# *Progress toward the Restoration of Chesapeake Bay in Time and Space*

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## Executive Summary

Three decades of monitoring in Chesapeake Bay and tributary rivers has allowed for an examination of the spatial and temporal patterns of water quality change in response to watershed restoration activities. This review of past monitoring data has revealed clear signs of successful water quality remediation in some Chesapeake regions. Upgrades to waste water treatment plants (WWTP) have led to measurable reductions in nutrient concentrations and algal biomass, with associated recoveries of submerged aquatic vegetation and reductions in sediment and nutrient levels. Point-source related improvements were observed in waters local to the WWTP facility, which are generally in oligohaline and tidal freshwater regions of tributaries. Reductions in atmospheric deposition of nitrogen within the Bay watershed has resulted in marked reductions in nitrogen inputs from the Susquehanna and Potomac Rivers, and these reductions in watershed input have resulted in  lower concentrations within the estuary. Coastal plain watersheds with high agricultural intensity continue to yield high amounts of nutrients, and water quality has not improved in the receiving waters of many of these tributaries. Signs of eutrophication remediation are clearest where nutrient load reductions are large and local. In more seaward estuarine reaches, recovery from eutrophication appears to be season- and region-specific, where the late growing season period in high-salinity waters, which is most vulnerable to nutrient limitation and oxygen replenishment, appear to have recovered first. These findings suggest a refinement of our existing conceptual models of the eutrophication process in Chesapeake Bay, where time of year and proximity to nutrient sources are important to understanding spatial and temporal variation in recovery.

## Sources of Data

We evaluated the following data sets in this review of water quality change in Chesapeake Bay

- Nutrient and freshwater loading rates from nine USGS gauging stations which include all major tributaries to the Bay
- Nutrient and freshwater loading rates for watershed areas not included in the gauged regions
- Nutrient loading rates from wastewater treatment plants
- Nutrient and chlorophyll concentrations and Secchi Depths in the Bay and its tributaries
- Results from recent trend analyses addressing water quality change in the Bay

