Evaluating Virginia Water Quality Monitoring Stations for Potential Reservoir Chlorophyll Studies

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Introduction:

The availability of light within aquatic ecosystems largely determines the roles and forms of primary producers within such environments. Light availability directly affects the amount of photosynthesis that takes place within waterbodies, as well as the specific types of organisms that survive under the conditions (Kirk, 1994). Typically, this is represented by either a clear water macrophyte-dominated regime or a light-limited phytoplankton-dominated ecosystem (King et al., 2023). The increased presence of pollutants such as sediment and nutrients in water can greatly affect the light dynamics of various waterbodies (Squires & Lesack, 2003). Pollutants such as excess nitrogen and phosphorous inputs can cause increased algae concentrations as the organisms typically exhibit nutrient-limited growth (US EPA, 2010).

Areas with high agricultural land use typically have larger amounts of nutrient input into waterbodies from agricultural runoff. In Virginia particularly, the focus of the Chesapeake Bay Total Maximum Daily Load (TMDL) on nitrogen, phosphorous, and sediment has caused an even higher need for proper freshwater management (US EPA, 2010). Healthy reservoirs provide opportunities for natural pollutant sinks within freshwater systems by serving as breaks in pollutant transport and habitats for macrophyte communities. Macrophytes, also commonly called Submerged Aquatic Vegetation (SAV), are crucial to maintaining healthy aquatic environments as they typically prevent sediment resuspension, absorb nutrients, and limit pollutant transport downstream (US EPA, 2010, James, Best, & Barko, 2004). As pollutant loads increase, however, light becomes less available, typically causing a decline in submerged aquatic vegetation populations while phytoplankton and algal blooms become more dominant (King et al., 2023).

This phenomenon has taken place across Virginia, causing issues not only with sediment and nutrient dominance for the Chesapeake Bay but also environmental and human health concerns within local reservoir communities (Backer, 2012). Increased algal blooms and eutrophication are common in more stagnant bodies of water such as reservoirs and can cause ecological issues ranging from mass fish kills to the release of toxins harmful to humans and livestock (Backer, 2012).

The amount of algae in a waterbody is found by collecting water samples and testing the amount of Chlorophyll-a (CHLa) within them. CHLa marks the amount of chlorophyll cells that are free-floating in the water column and, therefore, is representative of the algal communities of waterbodies (Squires & Lesack, 2003). Chlorophyll-a itself is contained in the cells responsible for photosynthesis and causes the green coloration that is seen in photosynthetic organisms. As algae float in the water column and photosynthesize, they not only scatter incoming light, but also absorb it and incorporate its energy in the process of photosynthesis (Squires & Lesack, 2003). These are the main processes in which algae affect light environments and the health of primary production in aquatic ecosystems.

Previous studies have taken place to identify the factors controlling light attenuation in key global regions, primarily focusing on intra-lake variations. Across these studies, measures of total suspended solids (TSS), Chromophoric Dissolved Organic Matter (CDOM), and Chlorophyll-a were found to be the primary factors influencing light availability limitations (Squires & Lesack, 2003, Loiselle et al., 2008). These studies have been effective in determining the sensitivities of lakes to specific events like nutrient inputs and algal blooms, however, these concepts have yet to have widespread application in Virginia.

While monitoring of TSS is common in many Virginia waterbodies, CHLa monitoring, particularly in reservoirs, is not yet as established. To better manage Virginia's reservoirs, effective identification of the sources causing disparities in reservoir light attenuation is necessary. To bridge this gap in water quality data, an increase in CHLa monitoring must be carried out. The repercussions of decreased water clarity are evident in Virginia reservoirs as eutrophication trends continue to rise, thus, further analysis of these ecosystems is needed to properly identify hazardous algae-rich/bloom-prone environments and better manage them.

