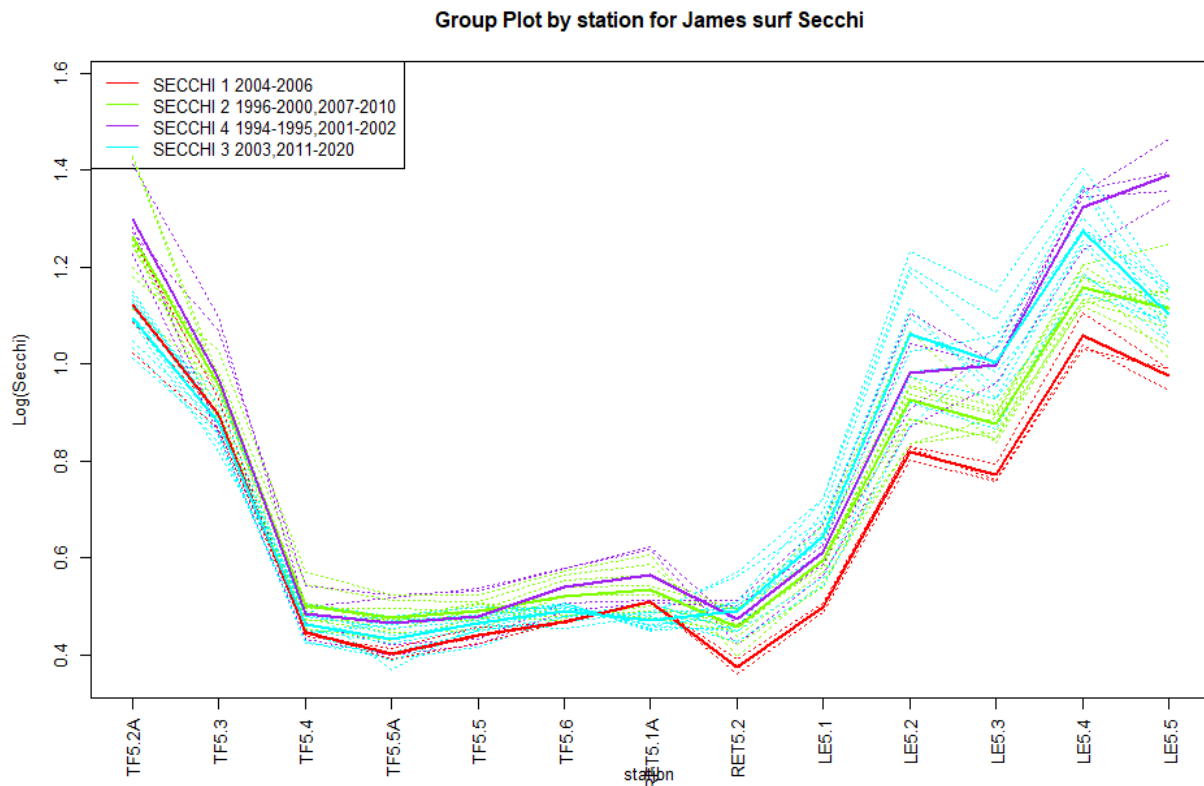


Figure 33. Station means of Secchi plotted from upstream to downstream with year groups segregated by color. Multiple dashed line traces within group show variability among years within groups.

The longitudinal pattern for water clarity as measured by the Secchi disk is almost the inverse of the pattern exhibited by TP (Figure 31). Freshwater input to the tidal fresh is relatively clear (TF5.2A, TF5.3). In the lower tidal fresh through the RET water clarity is lowest (TF5.4 – RET5.2). In the lower estuary, clarity improves with proximity to the Bay. This pattern is primarily due to estuarine mixing associated with riverine flows/inputs maintaining suspended particles in the water column, thus reducing water clarity in the lower tidal fresh and RET. It should also be noted that lower tidal fresh and RET form a zone where phytoplankton are abundant, which also tends to reduce water clarity (Figure 33).

Like chlorophyll *a*, Secchi does not exhibit the consistent improvement over time that is shown by the nutrients TN and TP. From the lower tidal fresh down to the mouth of the estuary, the poorest water clarity occurs in 2004-2006 (red). This corresponds to a period of high chlorophyll *a* in the lower estuary, but chlorophyll *a* was lower than average in the tidal fresh (Figure 32). It is encouraging that the lower estuary appears to have improved clarity in recent years (2011-2020, cyan), but the lower tidal fresh does not show improvement in this period.

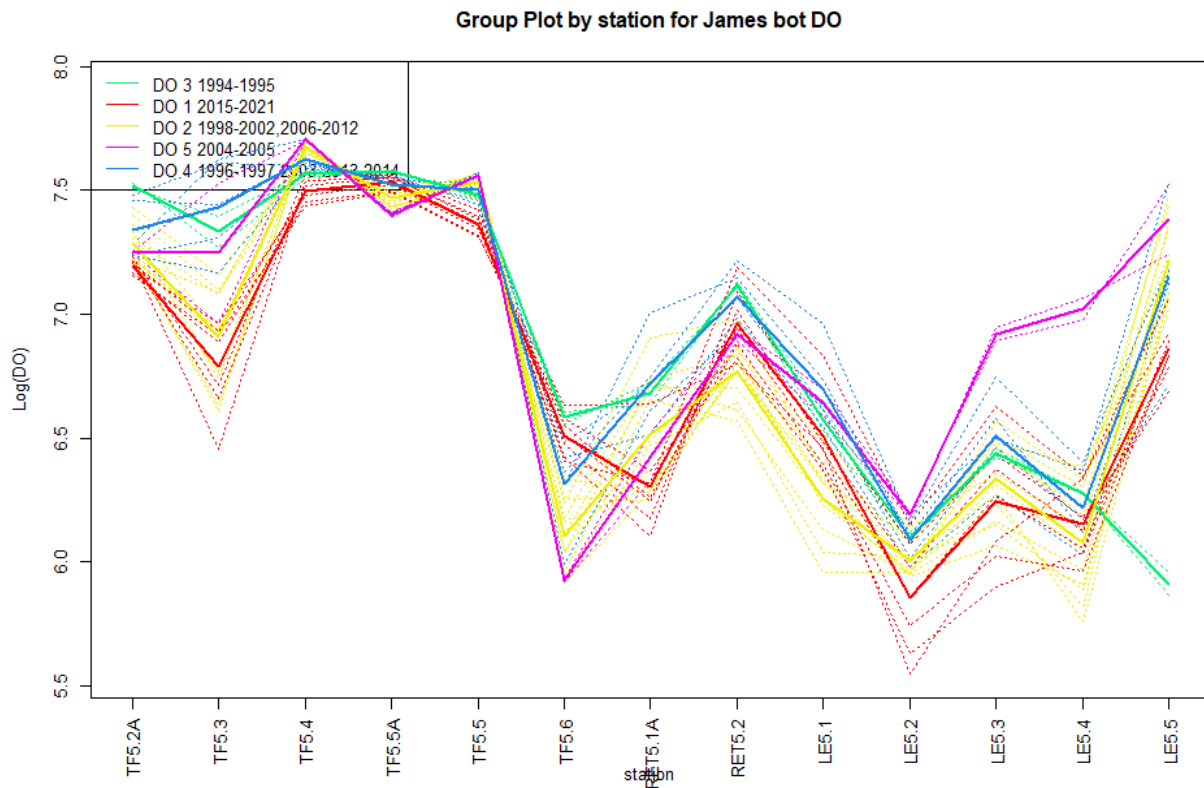


Figure 34. Station means of summer bottom DO plotted from upstream to downstream with year groups segregated by color. Multiple dashed line traces within group show variability among years within groups.

The James is unique among western shore tributaries in that bottom waters rarely become hypoxic in summer. The poorest DO conditions occur at the most downstream of the tidal fresh stations, TF5.6, and station LE5.2 in the lower estuary.

It does appear that DO conditions in the lower estuary are below average in recent years (2015-2021, red).

5.3 Climate Change Factors

The existence and influence of climate change is well demonstrated both globally (IPCC, 2014) and in the Chesapeake Bay (Hinson et al., 2022). As one of the most vulnerable areas in the nation, all aspects of the Chesapeake Bay watershed and tributaries are at risk from the effects of climate change, and the impacts are already being observed. Overall, the watershed is experiencing an increase in precipitation, temperatures, and climatic variability, which shape Chesapeake Bay tributary recovery trends (Najjar et al., 2010). These trends differ spatially and temporally throughout the watershed, and climate impacts are exacerbated by local non-climate stressors (e.g., land-subsidence, land use change, growth and development). Therefore, this section of the Tributary Summary is not an exhaustive discussion of how climate change is influencing water quality in Chesapeake Bay tributaries, but instead is an acknowledgement of the influence of climate change on the trends discussed in this report. Efforts

aimed to increase understanding of climate change impacts on water quality patterns can help explain the actual progress gaps and transform monitoring findings into actionable information.