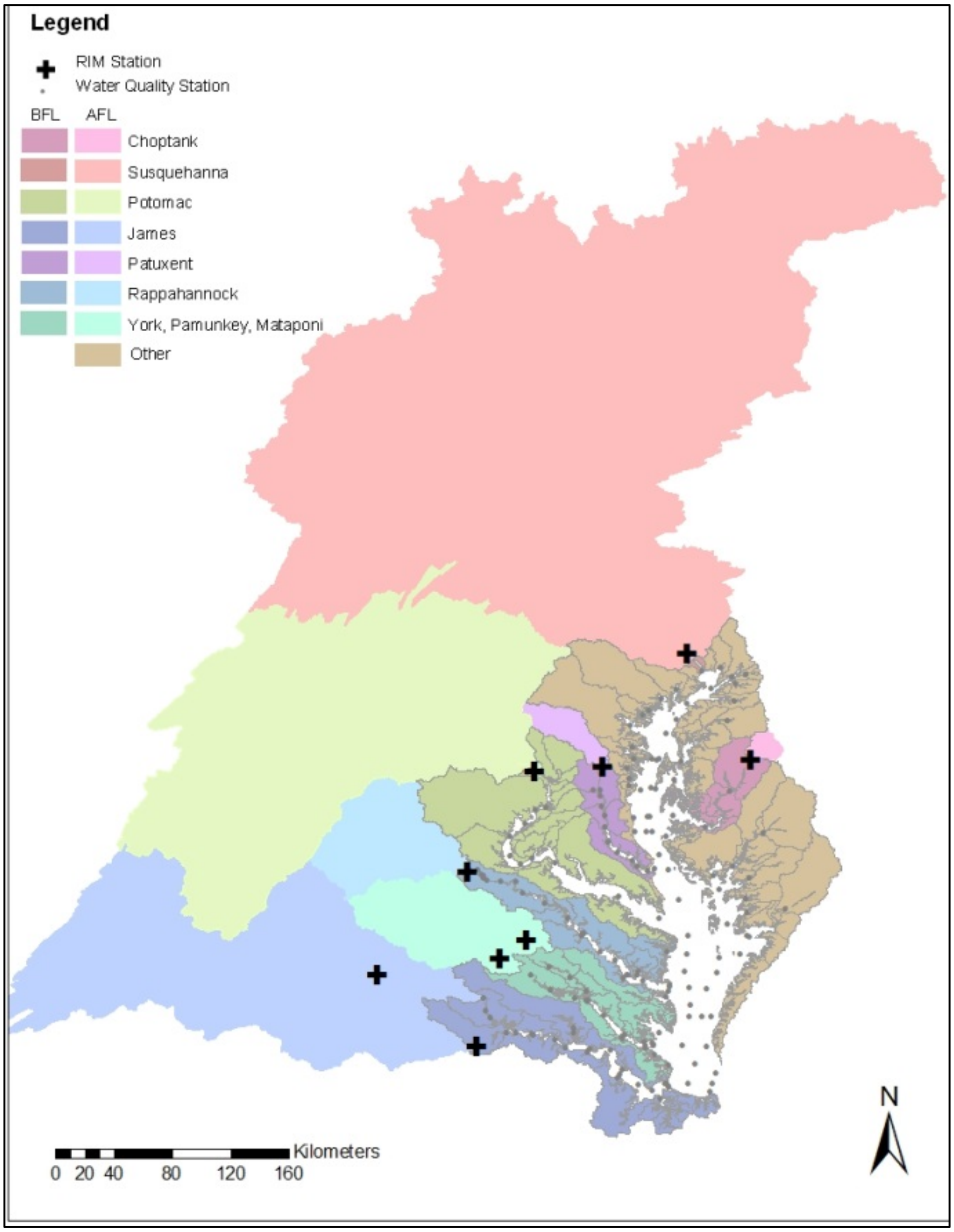

Figure 1. Map of Chesapeake Bay watershed, with USGS gauging stations (+. Above Fall-Line, or AFL) and non-gauged watershed areas (Below Fall-Line, or BFL and bounded by black lines) defined, as well locations of long-term water quality monitoring stations (circles)

### *Finding #1 Advances in Wastewater Treatment have led to Clear Improvements*

(a) *Advances in wastewater treatment have resulted in widespread reductions in nutrient loads to the Bay*. This includes the Back River, Potomac River, James River, Patuxent River, and Patapsco River (Fig. 2). While many of these systems continue to have degraded water quality in some regions or times of year, conditions have measurably improved in many.

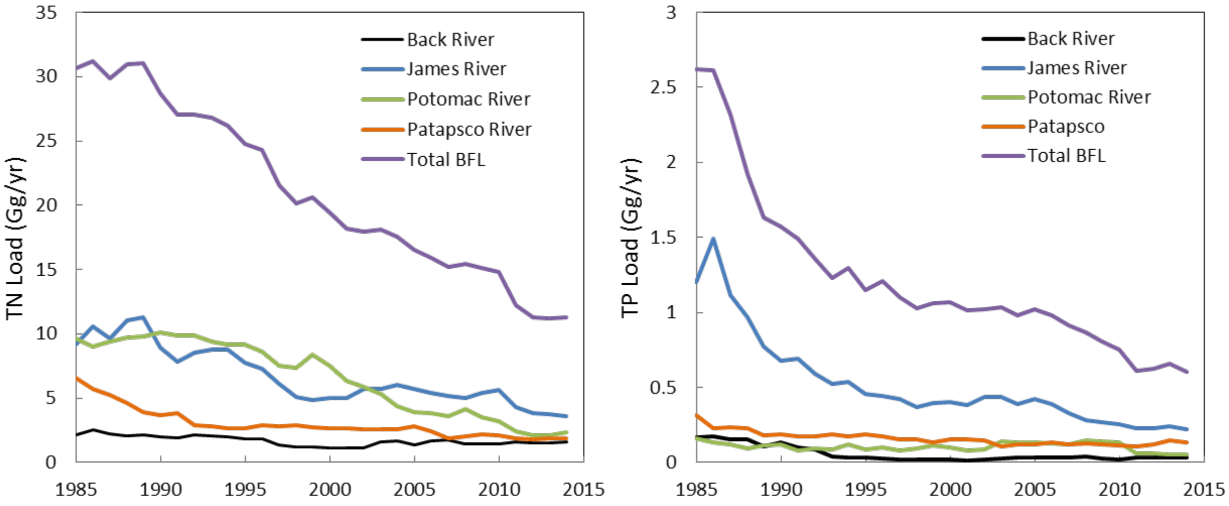

Figure 2: Long-term WWTP nutrient inputs to below fall line waters for TN (left) and TP (right) for four major tributaries and the overall Chesapeake Bay.

(b) *Ecological recovery has been observed in response to WWTP load reductions*. In selected tributaries of Chesapeake Bay where large reductions in nutrient loads from WWTPs and other sources have occurred, water quality and SAV coverage improved, such as in Mattawoman Creek (SAV recovery; Fig. 3), the upper Patuxent and James estuaries (nutrient concentrations), and the Back river (reduced chlorophyll-a).

