4. Eutrophication

Background

Estuaries are among the most productive ecosystems on earth. They can produce organic material at rates comparable to those in the most intensively cultivated farm fields. Generally, high productivity is a welcome attribute in ecosystems because organisms can use the extra food to build larger and more complex communities. It is, therefore, ironic that some of the most pressing problems in modern estuaries stem from too much production, a condition called eutrophication.

> *Eutrophication - an increase in the rate of supply of organic matter to an ecosystem.*
>
> *- Scott Nixon (1995)*

The concise definition of eutrophication quoted above is deceptively simple. It focuses on the supply rate of organic matter to a water body. In the case of estuaries, this usually refers to the production of plant material via photosynthesis by algae and macroalgae. The organic matter may also originate externally, for example, from pulp mills or sewage plants. Organic matter is important because it is the food that supports all other estuarine organisms.

The definition also stresses that eutrophication is an increase in the supply rate of organic matter. Eutrophication does not refer to estuaries that are especially rich in nutrients or organic matter; rather it pertains to systems that are in transition– a system that is increasing its capacity to generate organic material. If the transition is slow enough that established communities can grow along with the expanding food supply, the result is a bigger, stronger ecosystem. Originally, eutrophication was considered to be a beneficial process. However, if eutrophication is too rapid, the community of organisms cannot keep pace, and excess organic material accumulates and decays, creating serious problems throughout the estuary.

Eutrophication can be attributed to many causes, both natural or anthropogenic. For example, organic production may increase in response to a build up of nutrients in the watershed; eased grazing pressure by herbivores; improved water clarity (which can promote photosynthesis); a diminished flushing rate; or an increase in external sources of organic material in an estuary. In recent decades, the dominant factor has been an intensified supply of nutrients to estuaries, a consequence of the accelerated development of cities, farms, and industries in the watersheds (National Research Council 2000).

The effect of the nutrient over-enrichment has been largely detrimental. The excess nutrients promote episodes of excessive growth of algae in estuaries. The excess algae can form noxious mats that choke beaches and hamper navigation. As the uneaten organic material decays, it depletes oxygen from water and sediments, most persistently in the deep isolated trenches in the region's estuaries, and more ephemerally elsewhere in the water column. The excessive amount of algal material (along with other suspended material) also reduces water clarity, thereby endangering the survival of the critical seagrass habitat. Moreover, rampant algal blooms are often dominated by a single species of non-native algae. On rare occasions, the invading algae may produce toxins that are harmful to fish, shellfish, birds and mammals (including humans). Perhaps the most familiar example involves the organism *Pfiesteria*, which was publicized in outbreaks in North Carolina and Maryland.

It is clear that eutrophication is a complex process, with multiple factors influencing its progress and a diverse array of possible consequences, both beneficial and harmful. It is easy to confuse the causes or effects of eutrophication with the process itself. For instance, an estuary is often considered to be undergoing eutrophication if it is enriched in nutrients or if it has suffered fish kills. It is helpful to use the definition based on the supply rate of organic matter, as was recommended by Nixon (1995). We may then focus on conditions that promote the excess production of organic matter, and further focus on the harmful consequences of the excessive quantities of organic matter. In this way, we may better understand the processes that govern eutrophication, and have a better chance of controlling the adverse effects.

Eutrophication Indicators

A broad suite of physical, chemical, and biological parameters was measured during the MAIA-E program. Six of these parameters describe important aspects of eutrophication and are used to assess conditions in the mid-Atlantic estuaries. These "indicator parameters" are:

- Total Nitrogen in surface water
- Total Phosphorus in surface water
- Chlorophyll *a* in surface water
- Total Organic Carbon in sediments
- Water Clarity (Secchi depth)
- Dissolved Oxygen in bottom water

Total nitrogen and phosphorus are nutrients that are likely causes of eutrophication. Chlorophyll *a* and total organic carbon are measures of the buildup of organic matter which defines eutrophication. Diminished water clarity and depleted oxygen supplies represent harmful consequences of eutrophication. None are a perfect indicator, but together they may identify estuaries undergoing eutrophication.

Note on the presentation of data

The measured data are displayed on maps, using three categories to show condition. When the categories are defined in terms of well-established criteria, they are labeled "good," "fair," and "poor" and the map symbols are colored green, yellow, and red as an aid to interpretation. In several cases the categories are defined by criteria that are still under evaluation; therefore, the maps are colored and labeled more neutrally. Included on each map is a graph that shows the percentage of estuarine area that falls into each condition category. A listing of these estimates is included in Appendix E, and measured values are displayed on plots in Appendix D.

Total Nitrogen in Surface Water

Estuarine plants need both nitrogen and phosphorus nutrients provided roughly in a fixed ratio in order to grow. Normally, there is plenty of phosphorus in estuarine waters but relatively little nitrogen. Nitrogen is, therefore, called the "limiting" nutrient because algal growth stops when nitrogen is depleted. When too much nitrogen is available, the algae may grow unchecked and cause harmful blooms. Excess nitrogen also promotes the proliferation of epiphytes (surface algae) to the detriment of seagrasses.

The nitrogen cycle in estuaries is complex. There are several types of nitrogen nutrients, each serving a distinct function. Dissolved inorganic nitrogen or DIN (e.g., nitrate, nitrite, and ammonium) is preferred by plants but is usually depleted by early summer. Dissolved organic and particulate forms of nitrogen are released more gradually during summer and are used by algae to sustain plant blooms. Total nitrogen (TN) is the combination of all organic and inorganic, and dissolved and particulate forms of nitrogen nutrients.

Ecologists have historically measured DIN in estuarine assessments, largely because of the difficulty of measuring other components reliably. Thresholds indicating impairment are, therefore, most often defined in terms of DIN. Federal and state regulatory agencies now recommend using TN as the best measure of year-round availability of nitrogen nutrients (EPA 2001). Accordingly, we use TN as the indicator of nutrient condition in this summary. As yet, there are no firm criteria for defining TN categories of impairment. We, therefore, define three categories based on relative values measured in the MAIA program.

Total Nitrogen - Surface Layer

Method: Total Nitrogen (TN) is calculated as the sum of two parameters measured in the MAIA program: the concentrations of total dissolved nitrogen and particulate organic nitrogen. This is equivalent to the sum of all organic and inorganic, dissolved and particulate forms of nitrogen. Water samples were collected one meter below the surface.
Units: mg N/L; equivalent to ppm.
Assessment categories:
- Low: < 0.5 mg N/L
- Intermediate: > 0.5 to 1.0 mg N/L
- High: > 1.0 mg N/L

Range of data: 0.1 to 2.9 mg N/L

The thresholds used to define these categories are the 25th and 75th percentile of all MAIA TN values. While not definitive indications of degradation, the categories are useful when comparing the availability of nutrients among neighboring estuaries.

Figures 4-1 and 4-2 are maps showing the distributions of total nitrogen in the MAIA region and in the intensively-sampled systems.

- Delaware Estuary exhibits the highest concentrations of TN in the mid-Atlantic region. Levels in the Delaware, Schuylkill, and Salem Rivers are 3-4 times larger than are found elsewhere (see Appendix D). Delaware Bay has moderately high concentrations of TN.

- All tributaries in the Chesapeake Bay show moderate to high concentrations of TN, particularly at the mouths of the Susquehanna, Patuxent and Potomac Rivers. The upper Chesapeake mainstem is moderately enriched, while its lower stretches are relatively free of TN.

- All of the coastal bays are relatively enriched in TN, especially Newport and Sinepuxent Bays. Contamination by groundwater draining from the surrounding farmlands and the slow flushing rates in the bays are likely reasons for high values.

- In the APES, only the well-flushed Pamlico Sound shows low TN concentrations. Otherwise, Chowan and Neuse Rivers exhibit intermediate levels of nitrogen nutrients.