5.3.1 Extreme Weather and Increased Precipitation

Under typical weather conditions, fresh water flowing from rivers and streams makes up about half of the Bay’s entire water volume. However, extremes in rainfall—whether too much or too little—can have varying effects on the Bay ecosystem. During large rain events, river flow increases, delivering more fresh water into the Bay and decreasing the Bay’s salinity (Murphy et al., 2019). Stormwater runoff delivers nitrogen, phosphorus, and sediment into rivers and the Bay causing an increase in nutrient concentrations, which create dead zones and feed algal blooms. During periods with little rainfall or extended drought, the decrease in freshwater flows results in saltier conditions, affecting habitats and aquatic species. More information capturing the extreme weather events occurring in the Bay watershed is shared seasonally by the Mid-Atlantic Regional Integrated Sciences and Assessments in the regional climate summaries (MARISA, 2023).

The correlation of water quality with extreme weather events is seen through the Chesapeake Bay Water Quality Standards Attainment Indicator (Fig 35). Dips in the long-term water quality standards show the responsiveness of the Chesapeake Bay to extreme events such as Hurricane Ivan in 2004 and Hurricane Irene in 2011. When viewed in isolation, these extreme events would lead to non-attainment. However, the Indicator shown in Figure 35 also shows that estimated attainment recovers relatively quickly in the aftermath of extreme events, thus highlighting the resiliency of the Bay.

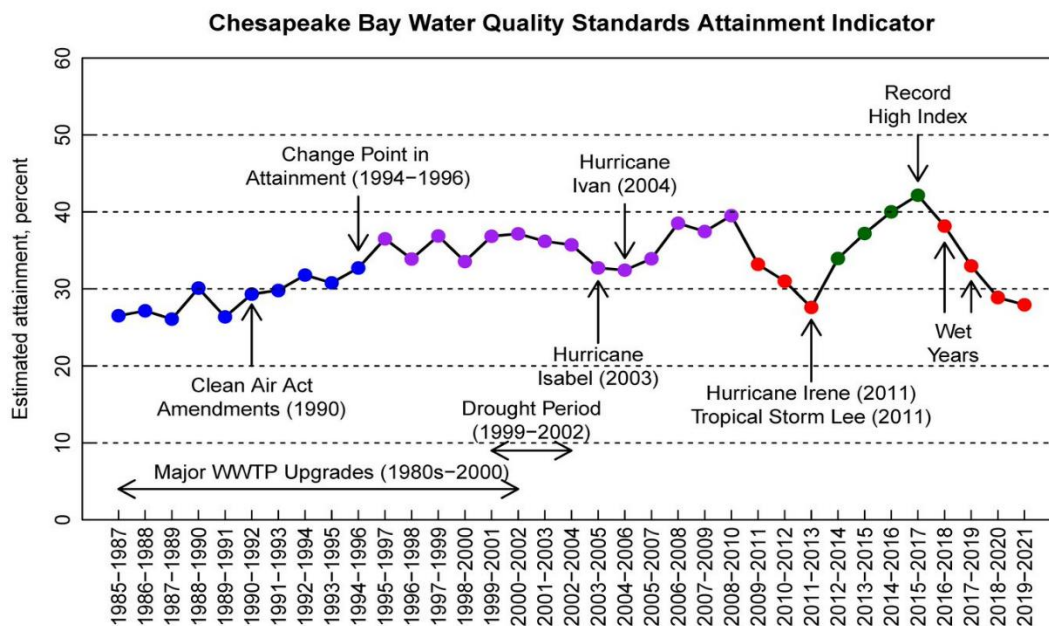


Figure 35. Chesapeake Bay Water Quality Standards Attainment Indicator valuated using three parameters from 1985 – 2021: dissolved oxygen, water clarity or submerged aquatic vegetation abundance, and chlorophyll *a*. Colors represent a different period: blue represents period before the change point, purple represents the period of steady attainment results, red represents the period of decreasing attainment after high flow years, and green represents the period of increasing attainment.

One-off events such as hurricanes are not the only measure influencing progress towards water quality attainment. Unusually prolonged wet weather in 2018 and 2019 caused higher than average river flows entering the Bay, delivering high pollutant loads during that period (Fig 36). Experts attribute the reduction in pollutant loads in 2020 to a combination of reduced river flow from less rainfall and to management actions controlling pollution in the Bay and watershed (Chesapeake Bay Program: ChesapeakeProgress, 2023).

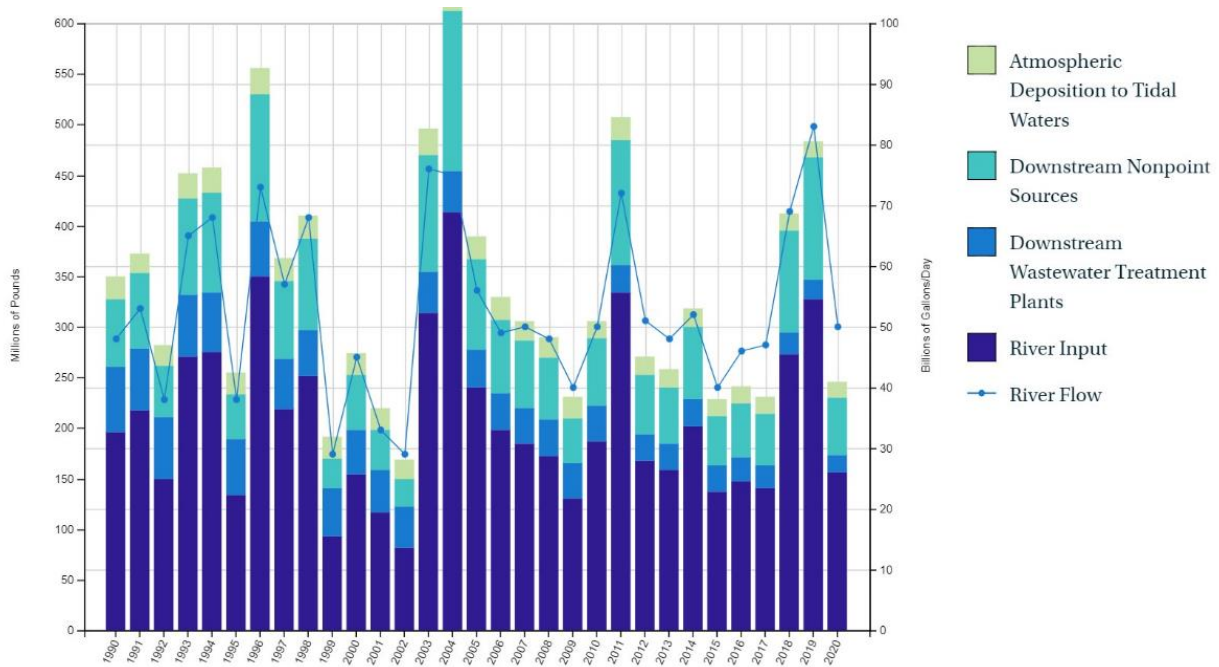


Figure 36. Pollution Loads and River Flow to the Chesapeake Bay (1990-2020): River and Watershed Input of Pollution Loads. Years denote the water year measured between October 1 and September 30. Figure from (Chesapeake Bay Program, 2023).

Many models predict increases in average annual precipitation for the Chesapeake Bay region, but studies have found greater seasonality in the projected precipitation change (Kunkel et al. 2013). Winter and spring projections show increased precipitation, followed by periods of drought (Pyke et al. 2008; Najjar et al. 2010). These studies are supportive for understanding stream flow, but local assessments of climate change and variability are still needed for determining climate vulnerability for the Bay (St. Laurent et al., 2021). Figure 37 shows Parameter-elevation relationship on independent slope model (PRISM) data at the land-river scale spatially aggregated to the James tributary basin. Mean annual precipitation for the James Tributary from 1981 to 2021 shows a gradual increase over the period of record.

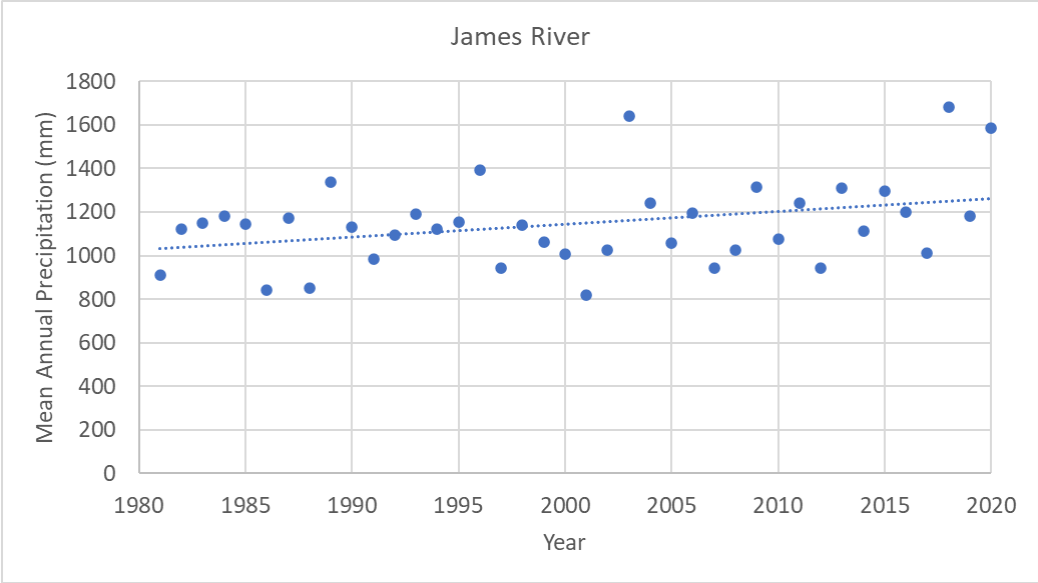


Figure 37. James River mean annual precipitation from 1981 – 2021 from the Parameter-elevation Relationship on Independent Slope Model (PRISM).