The primary focus of this project is on the distribution of water quality monitoring stations in Virginia in relation to state-identified reservoirs and monitoring parameters. Given that algae are typically a large threat to more stagnant bodies of water, like reservoirs, I will perform several spatial analyses relating to the presence of monitoring stations in, on, or nearby reservoirs that currently measure Chlorophyll-a. Additionally, as algal blooms become more common with high nutrient inputs, I will perform further spatial analyses to relate current reservoirs without CHLa monitoring to areas with high nearby nitrogen and phosphorous levels. In total, the intended objective of this project is to identify Virginia reservoirs that are the best candidates for a future chlorophyll monitoring program.

Methods:

Map 1: A shapefile of current water quality monitoring plan stations were obtained from the Virginia Department of Environmental Quality (DEQ) data hub. Next, shapefiles of Virginia reservoirs and DEQ region polygons were added. These shapefiles were projected with spatial reference NAD 1984. Within the water quality monitoring station data, there were a number of parameters that were tested at various locations. All stations that were not monitoring for chlorophyll in the water were deleted from the dataset. The points that were left were symbolized as green droplet icons to represent stations that monitor chlorophyll. Using the reservoir layer, a one mile buffer was put around all Virginia reservoirs. This extended the reservoir perimeters outward by one mile. This extension accounts for not only any seasonal fluctuations that there might be in reservoir area, but also shows other items that may be close, if not in, the reservoir boundaries. Next, a clip function was used to remove all water quality monitoring stations that did not lie within the boundaries of the reservoir buffer layer. The resulting output displays a visualization of all the monitoring stations within Virginia that are monitoring chlorophyll levels within one mile of reservoirs. All data layers except for the buffer layer, clipped monitoring stations, and DEQ regional boundaries were removed for interpretation. A legend, scale bar, title, and spatial reference information were added to the final map layout in ArcGIS Pro (Appendix B).

Map 2: This map used the same DEQ region, reservoir, and monitoring station data layers from Map 1. Focusing more on the reservoir data, a select by location was run in order to identify the reservoirs in Virginia that were within one mile of a monitoring station that tests for chlorophyll. As Map 1 was primarily focused on visualizing the stations, this map is related more on analyzing reservoir locations. Once these reservoirs were selected, they were made into a completely new layer and were symbolized with a green fill as to mark the presence of chlorophyll testing. Using the original reservoir layer, the selected locations were switched with the unselected locations. These newly selected stations were also made into a completely new layer and symbolized with red fill to mark the absence of any chlorophyll testing. A legend, scale bar, title, and spatial reference information were added to the final map layout in ArcGIS Pro (Appendix B).

Map 3: Here, a data layer of median station nutrient results 2010-2020 was sourced from the Virginia Department of Environmental Quality data hub and projected onto the map with the previous data layers. All other data layers were hidden for the creation of this map. This median nutrient results layer was symbolized as having graduated colors being defined by the value in the medianTN field. As outlined in the DEQ data hub, nitrogen data is categorized into low, medium, and high ranges. This layer was, therefore, further symbolized using 3 classes and a yellow, orange, red color scheme. The classes were set to have yellow represent the low values (0.02-0.99), orange represent medium values (0.99-1.99), and red represent high values (1.99-43), as these were the values defined by the data hub. The final output of the map kept all data layers hidden except for the median nutrient monitoring stations and DEQ regional boundaries. A legend, scale bar, title, and spatial reference information were added to the final map layout in ArcGIS Pro (Appendix B).

Map 4: Using the median station nutrient results 2010-2020 data layer from the DEQ data hub, both high nitrogen and high phosphorous data was analyzed. A select by attribute was carried out that selected stations in the layer that had a medianTN value of greater than 1.99. This layer was then created into a new data layer. This new layer was symbolized as a single symbol, poinsettia red circle 4, 6pt, and contains only stations with ‘high’ TN values as identified by the DEQ. Using the original median station nutrient data layer again, another select by attribute was carried out that selected stations with medianTP (total phosphorous) of greater than 0.1. Again, as defined by the DEQ data hub, this would be considered high. This was made into its own layer and was symbolized as a single symbol, lapis lazuli pentagon, 6pt. For the output map frame, all data layers were turned off except for the two new high P and N layers, as well as the DEQ regional boundaries. A legend, scale bar, title, and spatial reference information were added to the final map layout in ArcGIS Pro (Appendix B).