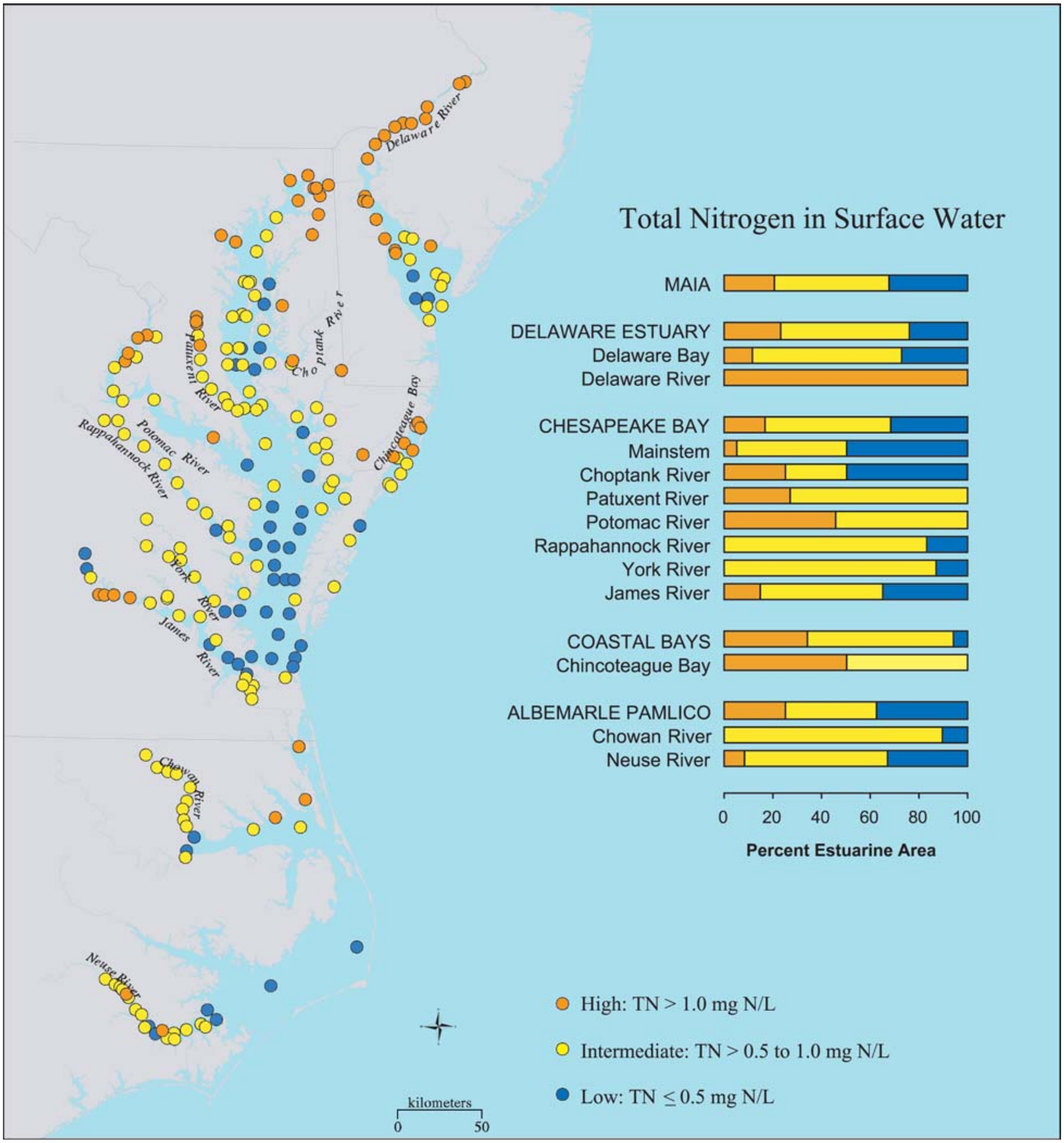


Figure 4-1. Concentration of Total Nitrogen in Surface Water.

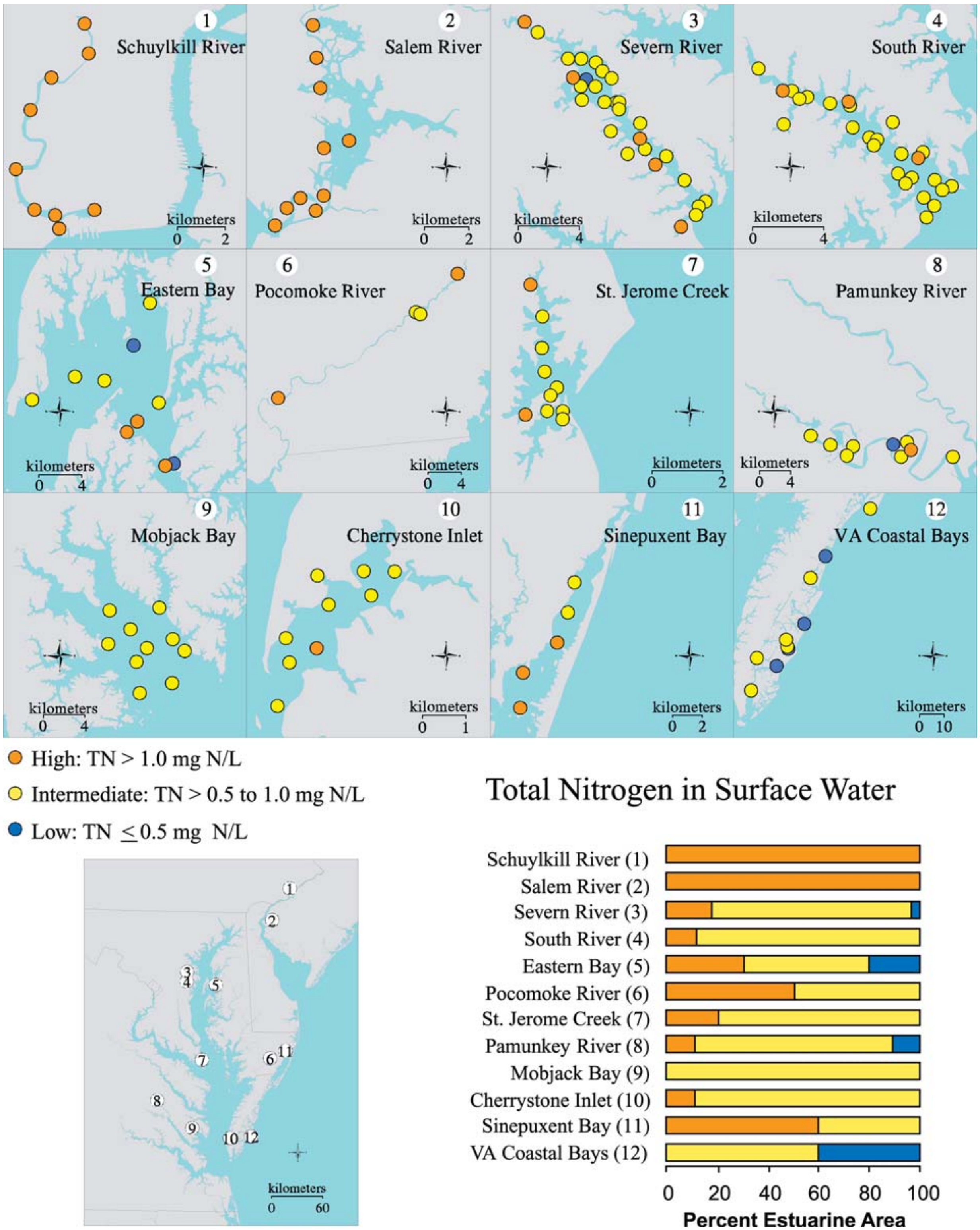


Figure 4-2. Concentration of Total Nitrogen in Intensively-Sampled Systems.

Total Phosphorus in Surface Water

Phosphorus, like nitrogen, is an essential plant nutrient. It is derived from natural mineral deposits in the watershed and increasingly from anthropogenic sources in the form of fertilizers, sewage, detergents, and pharmaceuticals. Phosphorus plays the role of the limiting nutrient in freshwater environments, such as lakes and streams and the fresher parts of estuaries. This means that phosphorus rather than nitrogen controls eutrophication in these regions. In fact, if nitrogen becomes so abundant that it is no longer the limiting nutrient in saltier waters, phosphorus may become the controlling nutrient there as well.

Phosphorus has several chemical forms and participates in complex seasonal cycles. Recent federal and state guidelines recommend using total phosphorus (TP) as the best measure of year-round availability of phosphorus nutrients in estuaries (EPA 2001). As with nitrogen, there are no well-established criteria that indicate "good" or "poor" categories of TP enrichment. Therefore, the upper and lower quartiles of all MAIA TP measurements are used to characterize "high" and "low" categories on maps.

Figure 4-3 and 4-4 present maps of total phosphorus concentrations in the surface waters of the MAIA region and intensively-sampled systems, respectively. Generally, the distribution of TP mirrors that of TN with a few exceptions.

- The highest concentrations of TP are again evident in the Delaware, Schuylkill, and Salem Rivers of the Delaware Estuary. The Delaware Bay is also moderately enriched in TP.

- All tributaries in the Chesapeake Bay are moderately to highly enriched, especially the Patuxent, Potomac, Severn, and Salem Rivers. The mainstem has relatively low levels of TP.

- The entire coastal bays, including the Sinepuxent Bay, Chincoteague Bay and the Virginia Coastal Bays are moderately enriched in total phosphorus.

- In the APES, total phosphorus levels are relatively high in the Chowan River and parts of the Neuse River.

In summary, both nitrogen and phosphorus nutrient levels are highest in the urban rivers in the upper Delaware Estuary and western Chesapeake tributaries, and in the agriculturally-influenced coastal bays. We can compare these nutrient-rich regions with the two following indicators that reflect organic enrichment – chlorophyll *a* and total organic carbon.

How do TN and TP compare with the more conventional measures of the dissolved nutrient classes, DIN and DIP (dissolved inorganic phosphorus)? Maps of the region are qualitatively similar regardless of the measure used. Generally, TN and TP were about twice the DIN and DIP values.

Total Phosphorus - Surface Layer

Method: Total phosphorus (TP) is calculated as the sum of particulate and dissolved forms of phosphorus: TP = total dissolved phosphorus + inorganic phosphate. Water samples were collected from one meter below the surface.
Units: mg P/L; equivalent to ppm.
Assessment categories:
Low: $\leq$ 0.05 mg P/L
Intermediate: > 0.05 to 0.1 mg P/L
High: > 0.1 mg P/L
Range of data: 0 to 0.34 mg P/L

The thresholds used to define these categories are the 25th and 75th percentile of all MAIA TP values measured.