5.3.2 Warming Water Temperatures

The Chesapeake Bay is shallow, with a mean depth of 6.5 m, which means that atmospheric variability has a large influence on water column temperatures (St. Laurent, 2021). As described in Section 4.7, both long-term and short-term surface water temperature trends across the tidal areas of the James River are experiencing statistically significant warming (Figure 38). Increased atmospheric temperatures are forcing factors that contribute to warmer water temperatures. Trends from resulting marine heat waves, or prolonged anomalously warm events, indicate increases in marine heat wave frequency, duration, and cumulative yearly intensity (Mazzini and Pianca, 2022).

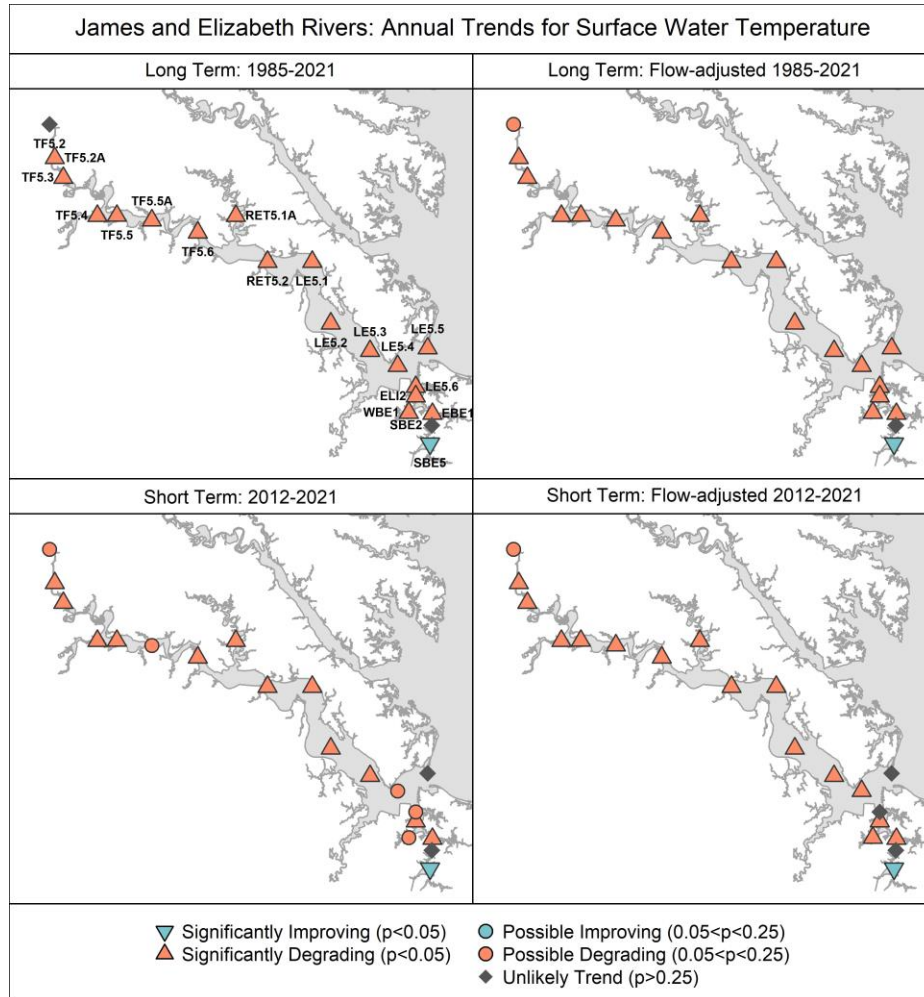


Figure 38. Annual surface water temperature trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

5.3.3 Sea-Level Rise

Sea-level rise and climate are closely linked. As the climate has warmed, sea-level has risen due to the thermal expansion of ocean water and melting of glaciers and ice sheets (USGS, 2018). Over the past century, Bay waters have risen by about one foot, and according to a USGS study, Bay waters are predicted to rise another 1.3 to 5.2 feet over the next 100 years (Eggleston and Pope, 2013). This rate is

higher than the global sea level rise average because the Chesapeake Bay region is also impacted by land subsidence, or sinking of land due to removal or displacement, half of which is estimated to be from groundwater removal (Eggleston and Pope, 2013).

NOAA Tides and Currents provides sea-level trends across the U.S. Sewells Point is at the mouth of the James tributary and shows a sea-level trend of 4.75 millimeters/year (Figure 38).

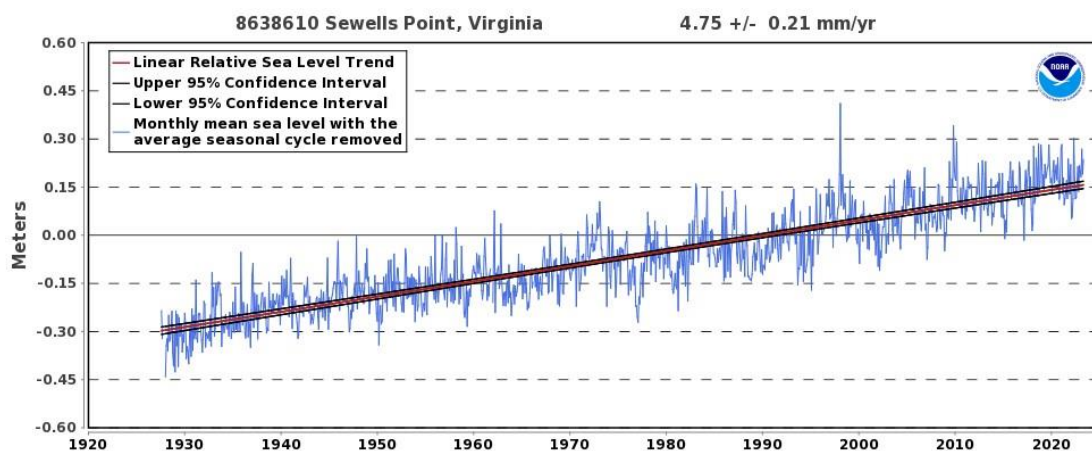


Figure 39. Sewells Point, Virginia monthly mean sea levels without the regular seasonal fluctuations from coastal ocean temperatures, salinity, wind, atmospheric pressure, and ocean currents. The relative sea level trend also shows the 95% confidence interval (NOAA, 2023b).

Higher water levels in the Bay can result in loss of marshes and wetlands due to saltwater inundation. This is occurring due to erosion rates that are outpacing marsh accretion and/or marsh migration being blocked by development (Eggleston and Pope, 2013; CBF 2023). Wetland habitat loss eliminates natural structures that trap pollution entering the Bay, which is why it is critical to integrate changing climate conditions, such as sea-level rise, when pursuing, designing, implementing, and maintaining restoration efforts (NOAA, 2023a).

5.3.4 Connection to Living Resources

Although measuring and discussing climate change impacts on water quality is critical, it is also important to understand these influences in the context of the living resources water quality standards were designed to protect. Warming water temperatures reduce the solubility of oxygen in water (Tian et al., 2021). With both higher water temperature averages and extremes, habitats are limited by both low oxygen and high temperatures. Key aquatic species with economic and cultural value to the Chesapeake Bay, such as striped bass (*Morone saxatilis*), encounter a habitat squeeze as bottom hypoxia and warm surface temperatures compress suitable habitat space in the water column (Parham et al., 2023). Another consideration is warming waters in the Chesapeake Bay favor pathogenic bacteria like *Vibrio vulnificus*, which threaten human health directly and indirectly through key living resources that are valued for human consumption, such as oysters (Archer et al., 2023; Wright et al., 1996). Additionally, phenological shifts due to warmer water temperatures threaten decoupling of predator-prey relationships and the key fisheries they support (Batiuk et al., 2023).

Increased precipitation also presents challenges for living resources by reducing suitable habitat. Heavier precipitation can yield increased hypoxia as the rate of phosphorus flushing from the landscape

increases, and for oysters, heavy freshwater flows may lower salinity to a harmful level (Kimmel et al., 2014).

The NOAA Seasonal Summaries offer more information on how climate change impacts living resources at finer spatial and temporal scales. These data describe salinity, DO, freshwater flow, and water temperature across the Chesapeake Bay, providing critical insight into ecosystem conditions. Applications of the NOAA seasonal summaries include informing ecosystem-based management for fisheries at the state and regional level and comparing the recent seasonal data with long-term averages. The NOAA Seasonal Summaries can be accessed at NOAA Chesapeake Bay Interpretive Buoy System (National Oceanic and Atmospheric Association, 2023c).

5.4 Insights on Changes in the James

Completion of Section 5.4 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 5.4.

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Appendix A: Glossary of Terms

Anoxic - condition in which the water column is characterized by a complete absence of oxygen. Anoxic conditions typically result from excessive decomposition of organic material by bacteria, high respiration by phytoplankton, stratification of the water column due to salinity or temperature effects or a combination of these factors. Anoxic conditions can result in fish kills or localized extinction of benthic communities.