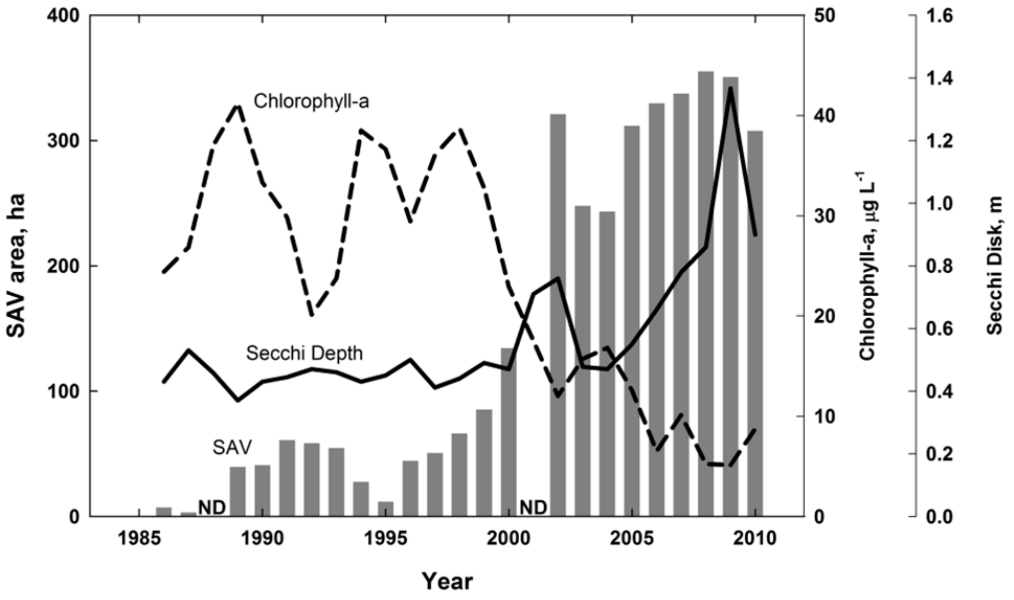

Figure 3: Long-term patterns of chlorophyll-*a*, Secchi Depth, and SAV coverage in Mattawoman Creek over the 1985 to 2010 period. Figure from Boynton et al. (2014).

### *Finding #2 The Bay has benefitted from both proximal and distant nutrient remediation*

Chesapeake Bay water quality responds to both proximate (local, WWTPs) and distant (watershed fertilizer inputs) nutrient inputs. In order to quantify the degree to which nutrient inputs to Chesapeake Bay have decreased during the past thirty years from both of these sources, we compiled estimates of *measurement-based* nutrient loads (TN and TP) from nine fall line monitoring stations (distant inputs; https://cbrim.er.usgs.gov/) with *model-based* estimates of nutrient inputs from coastal plain watershed areas (i.e. proximate inputs) from the Chesapeake Bay Program Watershed Model Phase 6 draft simulations. Both loading estimates include nutrient inputs associated with a combination of agricultural, urban, and wastewater inputs. The model estimates included model output for both *point* and *non-point* sources. Results from comparing three years periods at the beginning and end of the record indicate that TN and TP loads to the Bay were 27% and 23% (respectively) lower in 1989-1991 as compared to 2012-2014. Declines in distant and proximate inputs have contributed approximately equally to the overall change (Fig. 4), though proportional declines were greater for modeled proximate inputs (TN=37%, TP=32%) than for observed, distant inputs (TN=21%, TP=17%). Reductions in point sources accounted for the bulk (>80%) of proximate load declines.