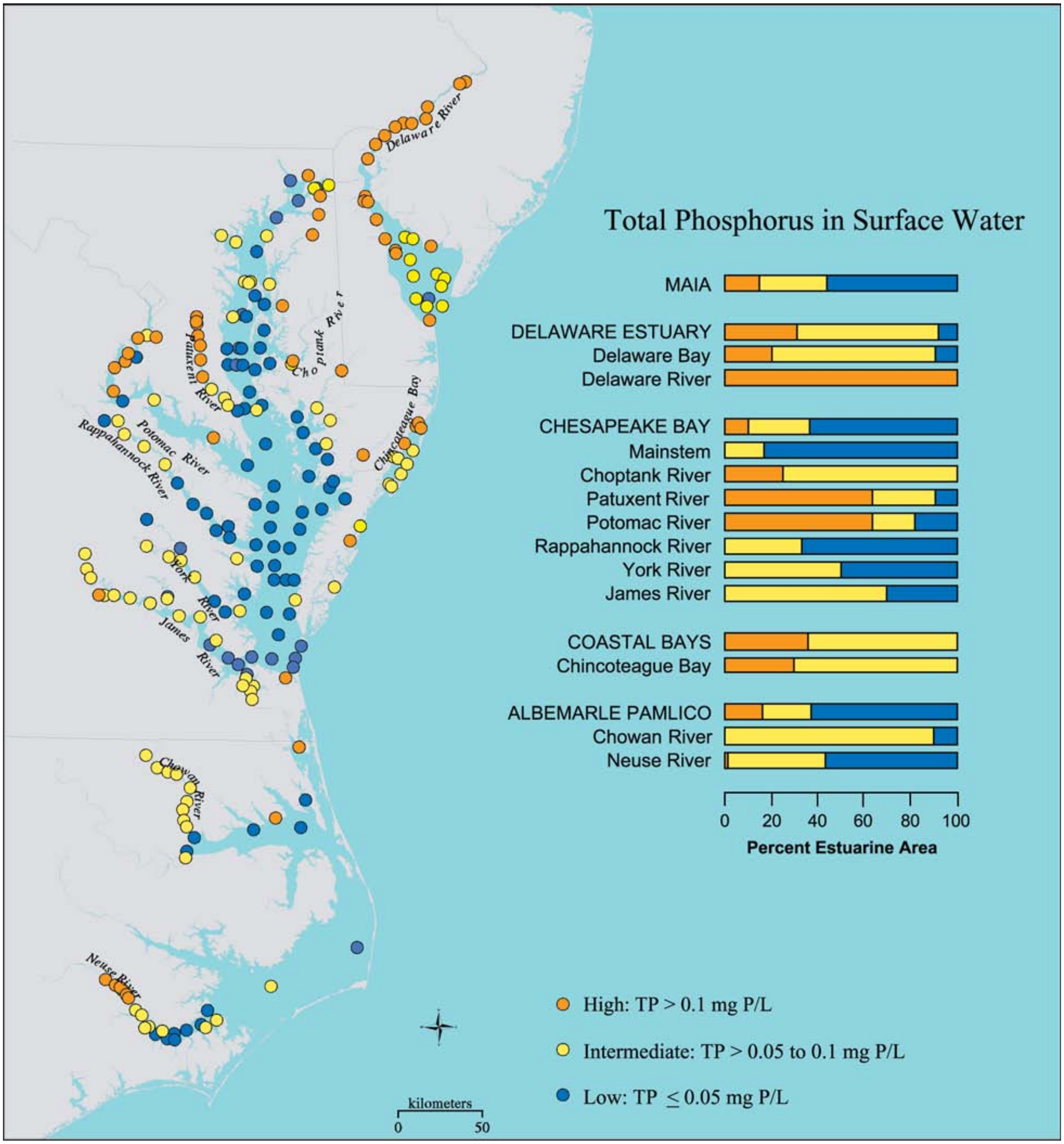


Figure 4-3. Concentration of Total Phosphorus in Surface Water.

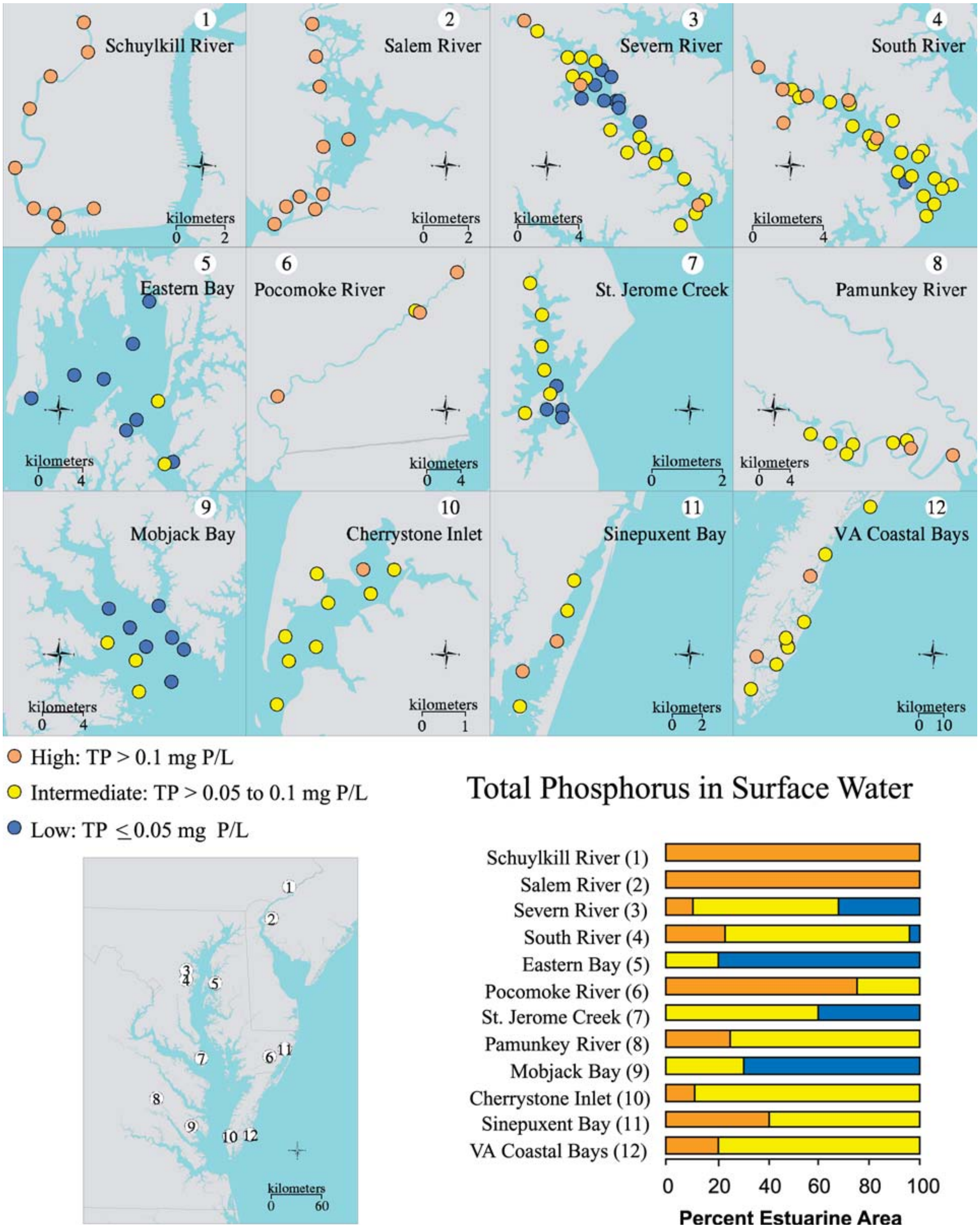


Figure 4-4. Concentration of Total Phosphorus in Intensively-Sampled Systems.

The categories used here to characterize nutrient levels are relative. That is, nutrient levels are considered to be high if they fell in the upper quartile of MAIA measurements. A more definite criteria of impairment would, of course, be preferable. Defining such absolute criteria is a high priority of estuarine research. However, the definitions of high nutrient concentrations used here (TN > 1 mg/L; TP > 0.1 mg/L) are conservative compared with criteria used in other assessments (Batiuk, et al. 2000, Bricker, et al. 1999). In other words, it is likely that conditions labeled "high" in this report really do represent concentrations that may adversely affect estuaries.

Chlorophyll *a* in Surface Water

The key symptom of eutrophication is the accumulation of organic material in an aquatic environment. In most situations, this usually refers to the accelerated production (i.e., photosynthesis) of algae in response to a rapid increase in the supply rate of nutrients. Normally, algae grow in "blooms" of limited extent and duration (see text box). However, the natural cycle can be disrupted if excessive quantities of nutrients are available.

Chlorophyll *a* is the green pigment present in all plants. The pigment is widely used as a surrogate for algal biomass, which is otherwise difficult and expensive to assess. High levels of chlorophyll *a* are interpreted as the likely presence of algal blooms. However, there is a drawback to the methodology used to measure the pigment. While phytoplankton is sampled representatively, macroalgae is not. The method is likely to underestimate the abundance of macroalgae.

In this report, we adopt the criteria used by the Chesapeake Bay in their restoration program for seagrasses and other submerged aquatic vegetation (SAV). Pigment concentrations over 15 µg/L represent algal concentrations large enough to shade and hinder growth of SAV (Batiuk, et al. 2000). As there is no common criteria designating bloom conditions, we consider chlorophyll *a* concentrations greater than 30 µg/L as "high," in general accordance with other assessments in the region (Paul, et al. 1999).

Algal Blooms

In healthy mid-Atlantic estuaries, algal production follows a striking boom-bust cycle in which algae "bloom" profusely for a few days or weeks when nutrients are available and other conditions are favorable. Growth is checked when the limiting nutrient is depleted. Herbivores graze the algae, zooplankton eat the herbivores, other consumers eat them, etc. The estuary is fed, and the waters clear until the next bloom.

However, when nutrients are continuously available, the algal blooms persist longer, and more algae are produced than the estuarine community can consume. The extra organic material accumulates and causes problems throughout the estuary.

The most common algae participating in blooms are the microscopic forms called phytoplankton. In shallower estuaries where sunlight illuminates the sediments, macroalgae (seaweeds) may dominate bloom activity.

Figures 4-5 and 4-6 show chlorophyll *a* levels in surface water in the MAIA region and intensively-sampled systems. About a third of the region displays pigment levels that suggest environmental impairment (concentrations > 15 µg/L; both yellow and red categories).