Anthropogenic - resulting from or generated by human activities.

Benthos - refers to organisms that dwell on or within the bottom. Includes both hard substratum habitats (e.g., oyster reefs) and sedimentary habitats (sand and mud bottoms).

B-IBI - the benthic index of biotic integrity of Weisberg et al. (1997). The B-IBI is a multi-metric index that compares the condition of a benthic community to reference conditions.

Biological Nutrient Removal (BNR) - A temperature dependent process in which the ammonia nitrogen present in wastewater is converted by bacteria first to nitrate nitrogen and then to nitrogen gas. This technique is used to reduce the concentration of nitrogen in sewage treatment plant effluents.

Biomass - a quantitative estimate of the total mass of organisms for a particular population or community within a given area at a given time. Biomass for phytoplankton is measured as the total carbon within a liter of water. Biomass for the benthos is measured as the total ash-free dry weight per square meter of sediment habitat.

Chlorophyll *a* - a green pigment found in plant cells that functions as the receptor for energy in the form of sunlight. This energy is used in the production of cellular materials for growth and reproduction in plants. Chlorophyll *a* concentrations are measured in $\mu\text{g/L}$ and are used as estimate of the total biomass of phytoplankton cells in the water column. In general, high levels of chlorophyll *a* concentrations are believed to be indicative of excessive growth of phytoplankton resulting from excess nutrients such as nitrogen and phosphorus in the water column.

Chlorophytes - algae belonging to the division Chlorophyta often referred to as true "green algae." Chlorophytes occur in unicellular, colonial and filamentous forms and are generally more common in tidal freshwater and oligohaline portions of estuaries.

Cryptomonads -algae belonging to the division Cryptophyta that have accessory pigments in addition to chlorophyll *a* which give these small, flagellated cells a red, brown, or yellow color.

Cyanophytes - algae belonging to the division Cyanophyceae that are procaryotic and that occur in single-celled, filamentous, and colonial forms. In general, high concentrations of cyanobacteria are considered indicative of poor water quality.

Diatoms - algae belonging to the division Bacillariophyta that have a cell wall that is composed primarily of silica and that consists of two separate halves. Most diatoms are single celled, but some are colonial and filamentous forms. Diatoms are generally considered to be indicative of good water quality and are appropriate food for many zooplankton.

Dinoflagellates - biflagellated, predominately unicellular protists that are capable of photosynthesizing. Many dinoflagellates are covered with cellulose plates or with a series of membranes. Some dinoflagellates periodically reproduce in large numbers causing blooms that are often referred to as "red tides." Certain species produce toxins and blooms of these forms have been implicated in fish kills. High concentrations of dinoflagellates are generally considered indicative of poor water quality.

Dissolved oxygen (DO) - the concentration of oxygen in solution in the water column, measured in mg/L . Most organisms rely on oxygen for cellular metabolism and as a result low levels of dissolved oxygen

adversely affect important living resources such as fish and the benthos. In general, dissolved oxygen levels decrease with increasing pollution.

Dissolved inorganic nitrogen (DIN) - the concentration of inorganic nitrogen compounds including ammonia (NH_4), nitrates (NO_3) and nitrites (NO_2) in the water column measured in mg/L. These dissolved inorganic forms of nitrogen are directly available for uptake by phytoplankton by diffusion without first undergoing the process of decomposition. High concentrations of dissolved inorganic nitrogen can result in excessive growth of phytoplankton which in turn can adversely affect other living resources.

Dissolved inorganic phosphorus (PO₄F) - the concentration of inorganic phosphorus compounds consisting primarily of orthophosphates (PO_4). The dissolved inorganic forms of phosphorus are directly available for uptake by phytoplankton by diffusion without first undergoing the process of decomposition. High concentrations of dissolved inorganic phosphorus can result in excessive growth of phytoplankton which in turn can adversely affect other living resources.

Estuary - A semi-enclosed body of water that has a free connection with the open sea and within which seawater is diluted measurably with freshwater derived from land drainage.

Eucaryote - organisms the cells of which have discrete organelles and a nucleus separated from the cytoplasm by a membrane.

Fall-line - location of the maximum upstream extent of tidal influence in an estuary typically characterized by a waterfall.

Fixed Point Stations - stations for long-term trend analysis whose location is unchanged over time.

Flow adjusted concentration (FAC) - concentration value which has been recalculated to remove the variation caused by freshwater flow into a stream. By removing variation caused by flow, the effects of other factors such as nutrient management strategies can be assessed.

Habitat - a local environment that has a community distinct from other such habitat types. For the B-IBI of Chesapeake Bay, seven habitat types were defined as combinations of salinity and sedimentary types - tidal freshwater, oligohaline, low mesohaline, high mesohaline sand, high mesohaline mud, polyhaline sand and polyhaline mud.

Hypoxic - condition in which the water column is characterized by dissolved oxygen concentrations less than 2 mg/L but greater than 0 mg/L. Hypoxic conditions typically result from excessive decomposition of organic material by bacteria, high respiration by phytoplankton, stratification of the water column due to salinity or temperature effects or a combination of these factors. Hypoxic conditions can result in fish kills or localized extinction of benthic communities.

Light attenuation (KD) - Absorption, scattering, or reflection of light by dissolved or suspended material in the water column expressed as the change in light extinction per meter of depth. Light attenuation reduces the amount of light available to submerged aquatic vegetation.

Loading - the total mass of contaminant or nutrient added to a stream or river generally expressed in kg/yr or lbs/yr.

Macrobenthos - a size category of benthic organisms that are retained on a mesh of 0.5 mm.

Mesohaline - refers to waters with salinity values ranging between 0.5 and 18.0 ppt.

Metric - a parameter or measurement of community structure (e.g., abundance, biomass, species diversity).

Non-point source - a source of pollution that is distributed widely across the landscape surrounding a water body instead of being at a fixed location (e.g., run-off from residential and agricultural land).

Oligohaline - refers to waters with salinity values ranging between 0.5 and 5.0 ppt.

Percent of light at the leaf surface (PLL) - the percentage of light at the surface of the water column that reaches the surface of the leaves of submerged aquatic vegetation generally estimated for depths of 0.5 m and 1.0 m. Without sufficient light at the leaf surface, submerged aquatic plants cannot perform photosynthesis and hence cannot grow or reproduce.

Phytoplankton - that portion of the plankton capable of producing its own food by photosynthesis. Typical members of the phytoplankton include diatoms, dinoflagellates, and chlorophytes.

P-IBI - the phytoplankton index of biotic integrity (Buchanan et al., 2005; Lacouture et al., 2006). The P-IBI is a multi-metric index that compares the condition of a phytoplankton community to reference conditions.

Picoplankton - phytoplankton with a diameter between 0.2 and 2.0 μm . Picoplankton consist primarily of cyanobacteria, and high concentrations of picoplankton are generally considered to be indicative of poor water quality conditions.

Pielou's evenness - an estimate of the distribution of proportional abundances of individual species within a community. Evenness (J) is calculated as follows: $J=H'/\ln S$ where H' is the Shannon - Weiner diversity index and S is the number of species.

Plankton - aquatic organisms that drift within and that are incapable of movement against water currents. Some plankton have limited locomotor ability that allows them to change their vertical position in the water column.

Point source - a source of pollution that is concentrated at a specific location such as the outfall of a sewage treatment plant or factory.

Polyhaline - refers to waters with salinity values ranging between 18.0 and 30 ppt.

Primary productivity - the rate of production of living material through the process of photosynthesis that for phytoplankton is typically expressed in grams of carbon per liter of water per hour. High rates of primary productivity are generally considered to be related to excessive concentrations of nutrients such as nitrogen and phosphorus in the water column.

Probability based sampling - all locations within a stratum have an equal chance of being sampled. Allows estimation of the percent of the stratum meeting or failing the benthic restoration goals.

Prokaryote - organisms the cells of which do not have discrete organelles or a nucleus (e.g., Cyanobacteria).

Pycnocline - a rapid change in salinity in the water column indicating stratification of water with depth, resulting from either changes in salinity or water temperature.

Random Station - a station selected randomly within a stratum. In every succeeding sampling event new random locations are selected.

Recruitment - The successful dispersal, settlement, and development of larval forms of plants or animal to a reproducing adult.

Reference condition - the structure of benthic communities at reference sites.

Reference sites - sites determined to be minimally impacted by anthropogenic stress. Conditions at these sites are considered to represent goals for restoration of impacted benthic communities. Reference sites were selected by Weisberg et al. (1997) as those outside highly developed watersheds, distant from any point-source discharge, with no sediment contaminant effect, with no low dissolved oxygen effect, and with a low level of organic matter in the sediment.

Restoration Goal - refers to obtaining an average B-IBI value of 3.0 for a benthic community indicating that values for metrics approximate the reference condition.

Riparian Buffer - An area of trees and shrubs a minimum of 100 feet wide located up gradient, adjacent, and parallel to the edge of a water feature which serves to: 1) reduce excess amounts of sediment, organic matter, nutrients, and other pollutants in surface runoff, 2) reduce soluble pollutants in shallow ground water flow, 3) create shade along water bodies to lower aquatic temperatures, 4) provide a source of detritus and large woody debris for aquatic organisms, 5) provide riparian habitat and corridors for wildlife, and 6) reduce erosion of streambanks and shorelines.