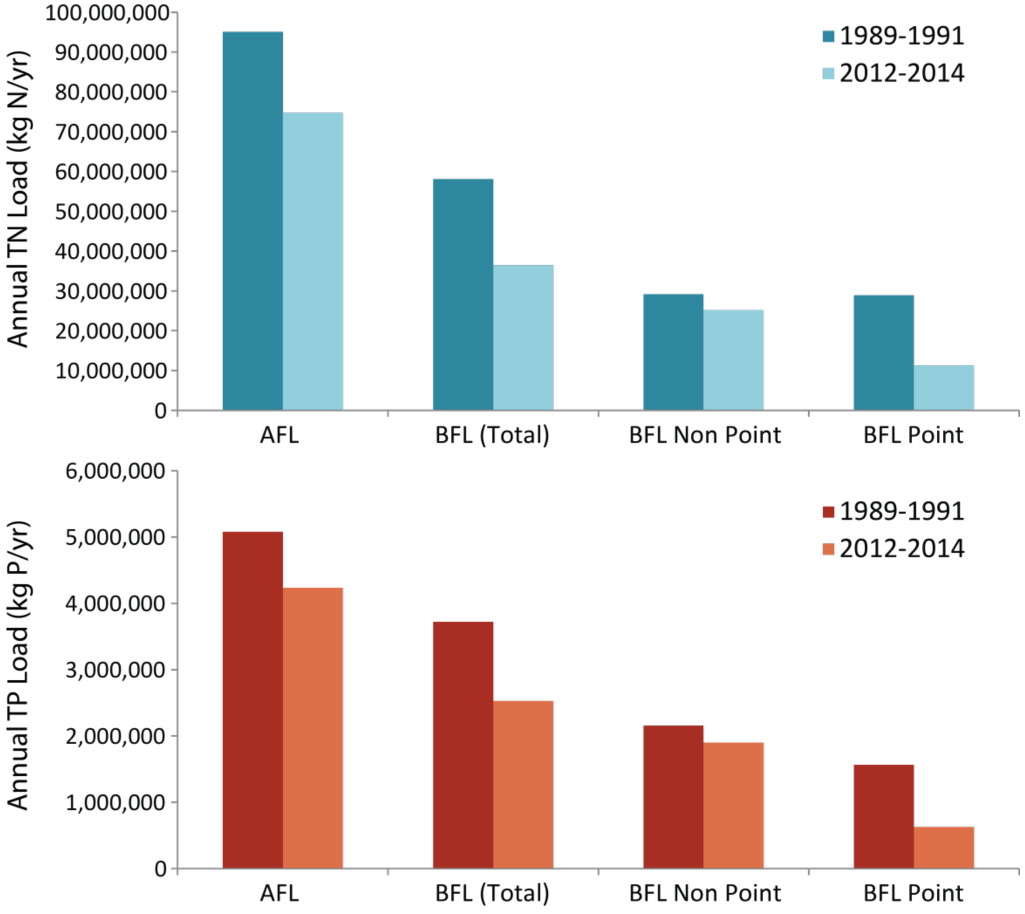

Figure 4: Annual average observed (distant) inputs and modeled (proximate) inputs nutrient loads to Chesapeake Bay during historical (1989-1991) and recent (2012-2014) periods (units are kg/y; multiply by 2.2 for million lbs/yr). Modeled proximate loads are separated into Non Point (runoff, streamflow) and Point (e.g., wastewater treatment plants) sources.

While there are a number of factors leading to nutrient load declines to Chesapeake Bay, the two clearest drivers include reductions in atmospheric deposition to the watershed and declines in loads from WWTPs (Fig. 2, 4 & 5). Applications of fertilizer and manure associated with agricultural activities remain high, but crop yields have increased over time, making it difficult to ascertain the transfer of these nutrients to tidal waters. This progress has been difficult to measure at USGS gauging stations because inter-annual variations in freshwater input – and the nutrients carried by those freshwaters – can dominate long-term patterns of nutrient input. Despite this confounding effect, the amount of nutrient load generated by a given freshwater input has declined in some regions, especially from the Susquehanna River (Fig. 5).

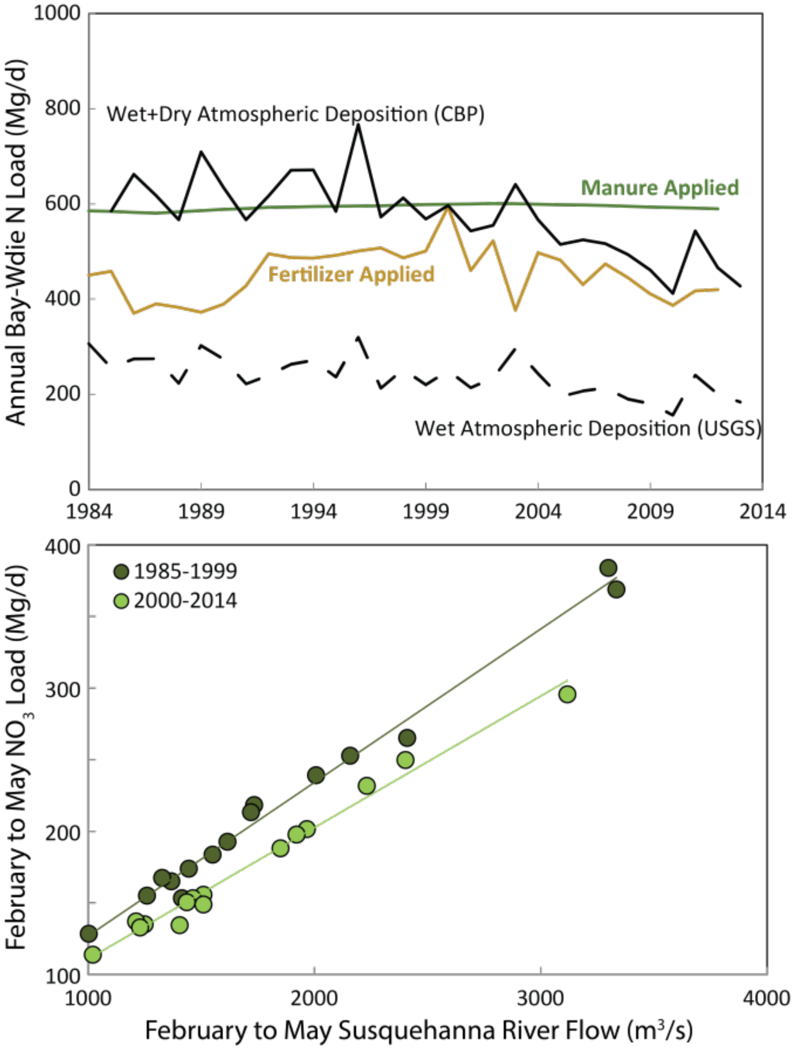

Figure 5: (top) Long-term nutrient inputs to the Chesapeake watershed from atmospheric deposition, fertilizer, and manure applications. (bottom) February to April nitrate load versus discharge (flow) from the Susquehanna River over historic and recent timeframes.