Maps 5, 6, and 7: All of these maps were made using the same data/processes and essentially just represent zoomed-in versions of one larger map. This map incorporated data from virtually all other maps, no new data was sourced for its creation. Here, a select by location was carried out using the layer with reservoirs that lacked chlorophyll monitoring (Map 2). Using the intersect function, only reservoirs from this layer that also had high median total nitrogen stations within one mile of them (Map 4) were selected. These reservoirs were symbolized with yellow fill and represent the reservoirs with high nearby N and no CHLa monitoring. Another select by location was completed for reservoirs with no chlorophyll monitoring and high median total phosphorous stations within one mile of them. These reservoirs were symbolized with pink fill and represent the reservoirs with high nearby P and no CHLa monitoring. For the map output, the high phosphorous and nitrogen layers, along with the DEQ regional boundaries from Map 4 were left on. Additionally, the new data layers containing the yellow and pink reservoirs remained unhidden. A legend, scale bar, title, and spatial reference information were added to the final map layout in ArcGIS Pro and each reservoir was zoomed to for its own individual map (Appendix B).

Results:

Within the distribution of the 1,795 water quality monitoring plan stations, only 682 were actively testing chlorophyll levels. Of these, just 203 of the chlorophyll testing stations were found to be within 1 mile of Virginia reservoirs (Map 1). The resulting map from this data analysis shows a visualization of these stations regarding the one mile buffer of reservoir perimeters.

Map 2 explores the same data but focuses instead on the reservoir counts and their proximity to chlorophyll monitoring stations. Of the 273 WGA IR Assessment reservoirs of 2022, only 116 were located within one mile of a chlorophyll monitoring station. Subsequently, 157 reservoirs were not located within one mile of a chlorophyll monitoring station. This discrepancy outlines the unequal distribution of chlorophyll monitoring on reservoirs. Map 2 displays reservoirs with monitoring as having a green fill, and those without chlorophyll monitoring as having a red fill.

Map 3 shows the distribution of median total nitrogen found at all Virginia testing stations between 2010 and 2020 (Appendix B). Of the 3341 total stations, 156 had high median nitrogen levels above 1.99, 551 had medium median nitrogen between 1 and 1.99, and 2624 found low median nitrogen less than 0.99. In percentages for nitrogen, approximately 5% were high, 16% were medium, and 79% were low. Similarly, although not displayed on the map, median phosphorous data was also available. For phosphorous, 2386 stations had low median levels that were below 0.05, 471 had medium median levels between 0.05 and 0.1, and 158 stations had high median phosphorous that was above 0.1. In percentages this means approximately 5% of stations were high, 14% were medium, and 71% had low phosphorous (not all stations had phosphorous data available).

Using the initial analyses performed for Maps 1, 2, 3, and 4, the specific reservoirs that lack chlorophyll monitoring and are within one mile of a station that had high 2010-2020 median nutrients were able to be found. Of the sample of 157 reservoirs without chlorophyll monitoring, only 3 reservoirs were found to meet the criteria of greater than 1.99 medianTN or greater than 0.1 median TP. These reservoirs were South Holsten Reservoir, Silver Lake, and Molly's Creek Reservoir. Of these, South Holsten Reservoir was found to be near both high nitrogen and high phosphorous, while the others were found only near one high nutrient concentration.

Discussion:

With only 38% of water quality monitoring plan stations including chlorophyll monitoring, it can be inferred that little emphasis is currently placed on widespread algal blooms in Virginia. This notable lack of established CHLa monitoring, especially in reservoirs, is further seen in the Map 2 analysis which shows that just 42% of reservoirs in Virginia have chlorophyll monitoring nearby them (within one mile). Moreover, this analysis fails to take into account whether these stations are located in a tributary of a reservoir or not, a consideration that should be evaluated in further analysis. In addition to this, while looking for CHLa monitoring within one mile of reservoirs shows which lakes have their surrounding CHLa monitored, it does not give an accurate depiction of how many lakes have testing stations within their actual waters. It can then be inferred that, while this analysis is useful in its main objective of identifying reservoirs that are in great need of chlorophyll monitoring, it can potentially overestimate the amount of current reservoir monitoring taking place.