Salinity - the concentration of dissolved salts in the water column measured in mg/L, ppt or psu. The composition and distribution of plant and animal communities is directly affected by salinity in estuarine systems. The effects of salinity on living resources must be taken into consideration when interpreting the potential effects of human activities on living resources.

Secchi depth - the depth of light penetration expressed in meters as measured using a Secchi disk. Light penetration depth directly affects the growth and recruitment of submerge aquatic vegetation.

Shannon Weiner diversity index - a measure of the number of species within a community and the relative abundances of each species.

Stratum - a geographic region of unique ecological condition or managerial interest.

Submerged aquatic vegetation (SAV) - rooted vascular plants (e.g., *Zostera marina* (eelgrass), *Ruppia maritima* (widgeon grass), *Stuckenia pectinata* (sago pondweed)) that grow in shallow water areas. SAV are important in marine environments because they serve as major food source, provide refuge for juvenile crabs and fish, stabilize sediments preventing shoreline erosion and excessive suspended materials in the water column, and produce oxygen in the water column.

Threshold - a value of a metric that determines the B-IBI scoring. For all metrics except abundance and biomass, two thresholds are used - the lower 5th percentile and the 50th percentile (median) of the distribution of values at reference sites. Samples with metric values less than the lower 5th percentile are

scored as a 1. Samples with values between the 5th and 50th metrics are scored as 3, and values greater than the 50th percentile are scored as 5. For abundance and biomass, values below the 5th and above the 95th percentile are scored as 1, values between the 5th and 25th and the 75th and 95th percentiles are scored as 3 and values between the 25th and 75th percentiles are scored as 5.

Tidal freshwater - refers to waters with salinity values ranging between 0 and 0.5 ppt which are located in the upper reaches of the estuary at or just below the maximum upstream extent of tidal influence.

Total nitrogen (TN) - the concentration of both inorganic and organic compounds in the water column which contain nitrogen measured in mg/L. Nitrogen is a required nutrient for protein synthesis. Inorganic forms of nitrogen are directly available for uptake by phytoplankton while organic compounds must first be decomposed by bacteria prior to being available for use for other organisms. High levels of total nitrogen are considered to be detrimental to living resources either as a source of nutrients for excessive phytoplankton growth or as a source of excessive bacterial decomposition that can increase the incidence and extent of anoxic or hypoxic events.

Total phosphorus (TP) - the concentration of both inorganic and organic compounds in the water column which contain phosphorus measured in mg/L. Phosphorus is a required nutrient for cellular metabolism and for the production of cell membranes. Inorganic forms of phosphorus are directly available for uptake by phytoplankton while organic compounds must first be decomposed by bacteria prior to being available for use for other organisms. High levels of total phosphorus are considered to be detrimental to living resources either as a source of nutrients for excessive phytoplankton growth or as a source of excessive bacterial decomposition that can increase the incidence and extent of anoxic or hypoxic events.

Total suspended solids (TSS) - the concentration of suspended particles in the water column, measured in mg/L. The composition of total suspended solids includes both inorganic (fixed) and organic (volatile) compounds. The fixed suspended solids component is comprised of sediment particles while the volatile suspended solids component is comprised of detrital particles and planktonic organisms. The concentration of total suspended solids directly affects water clarity which in turn affects the development and growth of submerged aquatic vegetation.

Appendix B

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

- Bottom Total Nitrogen

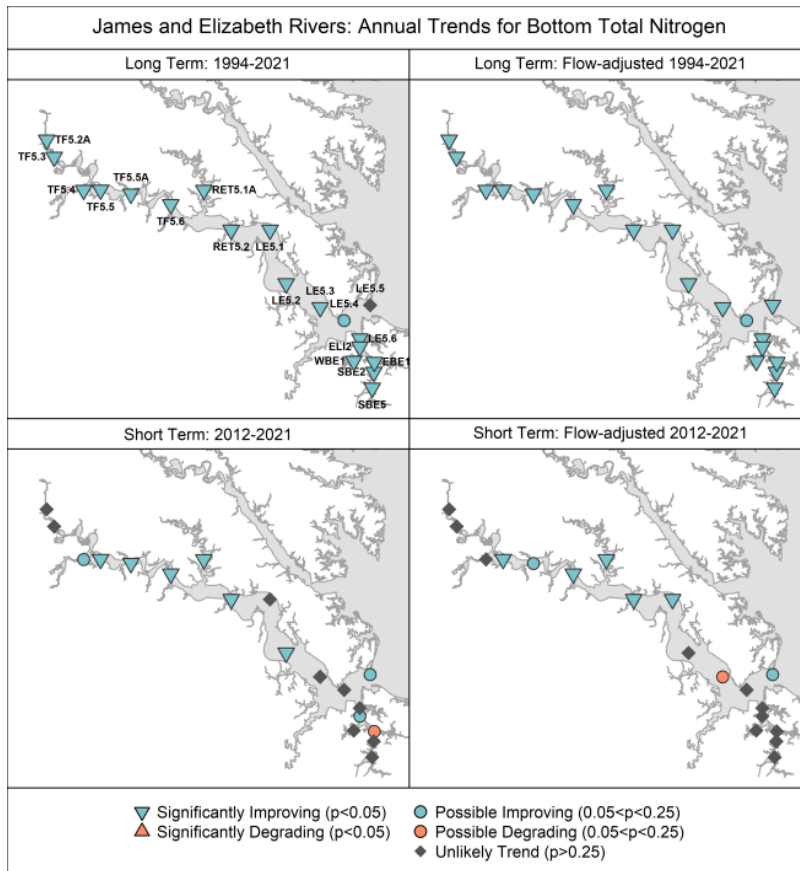


Figure A1. Annual bottom total nitrogen trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

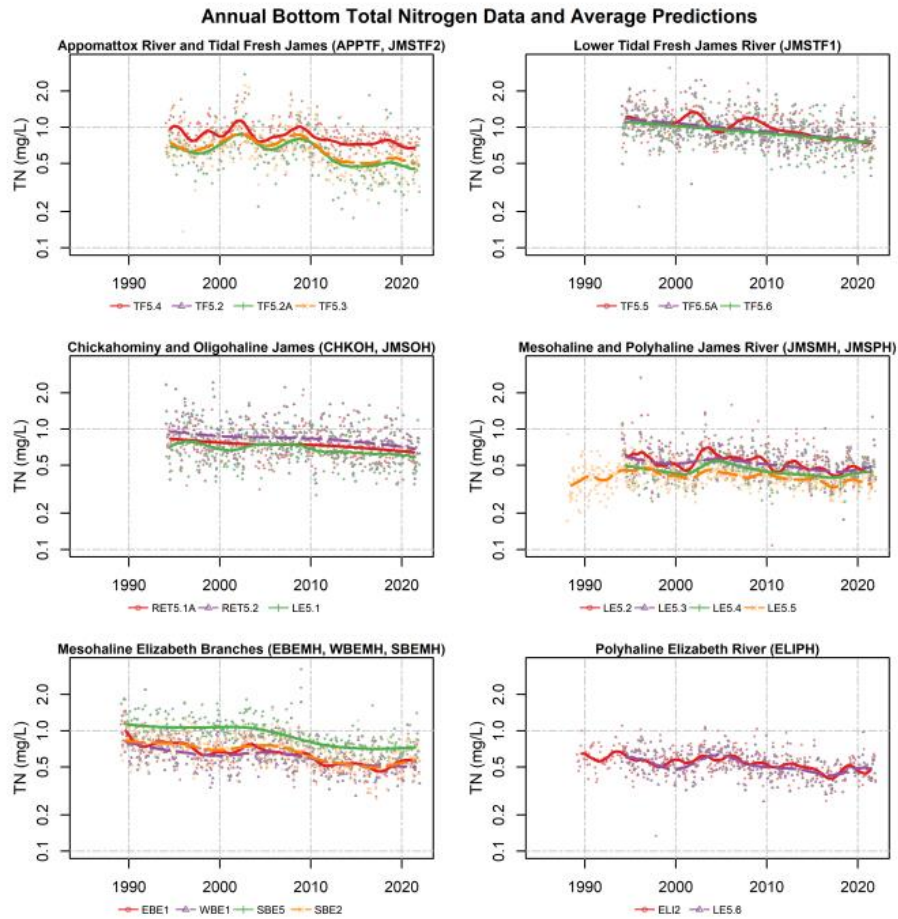


Figure A2. Annual bottom total nitrogen data (dots) and average long-term pattern generated from non-flow adjusted Generative Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