***Finding #3: Estuarine recovery tracks nutrient load reductions.***

We examined the idea that spatial variation in TN and TP concentration changes among estuarine monitoring stations could be explained by changes in TN and TP watershed loads, where both nutrient concentration change and load were aggregated for each of 92 CB segments. To quantify long-term changes, we computed average annual loads (kg/y) and estuarine concentrations (mg/L) for two periods (1989-1991) and (2012-2014). These periods were selected to represent the historic and recent portions of the monitoring record and because they had similar average annual flows (means = 78,667 versus 79,100 cfs) that were representative of long-term average conditions (78,563 cfs; Moyer et al. 2016). Despite the comparable flows broadly between these periods, there was still a local effect of flow on these comparisons on a segment-by-segment basis, where differences in load were strongly related to differences in flow. The results show that the majority of sites exhibited significant decreases between the historic and recent BFL segment loads and estuarine concentrations (79% and 62% of all sites for TN and TP, respectively; Fig. 6). Within this group, the average decline in segment loads (TN = 31%, TP = 34%) was comparable to the average decline in estuarine concentrations (TN = 34%, TP = 24%). A small subset of sites instead exhibited significant increases in both segment BFL load and estuarine concentration (8% and 4% for TN and TP, respectively). Focusing on the subset of estuarine stations exhibiting significant declines in estuarine concentration (N = 116 and 61 for TN and TP, respectively), there was a high concordance with declines in segment loads (87% and 84% agreement for TN and TP, respectively). Instances of stations showing significant increased estuarine concentrations and loads were rare by comparison.

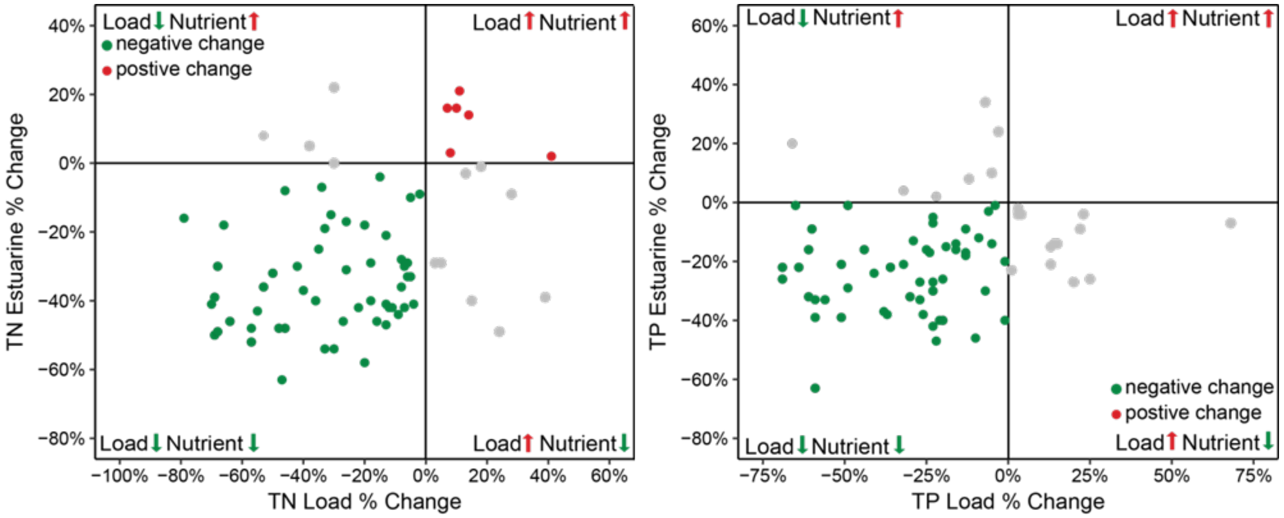

Figure 6. Variation in the % change in estuarine TN and TP concentrations as a function of the % change in segment BFL loads. Statistical analysis of these models is complicated by the fact that individual segments are represented by multiple stations, raising concerns about independent observations (i.e., the dataset includes multiple $y$ estimates associated with a single $x$ value). Therefore, no statistical assessment of these trends is provided.

***Finding #4: Spatial patterns in estuarine recovery are linked to successes in mitigating nutrient loads.***

The most consistent evidence of restoration in Chesapeake Bay is the widespread reduction in total nitrogen concentrations in the tributary-estuary system. Trend analyses of data from many monitoring stations indicated long-term declines in TN concentration during the past 15 years at the majority of the stations monitored (Fig. 7). Widespread reductions in TN are primarily associated with reductions in inputs, particularly the long-term decline in atmospheric deposition and reductions in inputs from many of the watershed's WWTPs, including all of the largest facilities. In general, low-salinity regions of tributaries and the mainstem stations displayed consistent declines in TN concentration, while the moderate salinity regions of the tributaries did not change substantially (Fig. 7). These concurrent declines in both TN input and concentrations display clear evidence that efforts to reduce inputs have direct and positive consequences for the estuary and reveal that nutrient management actions work.

The concentration of phosphorus in the Chesapeake Bay has also declined across large regions of the Bay (Fig. 7). Reductions in phosphorus are most evident in western shore tributaries and high-salinity Bay waters, primarily due to improvements in WWTP operations which resulted in reductions in dissolved phosphorus loads. In contrast, phosphorus concentrations in the middle and upper regions of Chesapeake Bay appear to be stable or increasing, which is likely related to increases in loads from some coastal plain watersheds (e.g., Choptank) and reduced trapping of particulate phosphorus behind Conowingo Dam (a large fraction of phosphorus inputs are associated with sediments). The degree to which particulate phosphorus loads contribute to excessive algal growth remains questionable.