- The sub-systems of the Delaware Estuary show a wide range of pigment concentrations. Chlorophyll *a* levels are low in the Delaware Bay, intermediate in the Delaware River, and very high in the Salem River (over 80 µg/L in parts – a likely indication of severe bloom activity). Schuylkill River shows very low levels

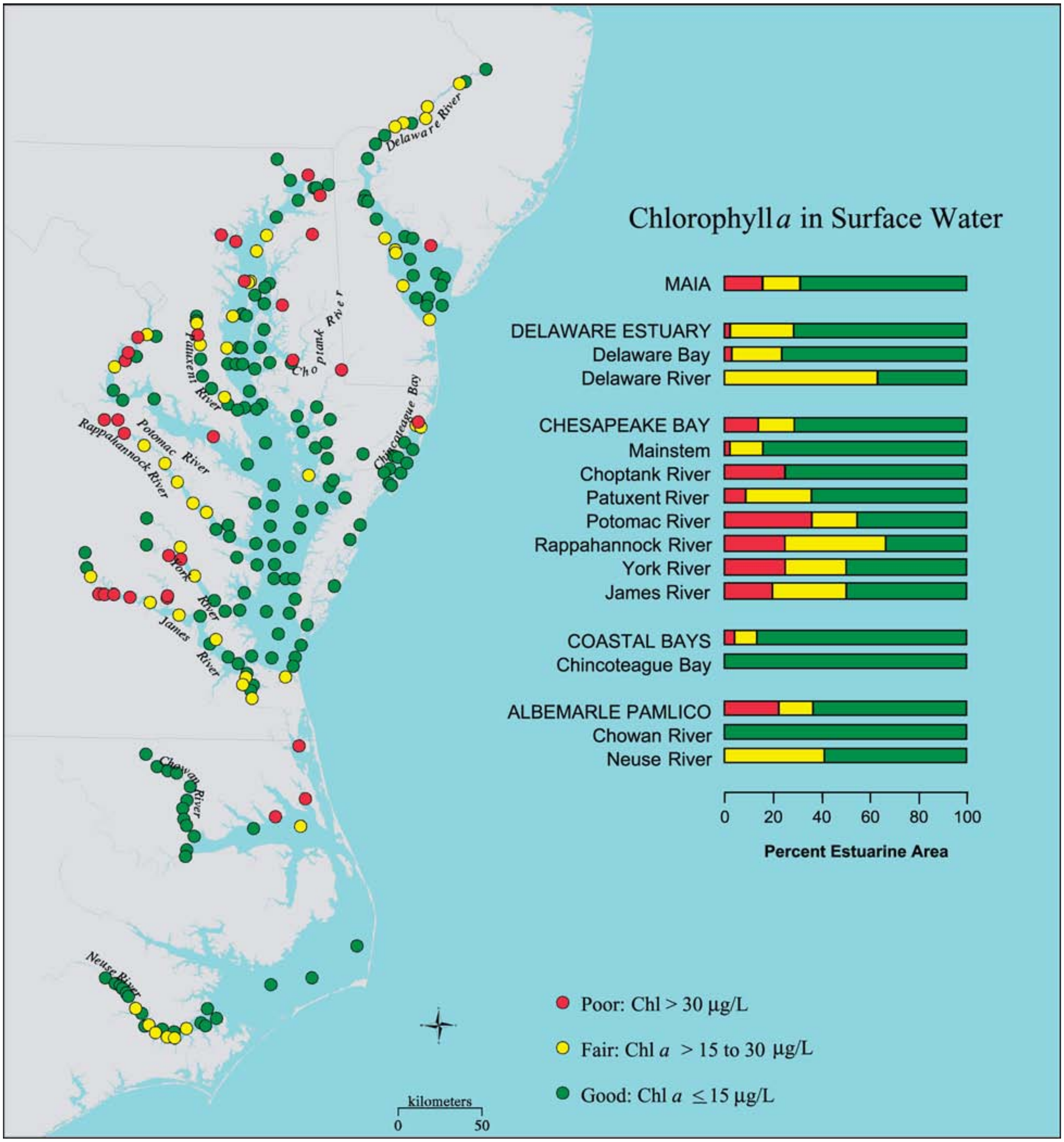


Figure 4-5. Concentration of Chlorophyll *a* in Surface Water.

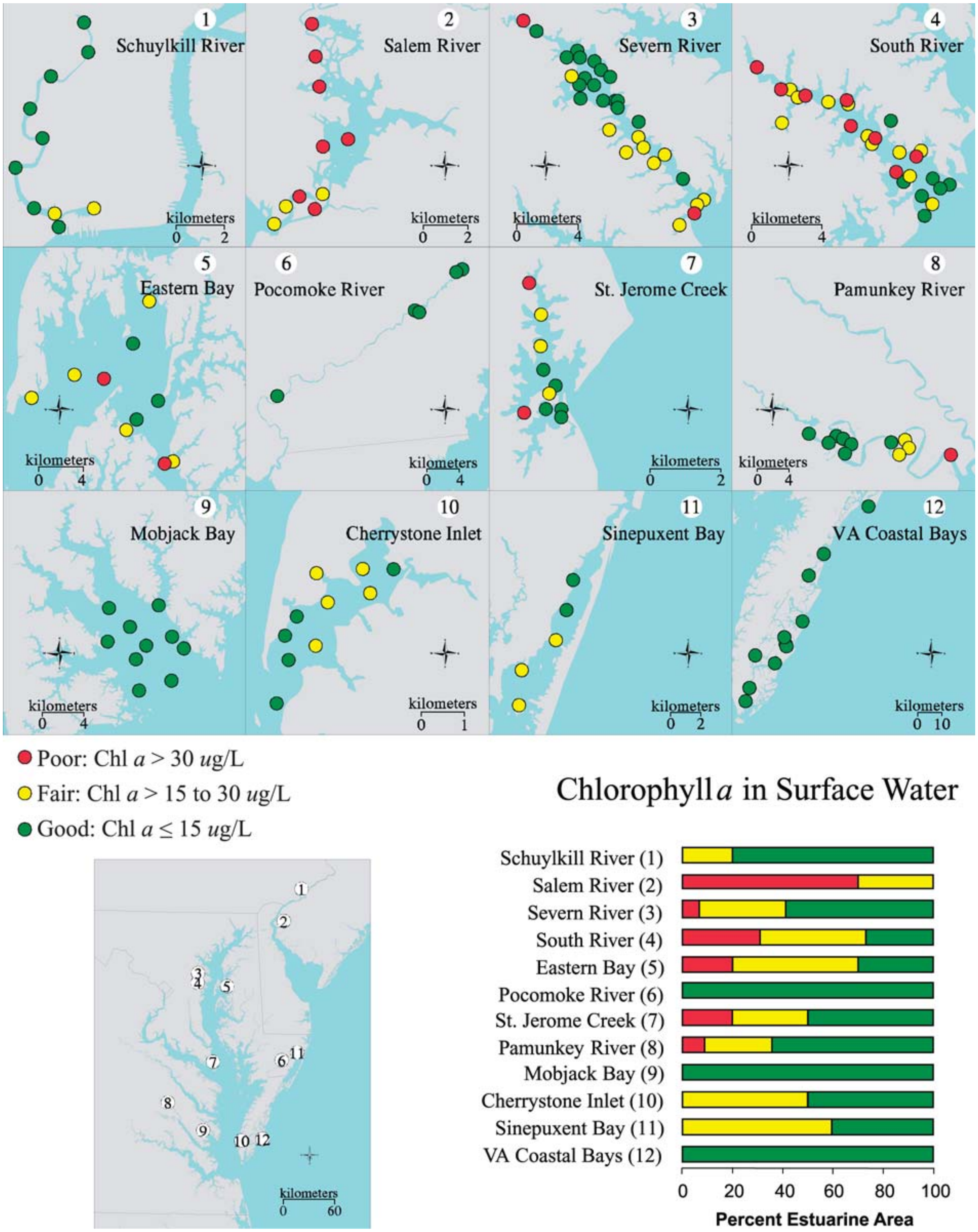


Figure 4-6. Concentration of Chlorophyll *a* in Intensively-Sampled Systems.

of chlorophyll *a* despite the very high TN and TP levels measured there. It is likely that turbid waters hinder algal productivity in this system.

- The western tributaries in the Chesapeake Bay are consistently high in chlorophyll *a*, with generally more than a quarter of their estuarine area showing concentrations greater than 30 µg/L. The entire mainstem is relatively low in the pigment.

- Pigment levels in the coastal bays are generally low despite a ready supply of nutrients. Blooms of macroalgae are common in these shallow systems but are not well-represented in the chlorophyll *a* measurements. Turbid waters may limit algal production in these bays as well.

- Much of the APES exhibit chlorophyll *a* levels less than 15 µg/L, with higher values in parts of the Neuse River and Albemarle Sound.

In short, chlorophyll *a* are high in the region. But the most interesting observation concerns the absence of high pigments in parts of the Delaware Estuary and coastal bays, despite the very high nutrient concentrations present. It is likely that the naturally high turbidity in the estuaries in the Delaware systems blocks the light available to algae. That is, the algae are light limited rather than nutrient limited, and, therefore, are insensitive to nutrient concentration.

Blooms are very ephemeral events, and "snap-shot" assessments, such as MAIA that sample estuaries once during the summer, cannot catch all events. Thus, these measurements should be viewed as minimum concentrations of chlorophyll *a*.

Researchers often use statistical tests to look for relationships among measured properties. Results of such tests (see Appendix F) indicate that chlorophyll *a* measurements correlate well with TN and TP concentrations in the upper Chesapeake Bay and coastal bays, but less so in the nutrient-rich Delaware Estuary.

Chlorophyll *a* – Surface Layer

Method: Water samples are collected one meter below the surface and analyzed by fluorometer.
Units: µg/L; equivalent to ppb
Assessment categories:
Good: ≤ 15 µg/L
Fair: > 15 to 30 µg/L
Poor: > 30 µg/L
Range of data: 0.7 to 95 µg/L
The lower threshold value of 15 µg/L is equal to the restoration goals recommended for the survival of SAV in Chesapeake Bay (Batiuk, et al. 2000). The upper limit of 30 µg/L maintains continuity with an earlier analysis in the region (Paul, et al. 2000) and is typical of values used to represent bloom conditions. Chlorophyll *a* is a measure of the concentration of phytoplankton but not macroalgae in the water column.

Total Organic Carbon in Sediments

Total Organic Carbon (TOC) is a measure of the concentration of organic matter in sediments. It represents the long-term, average burial rate of organic material in the sediments. High TOC values are viewed as evidence of frequent algal blooms in the overlying waters.

The rain of organic material to the sediments is the primary source of food to the benthos. The benthos is the community of worms, crustaceans, shellfish, and other organisms living in or on the estuary floor. Moderate fluxes of organic matter are, therefore, beneficial, but larger loads may be problematic if the benthic organisms are buried or deprived of oxygen as the organic material decomposes.