Algae is highly responsive to high nutrient levels and its growth is typically limited primarily by the amount of nutrients available in an ecosystem (US EPA, 2010). For this reason, the data shown in maps 3 and 4 are particularly important in evaluating sites that are in need of future monitoring. While it is easy to say that all reservoirs that do not have current CHLa monitoring should get it, this argument does not take into account relative *need* that nutrient analysis helps explain. It can be assumed that areas with consistently higher nutrient levels, like high median values over a ten year period, are in greater need of chlorophyll monitoring than those without such high background nutrient levels. For this reason, the three reservoirs identified as potential candidates by this study should be viewed as the best candidates rather than the only ones.

South Holsten Reservoir, Silver Lake, and Molly's Creek Reservoir represent the reservoirs that exhibit the highest risk of further light environment degradation as analyzed by this project's methods. While there are other spatial and data-heavy ways to perform analyses of reservoirs, this project should act as a starting point and a basis for any further work. Other evaluations may conclude with different findings, however, it is clear that in terms of the lack of current nearby CHLa monitoring and the excess of nearby nutrient levels, the three identified reservoirs should be the first potential candidates for any additional chlorophyll monitoring being done by DEQ regional offices. It should, however, be noted that it is not recommended that these findings be used to exclude any reservoirs from future monitoring of chlorophyll levels. The focus of this analysis is instead on creating a tool to be used to identify those reservoirs that are in the greatest need of monitoring efforts rather than identifying those that do not need further data collection.

By collecting chlorophyll data from Virginia reservoirs, more individual restoration recommendations for reservoir communities on how the light environments may be improved and eutrophication effects may be mitigated. Identification of high blooming areas, annual trends, and susceptible communities will lead to more effective management practices that can be imposed to reduce impacts and assess the changes needed to shift reservoirs towards clear-water regimes as seen in case studies in other global regions (King et al., 2023, Squires & Lesack, 2003).

Increased informed monitoring will also provide a basis for improving water quality issues in the Chesapeake Bay. The Chesapeake Bay currently exhibits issues of eutrophication, hypoxia, algal blooms, and more. These problems cannot be associated with a single source but are instead explained as a culmination of inadequate water resource management throughout the bay's watershed (US EPA, 2010). Moreover, these trends are being seen globally and show a need for more widespread and in-depth monitoring. Figure 1 shows a diagram of how eutrophication and nutrient levels have increased in recent decades as countries continue to develop (Appendix C). Not only does increased monitoring have local implications for communities near the reservoirs, but it will likely also reduce the amount of mismanaged water in the bay as agencies are able to identify and mitigate issues in upstream sources.

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Appendix A. Workflow

Map 1.

1. Shapefile of Virginia Department of Environmental Quality water quality monitoring stations projected to a map in ArcGIS Pro.
2. Shapefile of Virginia Department of Environmental Quality regions projected to a map in ArcGIS Pro
3. Select by attribute → Where ‘parameter’ is equal to ‘Algae identification, algal pigments, algal toxins’
    a. Repeat with “OR” statement for benthic algae, benthic stressors…, high frequency bacteria…, metals…, nutrients…, nutrients solids turbidity…, USEPA…
        i. Delete all selected rows
        ii. This removes all stations that do not monitor chlorophyll
4. Symbolize points as a single symbol, droplet icon, leaf green, 6pt
5. Shapefile of Virginia Department of Environmental Quality reservoirs (2022 Final WQA IR Assessment) projected to same map in ArcGIS Pro under the monitoring stations layer.
6. Buffer → Reservoirs layer → 1 mile
    a. This accounts for lake size fluctuations and rivers of extreme proximity.
7. Clip → water quality stations → intersect with reservoir buffer layer
    a. This shows a visualization of all the water quality monitoring stations that collect CHLa data within 1 mile of reservoirs.

Map 2.