Trends in chlorophyll-*a* paint a more complicated picture (Fig. 7). While surface chlorophyll-*a* values are decreasing in many of the high-salinity and southern tributary regions (consistent with TN and TP declines), chlorophyll-*a* is increasing in the low-salinity regions of Chesapeake Bay and in low-salinity reaches of the Patuxent and Potomac Rivers. In the mainstem, the upper Bay chlorophyll-*a* increases are primarily occurring in cold months (February to March), while the lower Bay declines are primarily occurring in April and May (Testa et al., in prep). Thus, the long-term changes in chlorophyll-*a* concentration appear to be location and season-specific.

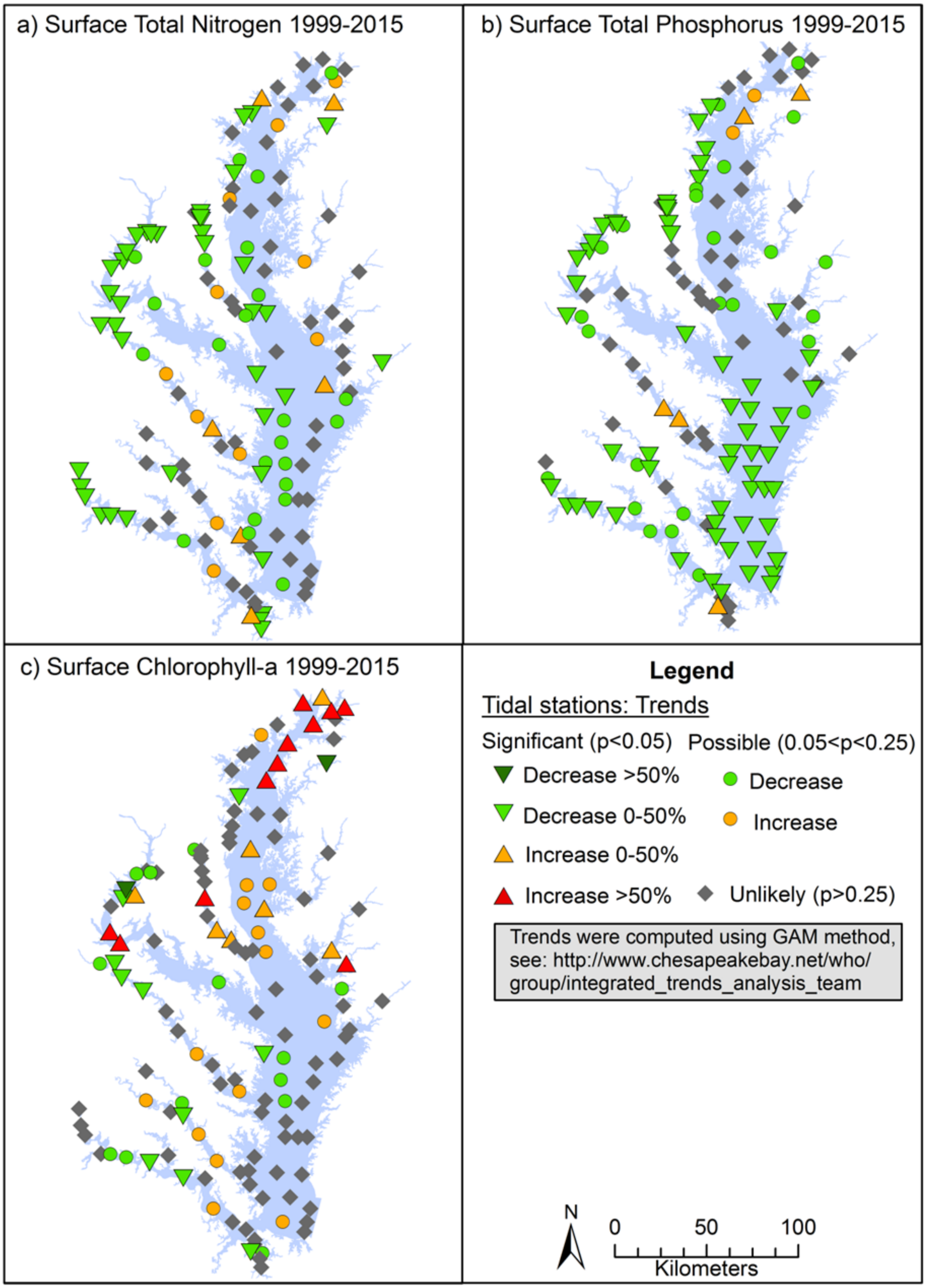

Figure 7: (top) Map of magnitude and direction of trend for total nitrogen (TN), total phosphorus (TP), and chlorophyll-a concentrations in Chesapeake Bay and tributary rivers during the period 1999-2015.

## *Finding #5: Ecological Recovery in Chesapeake Bay: SAV and Dissolved Oxygen*

Tidal water quality trend analyses suggest that over the last 10 years, there has been a reduction in chlorophyll-a (an indicator of phytoplankton biomass) and an associated increase in water clarity (as measured with Secchi Disk Depth) in much of the mainstem Chesapeake Bay (Fig.8). These recent patterns in improvements are consistent with reductions in TN concentrations and the resurgence of submerged aquatic vegetation in many regions of the Bay. Most notably, SAV has shown clear recoveries in low salinity regions of the Bay (e.g., Susquehanna Flats) over the last several decades and more recently in mesohaline regions of the Bay.