Figures 4-7 and 4-8 are the maps of TOC concentration in sediments throughout the mid-Atlantic region and the intensively-sampled systems. The thresholds used to define condition categories are still under evaluation; therefore, neutral colors are used on maps in this section.

- Within the Delaware Estuary, the sediments of the Delaware River and the Salem River are TOC-rich, while the Delaware Bay is TOC-poor, roughly mirroring the distribution of chlorophyll *a* in these systems. The mirror pattern breaks down in the Schuylkill River where TOC concentrations are very high, above 10% in spots, despite low chlorophyll *a* values.

- In the Chesapeake Bay, the upper mainstem has organic-rich sediments, while those in the lower mainstem are relatively carbon-free. The western tributaries and most of the intensively-sampled systems are moderately enriched. Severn River and South River have some of the richest sediments in the region.

Total Organic Carbon in Sediments

Method: Sediments were acidified to remove carbonate material, dried and combusted. TOC is calculated as the percent carbon in dry sediments.
Units: % carbon
Assessment categories:
Low: ≤ 1% carbon
Intermediate: > 1 to 3% carbon
High: > 3% carbon
Range of data: 0.02 to 13.7% carbon

The thresholds are based on an EMAP-VP analysis which indicated that TOC values in the 1 to 3% range were associated with impacted benthic communities, while values less than 1% were not (Paul, et al. 1999). These thresholds are still under evaluation.

Generally, these distributions do *not* mirror the chlorophyll *a* measurements.

- Sediments in the coastal bays have notably low concentrations of TOC. Sinepuxent Bay and the Virginia coastal bays have remarkably little buried carbon, on average less than 0.3%.

- The APES has sediments rich in TOC, especially in the Chowan and Neuse Rivers. Pamlico Sound sediments are generally low in organic carbon.

Water Clarity (Secchi Depth)

Estuaries are naturally murky places. Rarely can an observer see more than two meters (about 6 feet) through the waters of mid-Atlantic estuaries. Poor water clarity may be attributed to a number of sources, including suspended sediments, organic material (especially living and dead algae), or dissolved tannins. The turbid waters are beneficial because they provide food and building materials used by estuarine communities and can help small organisms hide from predators, but the particles can be harmful if they bury benthic communities or block light from the threatened seagrass beds.

The MAIA program used a very simple and effective method to measure water clarity. A white Secchi disk is lowered through the water, and the depth is noted when the disk becomes obscured by suspended material. Shorter Secchi depths indicate more turbid water. Waters with Secchi depths more than a meter (3 feet) are considered to be relatively clear, and turbid if visibility is less than 0.3 meter (about a foot). This method is similar to the “Bernie Fowler Sneaker Index,” an informal survey conducted annually since 1988 by the former Maryland State Senator, who wades into the water until he can no longer see his white sneakers.

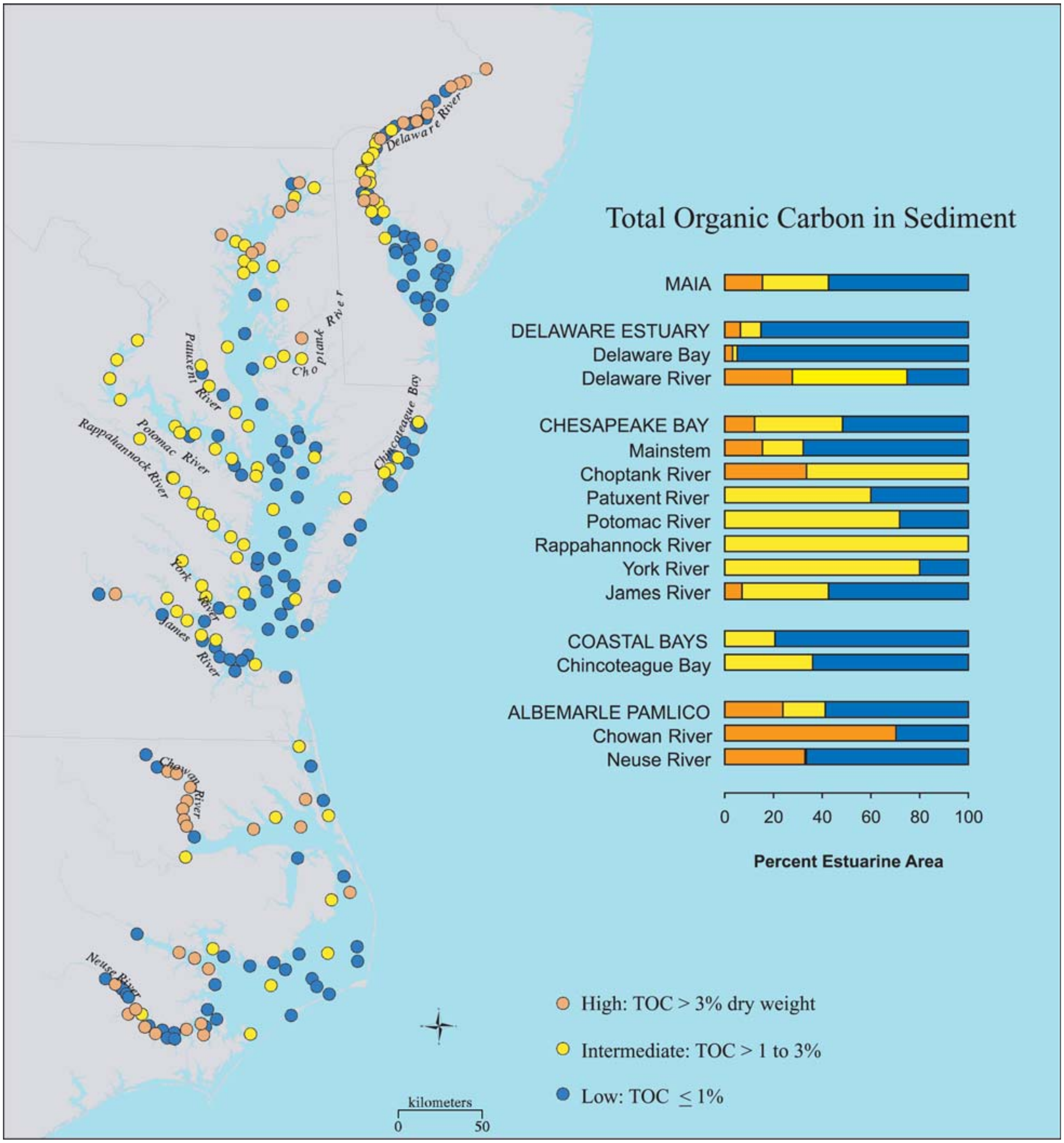


Figure 4-7. Concentration of Total Organic Carbon in Surface Water.

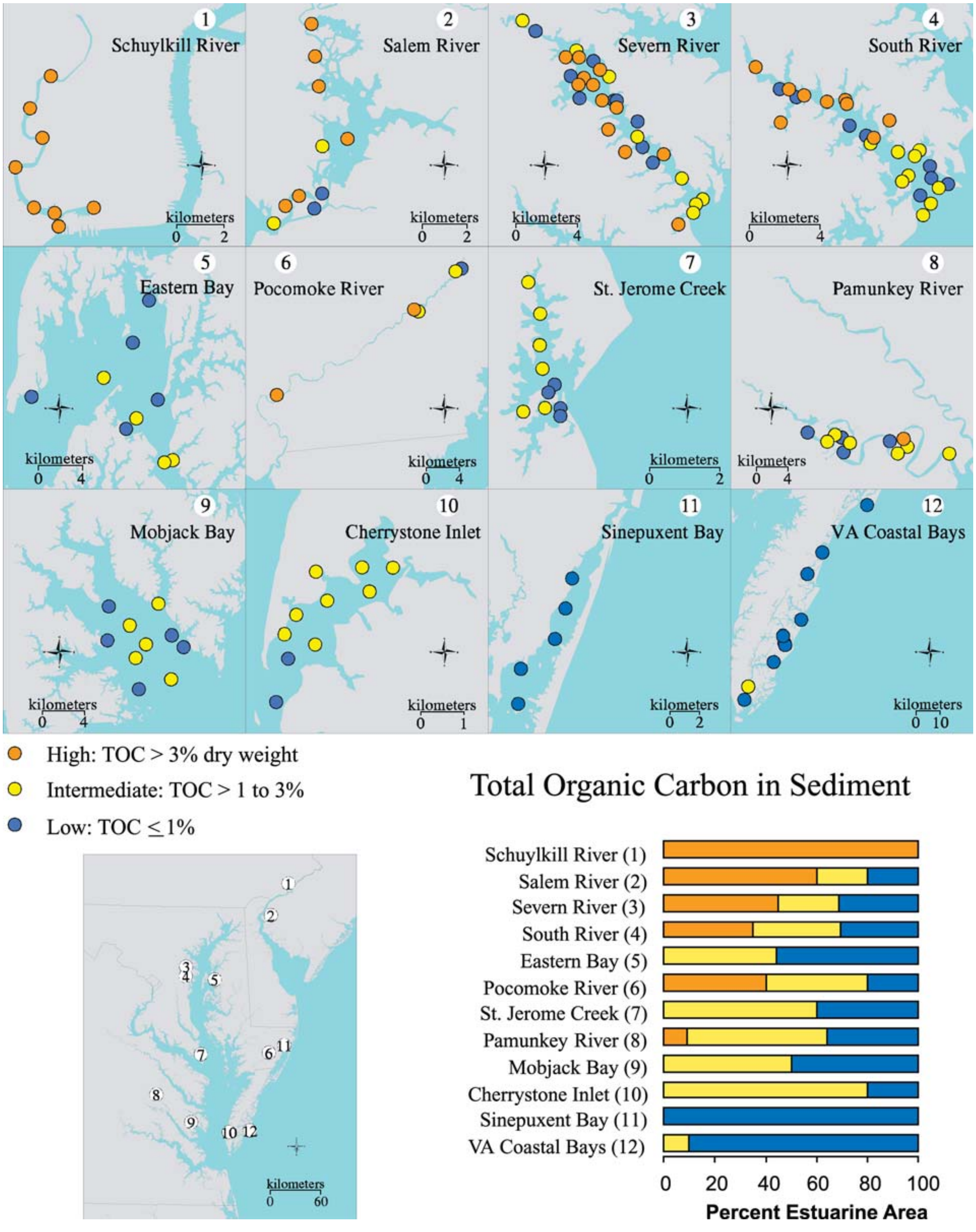


Figure 4-8. Concentration of Total Organic Carbon in Intensively-Sampled Systems.