1. Using original DEQ region, reservoir, and monitoring stations data layers from Map 1
    a. Select by location → input feature: reservoirs → intersect → selecting features: monitoring stations → search distance: 1 mile

        i. Right click reservoirs → selection → make layer from selected features
            1. Symbolize as green
        ii. Right click reservoirs → selection → switch selection → make layer from selected features
            1. Symbolize as red

Map 3.

1. With DEQ regions from Maps 1 and 2, Virginia Department of Environmental Quality median station nutrient results 2010-2020 was projected to a map in ArcGIS Pro.
2. Symbolized as graduated colors by medianTN field→ 3 classes, yellow orange red color scheme
    a. Set labels to match classifications as outlined on the DEQ data hub
        i. Low = 0.02-0.99, Medium= .99-1.99, High= 1.99-43

Map 4.

1. Using DEQ regions and median station nutrient results from map 3
    a. Select by attribute → median station nutrient results → where medianTN is greater than 1.99
        i. Right click layer → selection → make layer from selected features
            1. This shows all stations with high median nitrogen over the past decade
            2. Symbolize as single symbol, poinsettia red circle 4, 6pt
    b. Select by attribute → median station nutrient results → where medianTP is greater than 0.1
        i. Right click layer → selection→ make layer from selected features
            1. This shows all stations with high median phosphorous over the past decade
            2. Symbolize as single symbol, lapis lazuli pentagon, 6pt

Maps 5,6,7.

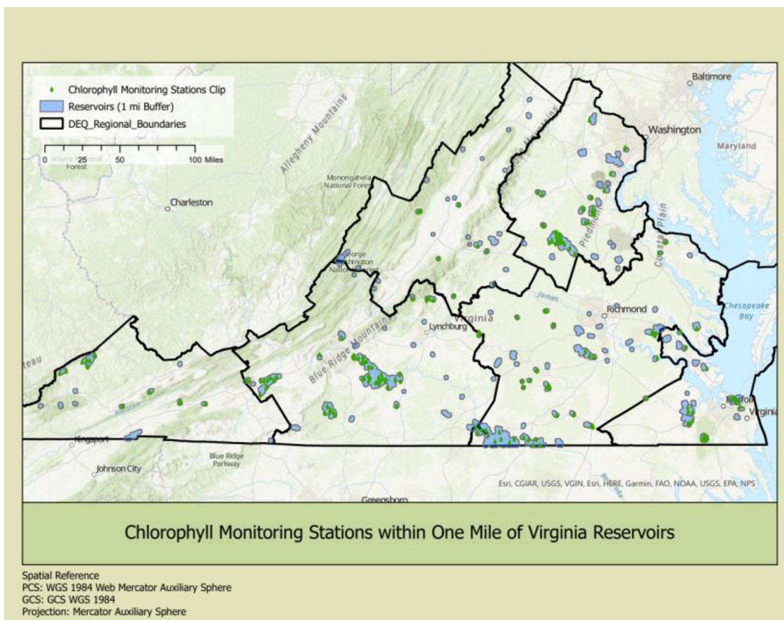
1. Using all previous data layers
    a. Select by location → input features: reservoirs with no chlorophyll monitoring → intersect → selecting features high median nitrogen layer → 1 mile
        i. Symbolize selected as yellow

        1. This shows the reservoirs that have no current chlorophyll monitoring AND have had high median total nitrogen levels (between 2010-2020) found within 1 mile of them