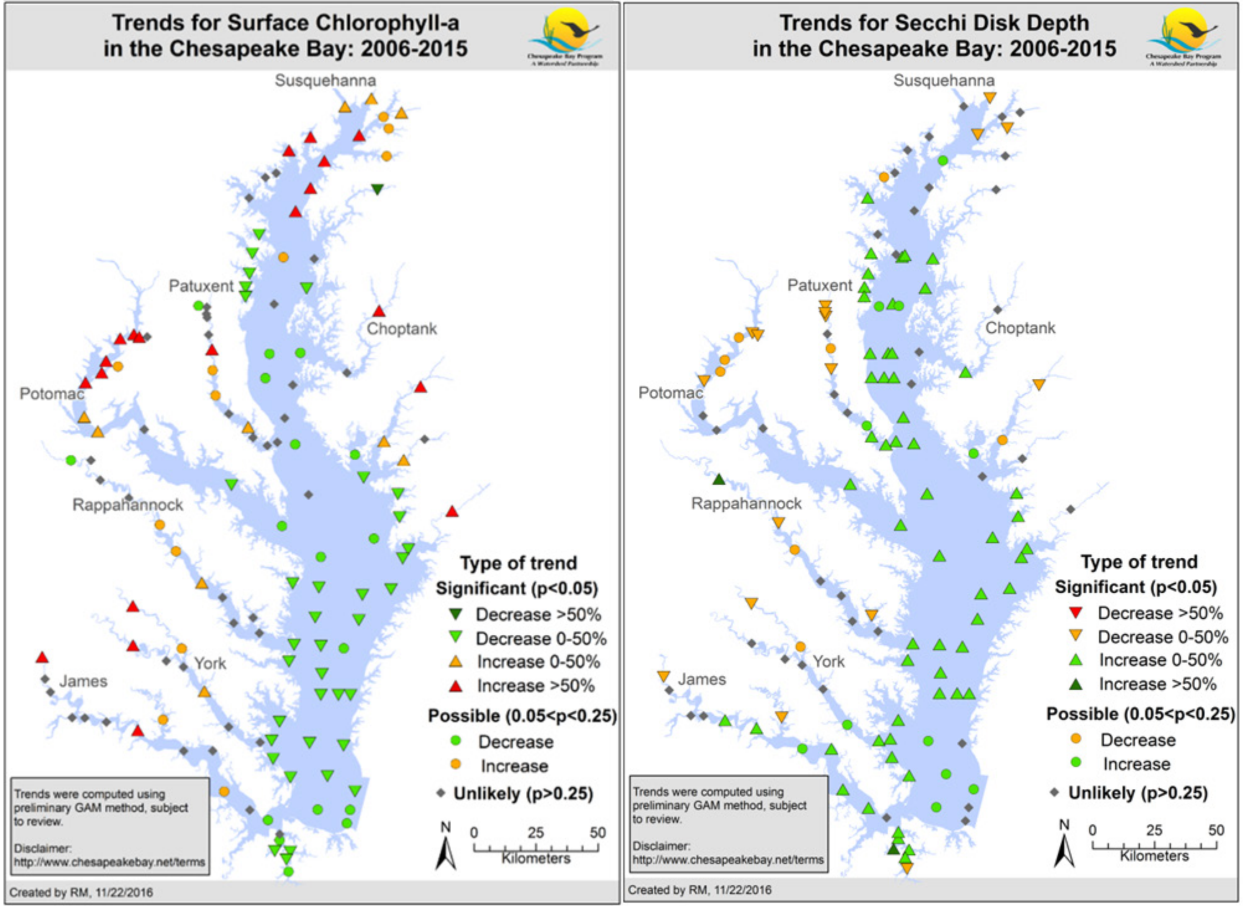

Figure 8: (left) Trend results for annual surface chlorophyll-a (right) and annual Secchi depth for the period between 2006-2015. Arrows indicate direction and color indicates trend significance.

Although annual metrics of hypoxic volume have not changed significantly over time, the late-summer volume of anoxia has declined over the past 30 years and the anoxic volume generated for a given nutrient load has declined. Late-summer (August-September) oxygen concentrations in middle and lower Bay regions have also began to increase, consistent with declines in lower Bay chlorophyll-a in this region during winter-spring and reductions in water-column nitrate concentrations (Fig. 9). In the most recent decade, bottom-water oxygen concentrations are increasing over a larger area of the Bay and its tributaries.