- Bottom Total Phosphorus

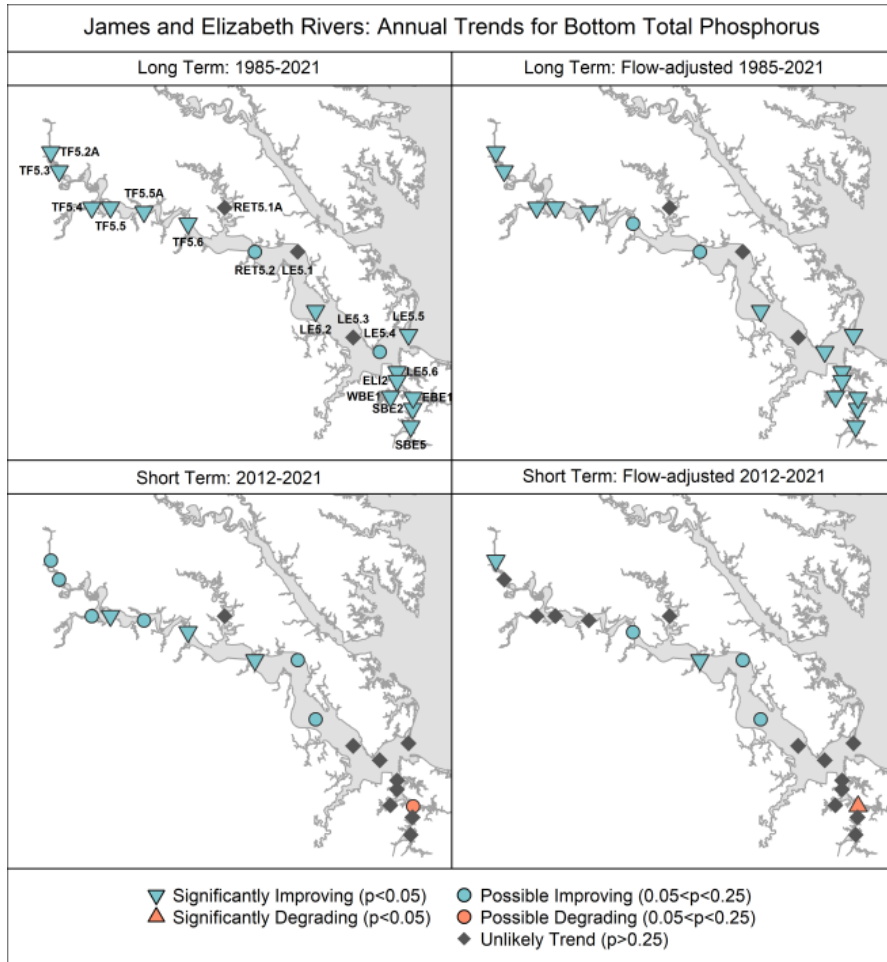


Figure A3. Annual bottom total phosphorus trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

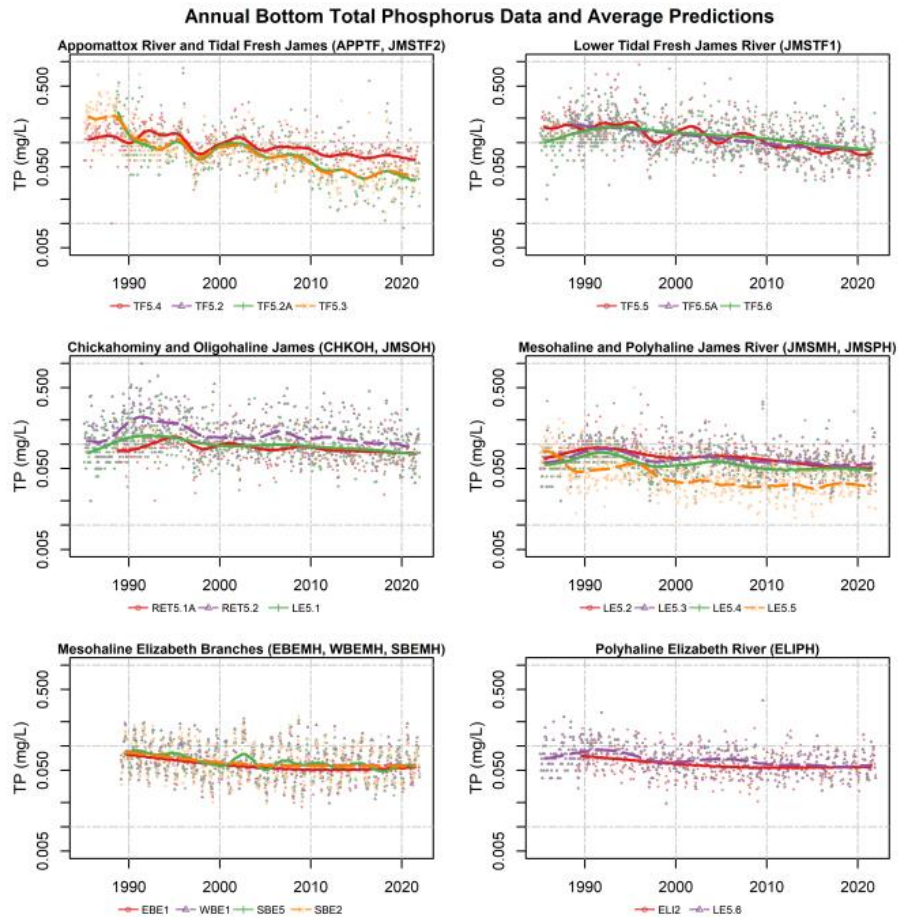


Figure A4. Annual bottom total phosphorus data (dots) and average long-term pattern generated from non-flow adjusted Generative Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

- Surface Dissolved Inorganic Nitrogen

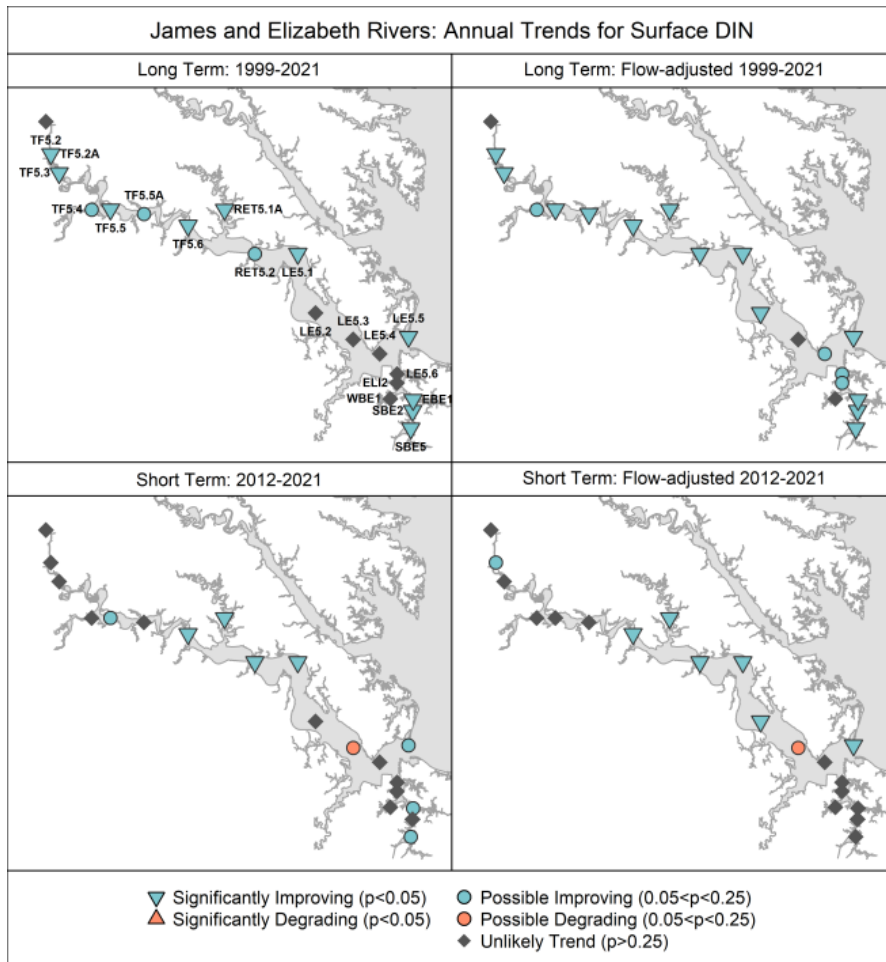


Figure A5. Annual surface dissolved inorganic nitrogen trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