Figures 4-9 and 4-10 show the patterns of water clarity throughout the mid-Atlantic estuaries. Overall the region is very murky, with only half of the estuaries in the region having Secchi depths more than a meter (i.e., visibility is limited to an arm's length).

- In the Delaware Estuary, the Delaware River and the Salem River are very turbid, while the Delaware Bay and the Schuylkill River are moderately turbid. These patterns do not closely match the distribution of chlorophyll *a*, suggesting that inorganic particles contribute to the turbidity as well as algal material.

- In the Chesapeake Bay, many of the western tributaries have visibility less than a meter, while the mainstem is relatively clear.

- Visibility is limited to less than a meter in all coastal bays. Chlorophyll *a* levels are low in these systems, implying that inorganic particles are the main cause of the turbidity.

- In the APES, about half of the estuarine area has moderately-limited water clarity (less than a meter). Again, resuspended inorganic particles are the likely cause of the turbidity.

Water Clarity (Secchi Depth)

Method: Secchi depth
Units: meters (m)
Assessment categories:
Clear: > 1 m
Intermediate: > 0.3 to 1 m
Turbid: ≤ 0.3 m
Range of data: 0.1 to 5.0 m

A Secchi depth of 1 meter is comparable to transmitting about 25% of ambient light at one meter depth, which is equivalent to the SAV restoration goals recommended for Chesapeake Bay.

Water clarity (Secchi depth) depends on many factors, both natural and anthropogenic. The fine particles blocking light may be organic (algae or their remnants) or inorganic (resuspended sediments or soil washed from farm lands). The poor correlation between visibility and chlorophyll *a* levels — evident on the maps and confirmed by statistical analysis (Appendix F) — suggests the waters are turbid because of sediment.

Dissolved Oxygen in Bottom Water

All organisms in estuaries, barring anaerobic microbes, need oxygen for survival. Normally, the concentration of dissolved oxygen (DO) in summertime estuarine waters is above 5 mg/L. When concentrations fall below 5 mg/L, sensitive biota experience reduced reproduction and growth. Many states use 5 mg/L as the criteria designating unacceptable water quality. When DO levels fall below 2 mg/L, the condition is called hypoxia. Sensitive organisms can tolerate hypoxia for only a few days before dying. The complete absence of oxygen is called anoxia.

The concentration of DO in a parcel of water is a dynamic balance between processes that provide oxygen and those that remove it. Oxygen is supplied by photosynthesis and transported from the atmosphere. The main process depleting DO from water is the respiration of biota, including bacteria that decompose organic material in water or sediments.

Oxygen depletion occurs naturally in mid-Atlantic estuaries, especially during summer, when respiration rates are highest, and in isolated places where oxygen replenishment processes are slow. A textbook example of a natural "dead zone" develops each summer in the deep trenches of the Chesapeake mainstem. The extent and severity of the oxygen depletion have increased in recent decades, in step with increased rates of eutrophication.

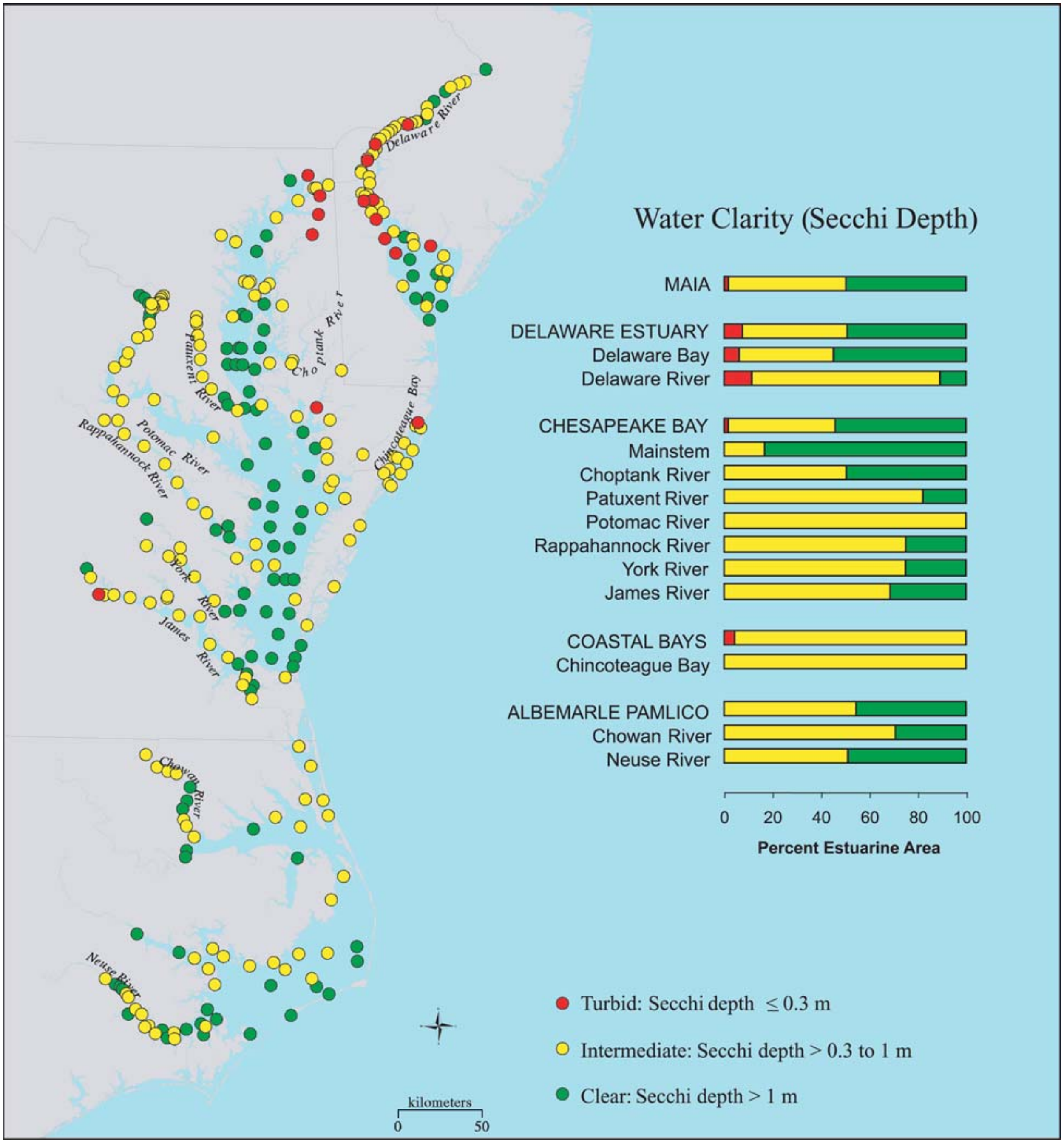


Figure 4-9. Secchi Depths as a Measure of Water Clarity.

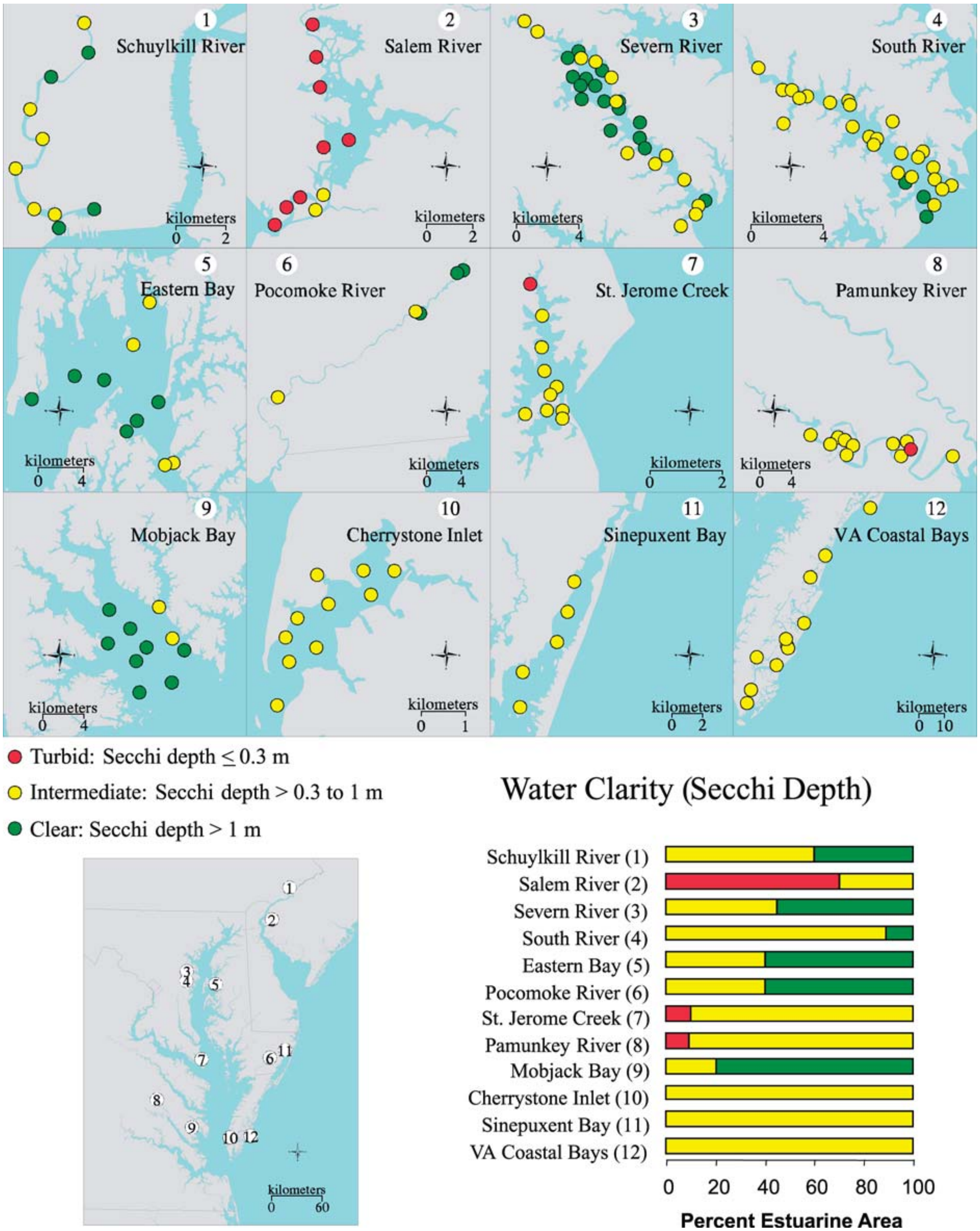


Figure 4-10. Secchi Depth (Water Clarity) in Intensively-Sampled Systems.