### *Finding #6: Some Aspects of Bay Water Quality Remain Degraded*

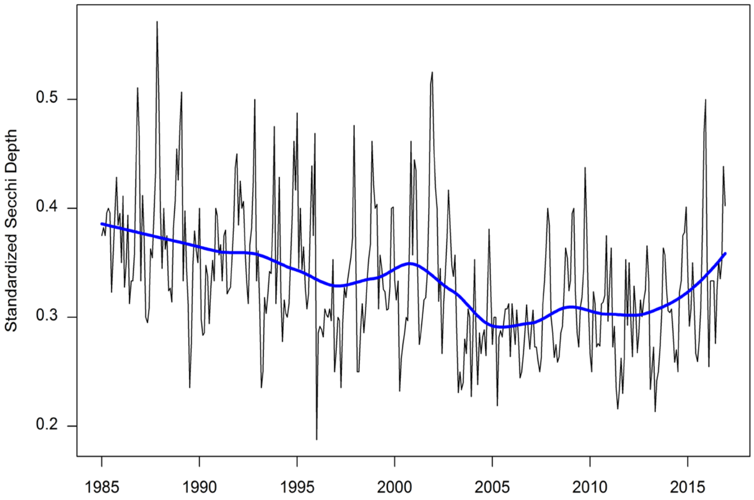

Figure 10: Median of monthly Secchi depths from 133 stations, standardized by the maximal monthly average Secchi depth observed at each station. The superimposed blue line is local regression smoothing (loess).

Clear water is necessary for SAV growth and the amount of light reaching SAV beds is dependent on the concentration of algae, sediments, and colored dissolved material in the water-column, as well as the growth of epiphytic algae on SAV leaves. While water clarity has been increasing over the last decade (Fig. 8), it had previously declined since 1985 (Fig. 10) and poor water clarity remains a problem in large regions of Chesapeake Bay. Trajectories for SAV coverage have been toward stable or lower in higher salinity regions in recent decades (Orth et al. 2017) and while some of these changes are linked to elevated temperatures, reductions in the availability of light and potential depth distribution of SAV has limited habitat for *Zostera* (Lefcheck et al. 2017).

Water temperature and sea level continue to rise (Orth et al. 2017, Ding and Elmore 2015), which will have uncertain future impacts on the Bay, but certainly some effects will inhibit restoration. Chesapeake Bay is perhaps most strongly impacted by freshwater inputs from major rivers (e.g., Harding et al. 2015a), and any future changes in river flow will determine the potential for high algal growth and hypoxic volumes. Recent positive signs in the estuary have come during an extended period of moderate to low freshwater and nutrient inputs and despite the fact that in-river dissolved nutrient concentrations are declining, future periods of elevated freshwater inputs may deliver high amounts of nutrients and support water quality degradation.

Despite reductions in nutrient inputs, integrated annual hypoxic volumes have remained relatively stable over the past 30 years. As the Conowingo reservoir has filled in to reach a state of "dynamic equilibrium", reduced particle trapping has led to increases in particulate nitrogen and phosphorus loading (Zhang et al. 2016). Reductions in nutrient inputs from agriculture have been difficult to achieve, and some eastern shore tributaries fail to show signs of recovery despite BMP implementation (e.g., Choptank River, Corsica River). Groundwater in these coastal plain watersheds has long residence times and may continue to deliver nutrients to local streams and rivers for multiple years to several decades.

## Concluding Comments

**Sewage Treatment Plant Upgrades Work**. Our synthesis, combined with prior studies in the Chesapeake Bay and around the globe, indicated that sewage treatment plant upgrades are an effective means to reduce eutrophication in places where they are the dominant nutrient source. These upgrades have a clear local effect, and help reduce eutrophication effects during periods where watershed freshwater and nutrient inputs are low.

**Nutrients Load Declines are Beginning to Emerge**. With clear declines in atmospheric deposition of nitrogen to the Chesapeake watershed and large reductions in wastewater treatment plant loads to tidal waters, clear reductions in nitrogen loads are apparent. In some cases, these nutrient reductions can be identified in large riverine loads, such as the Susquehanna River. It is difficult to track progress for other non-point sources, such as agriculture, urban and suburban stormwater, and groundwater, and thus it is difficult to quantify increases or decreases in these loads. It is clear, however, that estimated changes in total watershed nutrient inputs are clearly linked to changes in measured estuarine nutrient concentrations.

**The *Space and Time* of 'oligotrophication'.** It has become increasingly clear that the response of an estuarine region to restoration depends on its location along the estuarine salinity gradient. While TN and TP loads and concentrations have generally declined throughout Chesapeake Bay, only a subset of Bay regions have shown evidence for clear ecological recovery (such as SAV, hypoxia). The first of these locations is the tidal fresh and oligohaline regions of tributaries, where SAV recoveries have accelerated in recent years associated with reduced nutrient inputs, but also the expansion of invasive species. Algal biomass has also declined in some of these low-salinity regions, but primarily where substantial reductions of WWTP inputs have occurred. We might expect recovery in these low salinity regions first, given that they are closest to the watershed nutrient source. However, the other regions where recovery appears to have occurred is within the higher-salinity regions, especially during late summer. Nutrient limitation is at its most severe in Chesapeake Bay in this region and season, and we should also expect that recovery from eutrophication (i.e., reduced algal biomass, elevated oxygen) must first occur at the times and places most vulnerable to nutrient poverty (*see companion report*). It is clear that our ability to measure a response to eutrophication reduction is dependent upon the time of year and region of the ecosystem examined. These two features of eutrophication response are consistent with our basic understanding of nutrient impacts on estuaries.