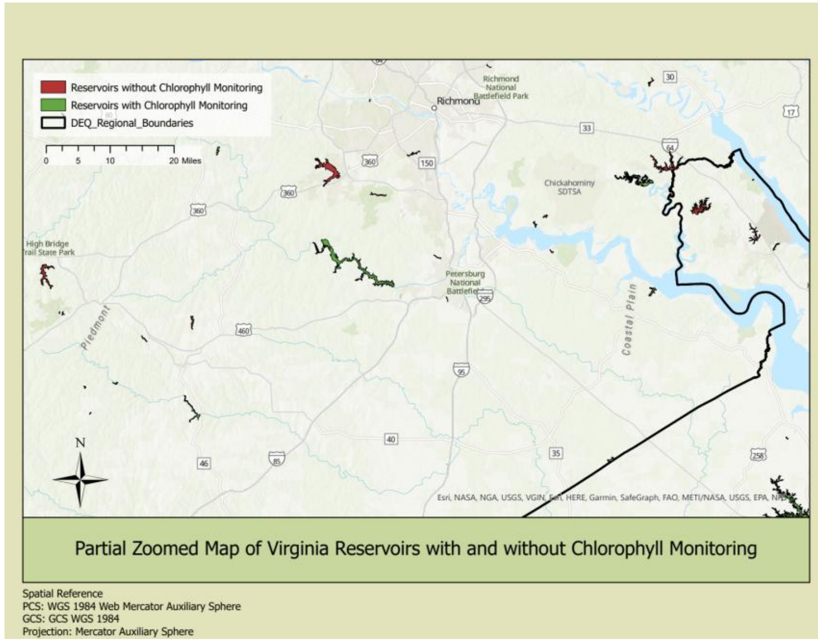
b. Select by location → input features: reservoirs with no chlorophyll monitoring → intersect → selecting features high median phosphorous layer → 1 mile
    i. Symbolize selected as pink
        1. This shows the reservoirs that have no current chlorophyll monitoring AND have had high median total phosphorous levels (between 2010-2020) found within 1 mile of them

Appendix B. Maps

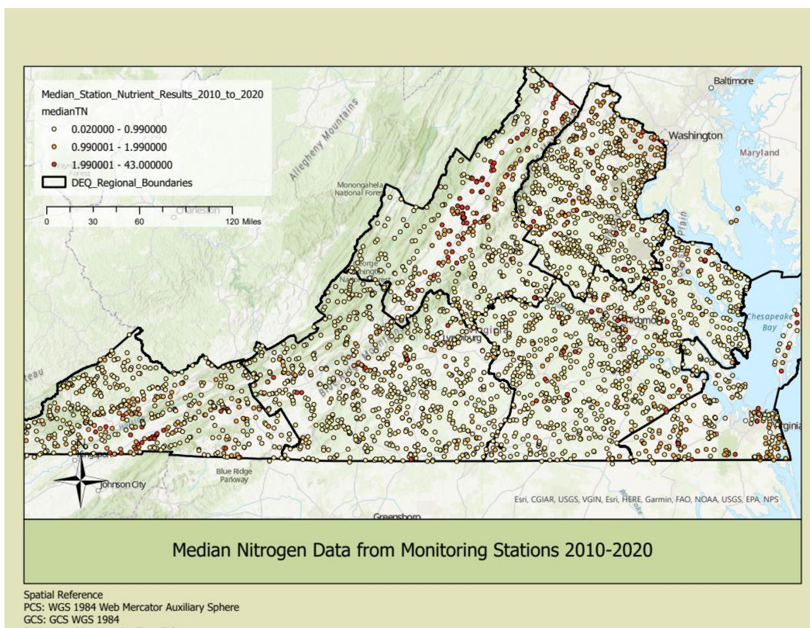
Map 1.