Reduced oxygen levels may also occur for a few hours during the night when the amount of oxygen being consumed by biota temporarily exceeds the amount being provided by photosynthesis. The effects of short-term oxygen stresses are poorly studied but probably adversely affect organisms found throughout the water column.

We report DO concentrations in bottom water where the most severe cases of depletion are generally found. The measurements were conducted during daylight hours; therefore, they do not accurately represent temporary changes that occur during the night. The assessment categories reflect the criterion used by states in regulating water quality (< 5 mg/L) and the conventional definition of hypoxia (≤ 2 mg/L).

Figures 4-11 and 4-12 show the distribution of dissolved oxygen in bottom waters.

- Oxygen depletion is not a widespread issue in the Delaware Estuary. Generally, DO levels were above 5 mg/L, with a few incidents of moderate and severe hypoxia evident in the Delaware River, Schuylkill River, and Salem River.

- The most severe cases of oxygen depletion are restricted to the upper mainstem and western tributaries in the Chesapeake Bay. James River is relatively well-oxygenated. Of the intensively-sampled systems, Severn River, South River, and the Eastern Bays are notably depleted in DO.

- Most of the waters in the coastal bays are well oxygenated.

- The APES shows little sign of oxygen depletion, except for moderate hypoxia noted in parts of the Chowan River.

Dissolved Oxygen – Bottom Water

Method: Dissolved oxygen (DO) concentrations in bottom water were measured by an *in situ* oxygen electrode method. The measurements were performed during daylight hours, one meter above the sediment surface.
Units: mg/L; equivalent to ppm.
Assessment categories:
  Good: DO > 5 mg/L
  Fair: DO > 2 to 5 mg/L
  Poor: DO ≤ 2 mg/L
Range of data: 0 to 11.7 mg/L

These measurements are likely to indicate long-term episodes of oxygen depletion in deeper water but are less likely to detect the temporary overnight incidents of hypoxia that may occur in productive surface waters.

As with most indicator parameters, the DO record reflects both natural and anthropogenic influences. The hypoxia and anoxia in the Chesapeake Bay trenches are well known and largely attributed to natural processes. The trenches are isolated, stratified sites where fine particles and organic matter accumulate--all attributes that naturally promote oxygen depletion. However, the extra organic loads contributed by anthropogenic eutrophication accentuate the problem as well.

The MAIA measurements capture persistent events of depletion in deep water but miss the short-term cases that may occur in surface water.

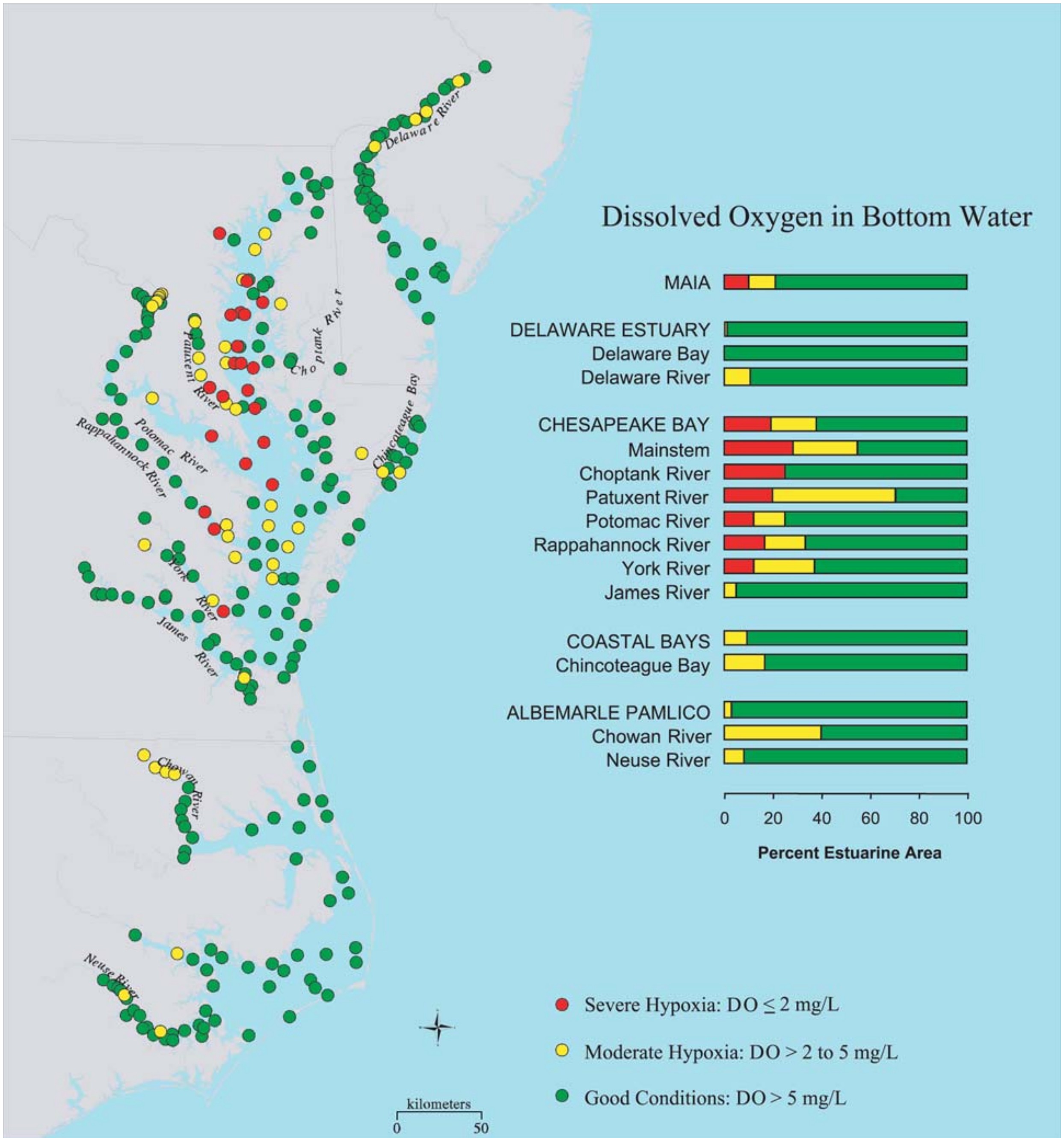


Figure 4-11. Concentration of Dissolved Oxygen in Bottom Water.