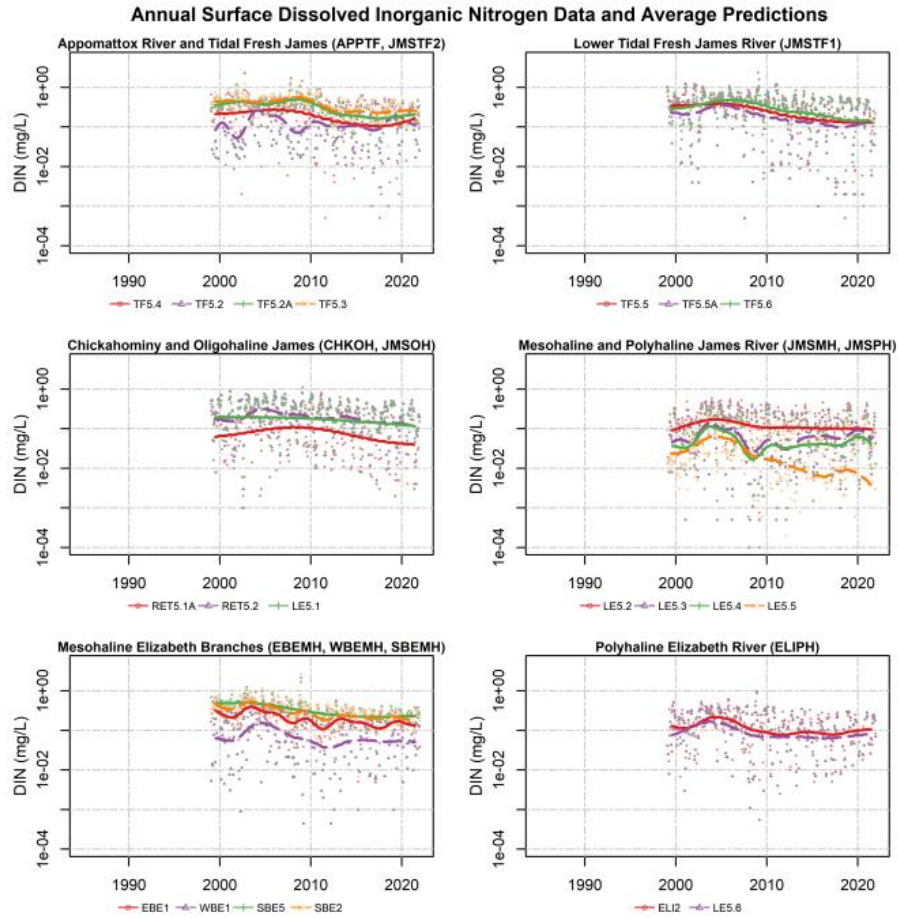


Figure A6. Annual surface dissolved inorganic nitrogen data (dots) and average long-term pattern generated from non-flow adjusted Generative Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

- Surface Orthophosphate

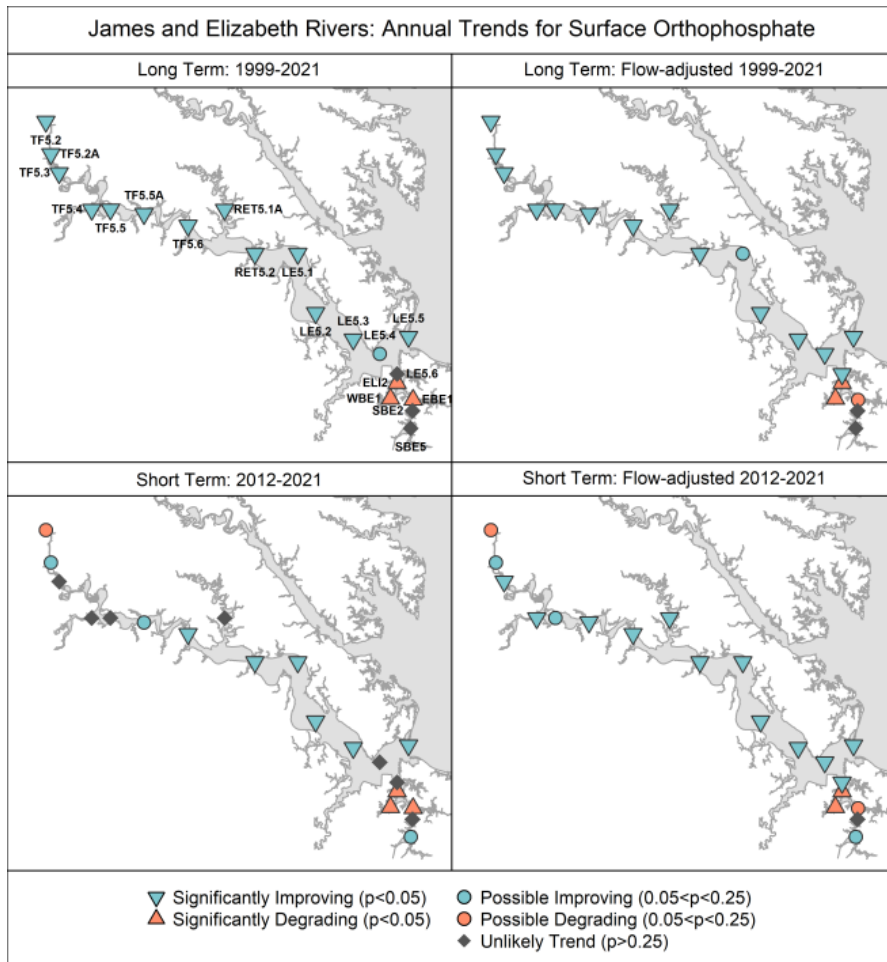


Figure A7. Annual surface orthophosphate trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Annual Surface Orthophosphate Data and Average Predictions

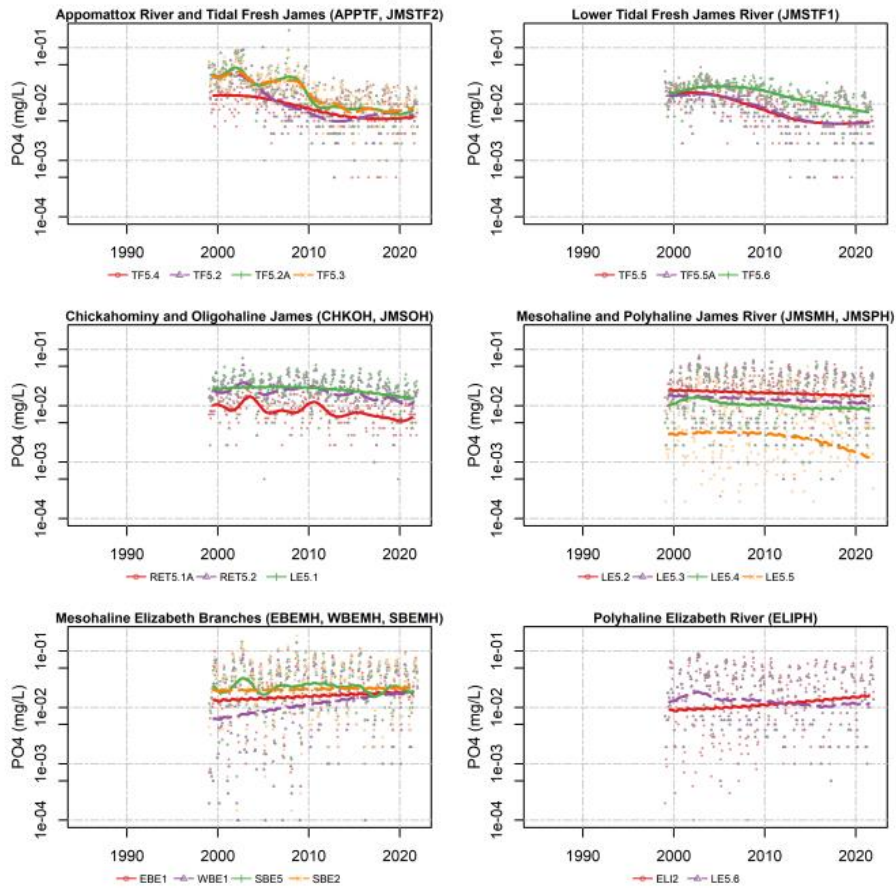


Figure A8. Annual surface orthophosphate data (dots) and average long-term pattern generated from non-flow adjusted Generative Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

- Surface Total Suspended Solids

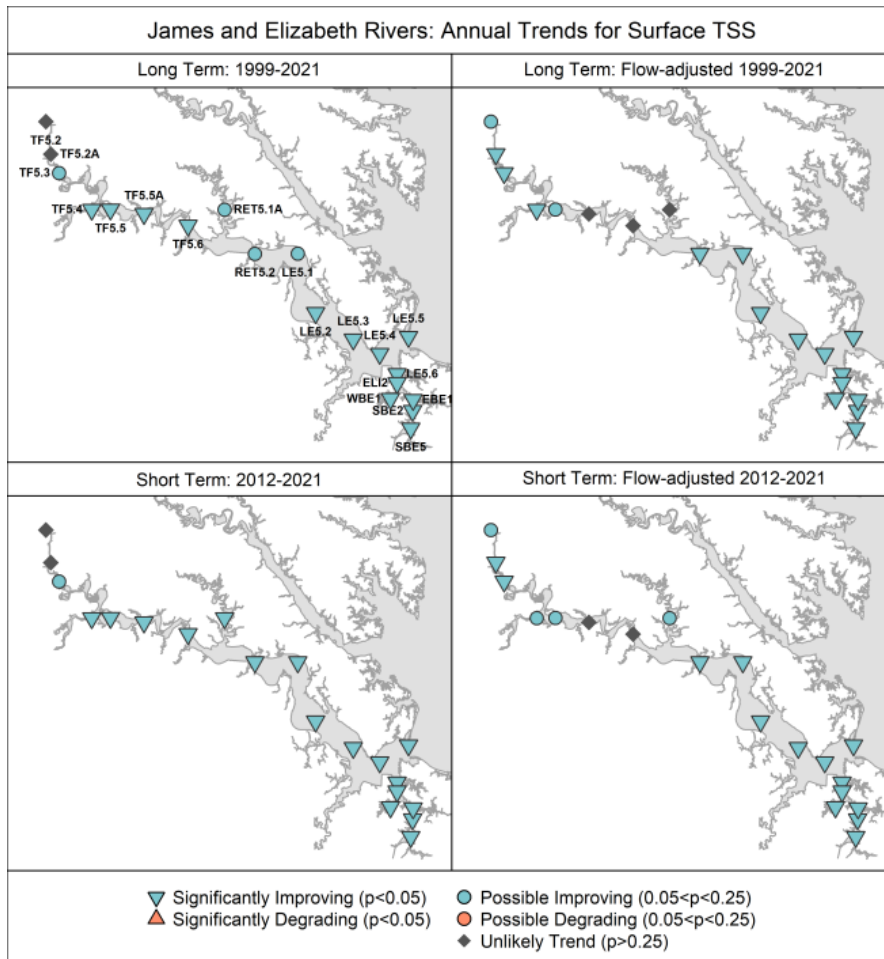


Figure A9. Annual surface total suspended solids trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Annual Surface Total Suspended Solids Data and Average Predictions