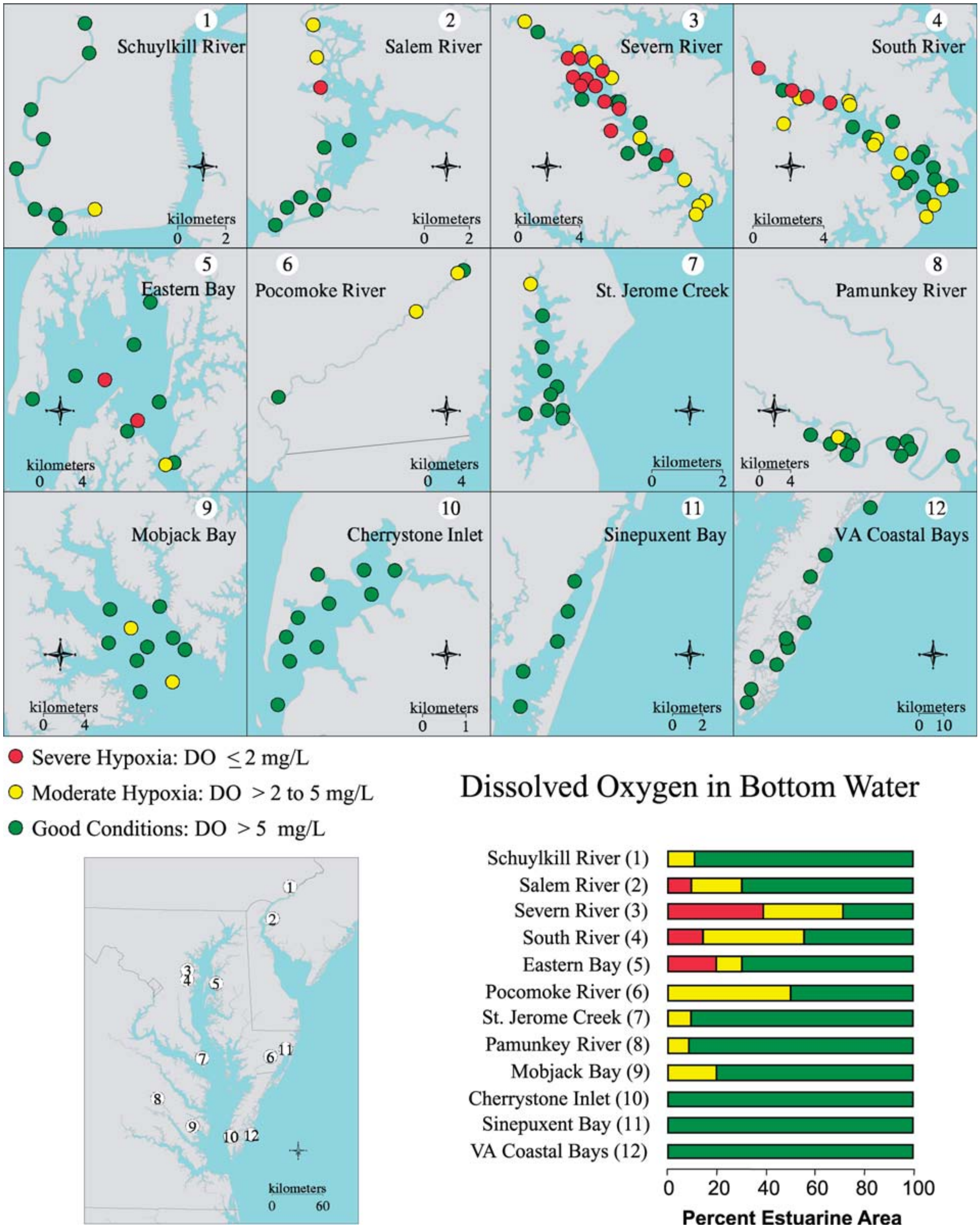


Figure 4-12. Concentration of Dissolved Oxygen in Intensively-Sampled Systems.

Summary: Eutrophication

Figure 4-13 presents a summary of the MAIA eutrophication indicators reviewed in this chapter. The vertical bars in the figure represent the percent of estuarine area exhibiting impaired (or excessive) conditions for each of the six indicators. An ideal estuary, unaffected by eutrophication, would display *no* bars. Estuaries featuring many full bars are likely to be experiencing eutrophication.

The first panel in Figure 4-13 summarizes conditions in the entire MAIA region. The percentage of estuarine area exhibiting potentially harmful conditions are as follows (and are reported in Appendix E):

Indicator	% Estuarine Area in MAIA Region	Threshold
Total N	21 ± 12%	> 1 mg N/L*
Total P	15 ± 11%	> 0.1 mg P/L*
Chlorophyll *a*	32 ± 10%	> 15 µg/L
TOC	16 ± 6%	> 3% carbon*
Secchi depth	50 ± 8%	≤ 1 meter
DO	21 ± 6%	≤ 5 mg/L

* Threshold under review

These figures show that about 20% or less of the MAIA region overall is affected by high nutrients, carbon enriched sediments, or depleted DO levels. About a third of the estuarine area has high chlorophyll *a* concentrations, and a half has visibility less than an arm's length. As was pointed out in each subsection, these estimates may be considered to be conservative or minimum estimates.

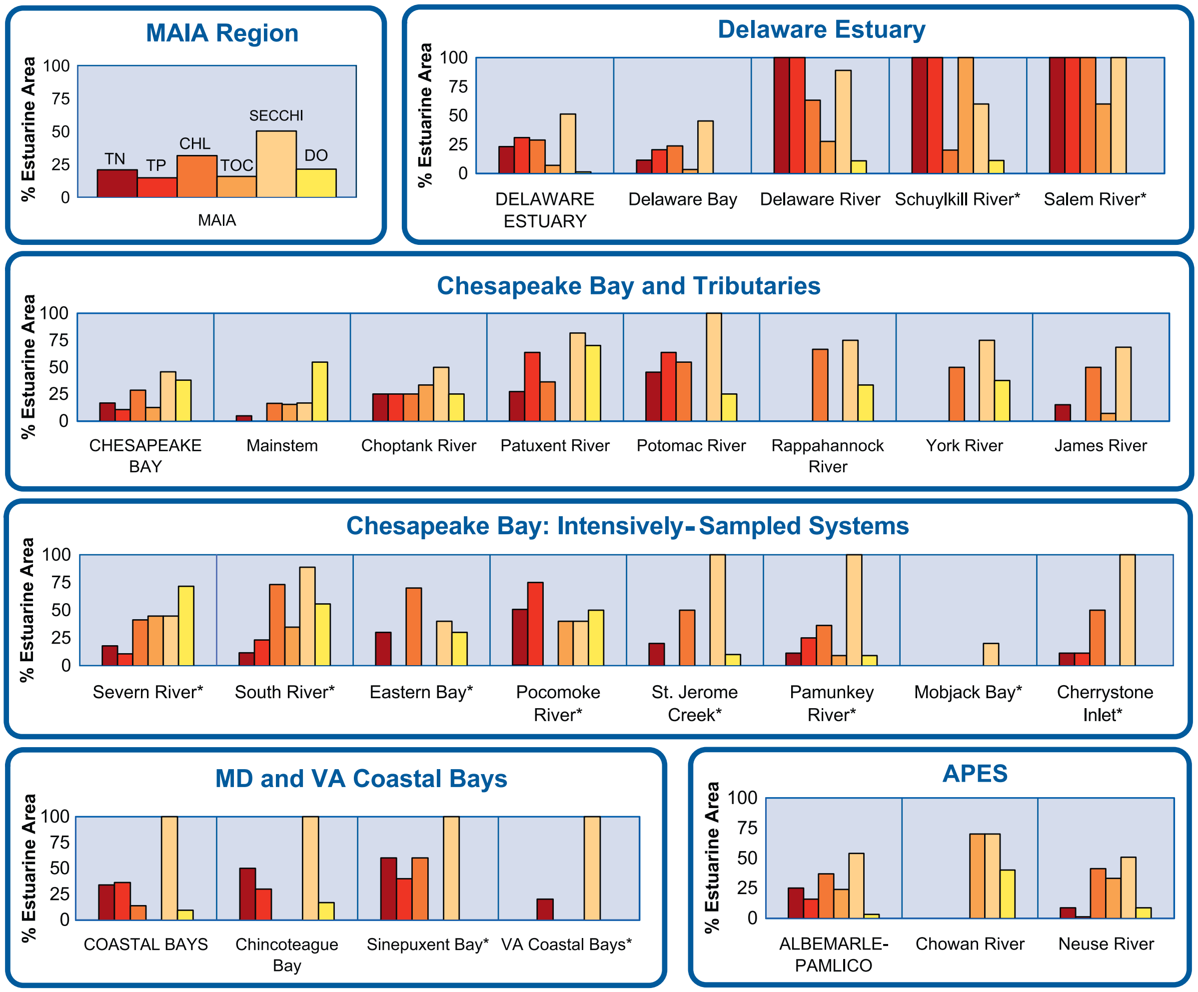
These values agree well with other assays conducted in mid-Atlantic estuaries. NOAA's Estuarine Eutrophication Survey (Bricker, et al. 1999) queried experts from over 120 estuaries in the continental United States. While using different methods and measures, the NOAA study found similar indications of eutrophication: about a third of mid-Atlantic estuaries exhibited moderate to high levels of chlorophyll *a* (> 15-20 µg/L), and 10 to 20% of estuarine area showed potentially harmful levels of nutrients and DO. Comparable conditions were also measured in USEPA's EMAP conducted in 1990-93 in parts of the mid-Atlantic region (see Chapter 7 for a comparison of EMAP and MAIA findings).

The following observations are evident in the sub-regions and particular estuaries.

- In the Delaware Estuary, the relatively fresh rivers show many signs of eutrophication. The Delaware, Schuylkill, and Salem Rivers all show widespread incidence of nutrient enrichment and poor water clarity. Abundances of chlorophyll *a* and TOC are high in some rivers but more moderate in others where algal growth may be limited by turbid conditions. In the turbid Delaware Bay, while nutrient levels are high in 10 to 20% of the bay's area, along with elevated chlorophyll *a* concentrations in about a quarter of the bay, DO depletion is a minor concern in the estuary.

- In the Chesapeake Bay, the mainstem shows little sign of eutrophication, although DO is depleted in 55 ± 18% of the mainstem's area. The Choptank, Patuxent, and Potomac Rivers are generally nutrient-rich, high in chlorophyll *a* (but low in sedimentary TOC), are turbid and likely to suffer dissolved oxygen depletion. The Rappahannock, York, and James Rivers have low nutrient levels but are turbid and chlorophyll-rich.

- The intensively-sampled systems in the Chesapeake Bay show a range of eutrophication symptoms. In Severn River, South River, Eastern Bay, and Pocomoke River, signs of eutrophication are generally present in moderate to severe proportions. St. Jerome Creek, Pamunkey River, and Cherrystone Inlet have fewer signs of nutrient excess, organic-rich sediments, or DO depletion but are otherwise high in chlorophyll *a* and turbidity. Mobjack Bay shows relatively few signs of eutrophication.



* Intensively-sampled systems

Legend. The six indicator parameters used to represent eutrophication along with the threshold indicating high values or impaired conditions. Thresholds for TN, TP and TOC are not based on well-established criteria; therefore, the bars above indicate "high" rather than "impaired" conditions.

TN	TP	CHL	TOC	SECCHI	DO
Total Nitrogen > 1 mg/L	Total Phosphorus > 0.1 mg/L	Chlorophyll *a* > 15 µg/L	Total Organic Carbon > 3%	Secchi Depth ≤ 1m	Dissolved Oxygen ≤ 5 mg/L

Figure 4-13. Summary of Eutrophication Indicators. This graphic presents the “preponderance of evidence” that an estuary is experiencing eutrophication. The vertical bars represent the percentage of estuarine area exhibiting impaired conditions. Threshold values indicating impaired conditions are listed in the legend.

- The coastal bays are very turbid and well oxygenated. The Virginia coastal bays are largely symptom-free, while other bays exhibit high levels of nutrients. Only the Sinepuxent Bay shows signs of organic enrichment.

- In the turbid APES, nutrient levels are relatively low, but there are indications of organic enrichment in the sediments and water column, especially in the Chowan and Neuse Rivers.