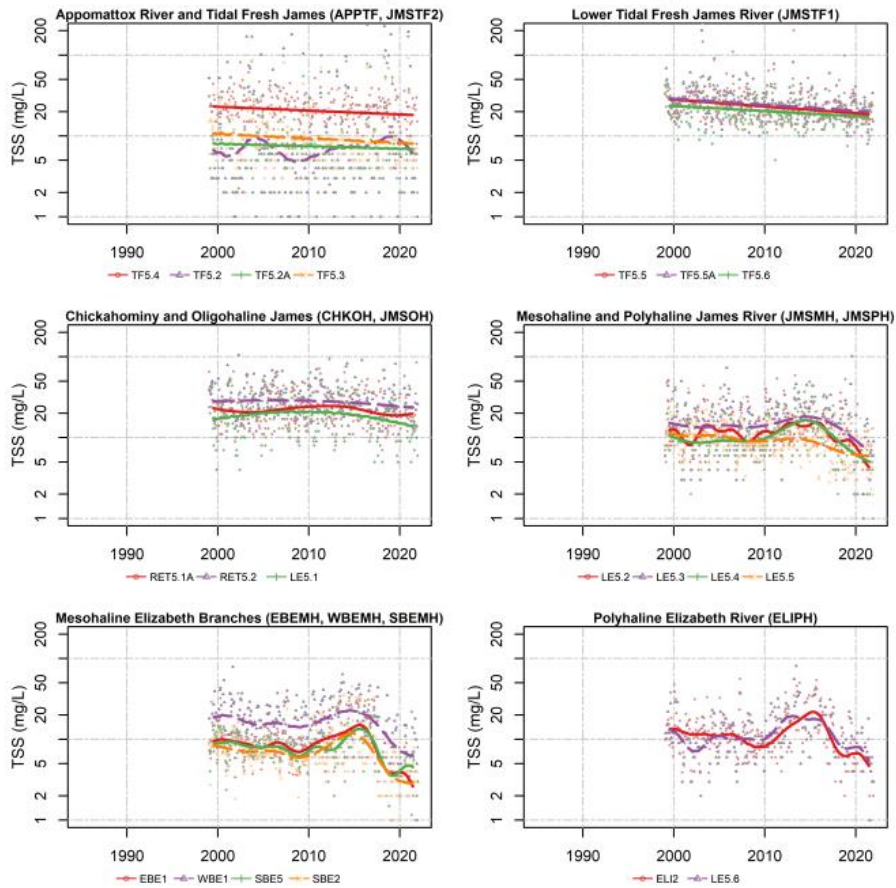


Figure A10. Annual surface total suspended solids (dots) and average long-term pattern generated from non-flow adjusted Generative Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.

- Summer Surface Dissolved Oxygen

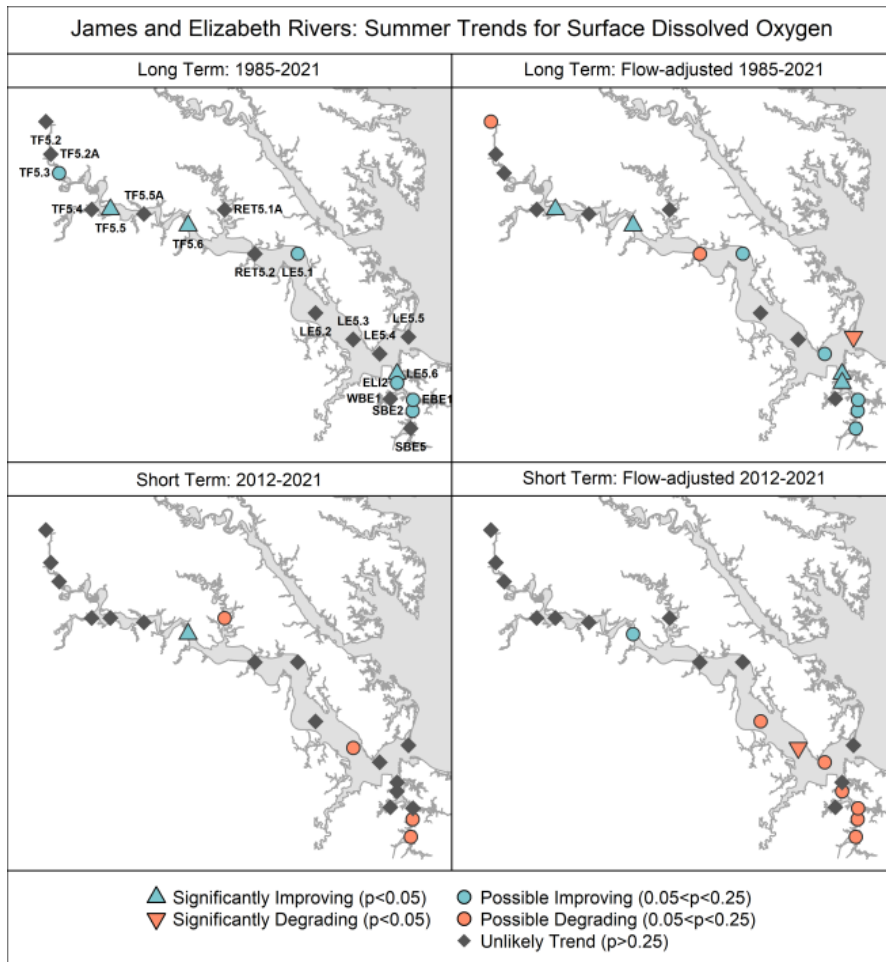


Figure A11. Annual surface dissolved oxygen trends. Base map credit Chesapeake Bay Program, www.chesapeakebay.net, North American Datum 1983.

Summer (June-Sept) Surface DO Data and Average Predictions

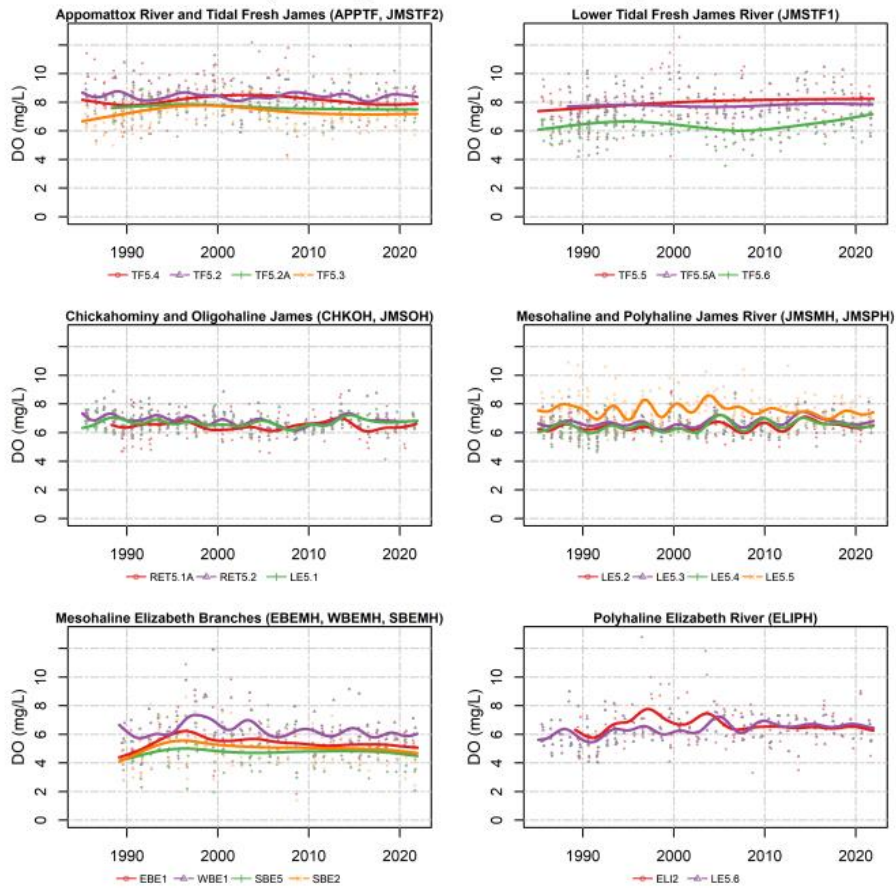


Figure A12. Annual surface dissolved oxygen data (dots) and average long-term pattern generated from non-flow adjusted Generative Additive Models (GAMs). Colored dots represent data corresponding to the monitoring station shown indicated in the legend; colored lines represent mean annual GAM estimates for the noted monitoring stations.