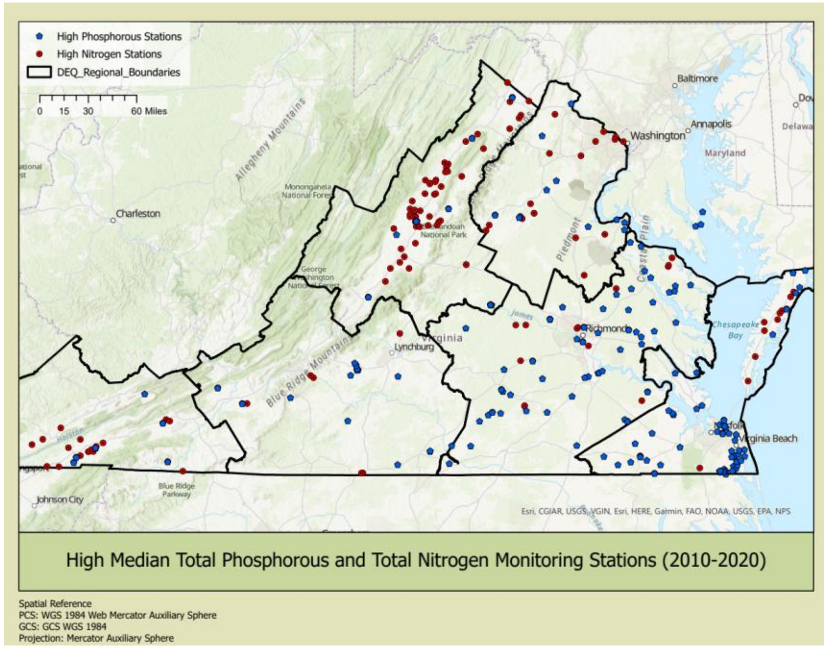
Map 2.


Reservoirs without Chlorophyll Monitoring
Reservoirs with Chlorophyll Monitoring
DEQ_Regional_Boundaries
0 5 10 20 Miles
Richmond
Richmond National Battlefield Park
Chickahominy SDTSA
High Bridge Trail State Park
Petersburg National Battlefield
Piedmont
Coastal Plain
N
Esri, NASA, NGA, USGS, VGIN, Esri, HERE, Garmin, SafeGraph, FAO, METI/NASA, USGS, EPA, NPS
Partial Zoomed Map of Virginia Reservoirs with and without Chlorophyll Monitoring
Spatial Reference
PCS: WGS 1984 Web Mercator Auxiliary Sphere
GCS: GCS WGS 1984
Projection: Mercator Auxiliary Sphere

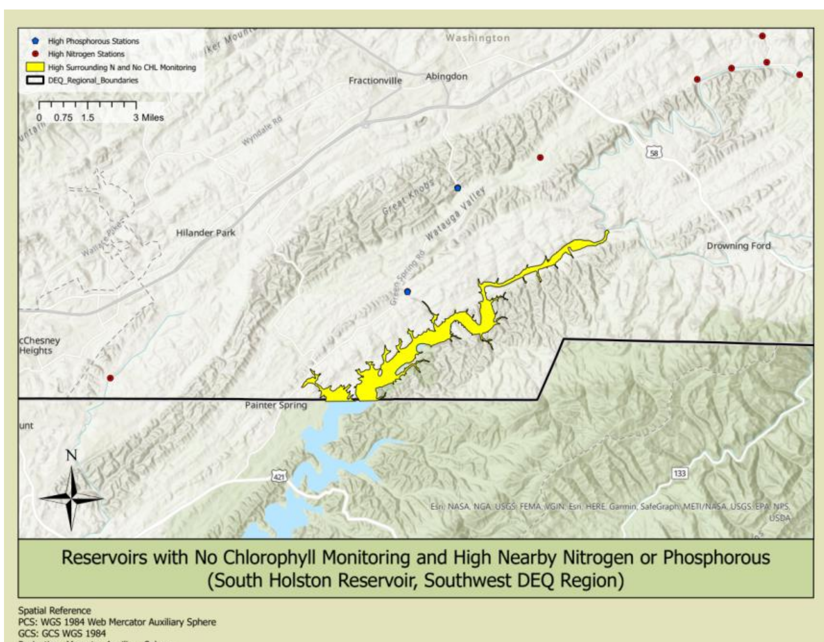
Map 3.


Median_Station_Nutrient_Results_2010_to_2020
medianTN
0.020000 - 0.990000
0.990001 - 1.990000
1.990001 - 43.000000
DEQ_Regional_Boundaries
0 30 60 120 Miles
Baltimore
Washington
Maryland
Allegheny Mountains
Monongahela National Forest
Chesapeake Bay
Johnson City
Blue Ridge Parkway
Greensboro
Esri, CGIAR, USGS, VGIN, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NPS
Median Nitrogen Data from Monitoring Stations 2010-2020
Spatial Reference
PCS: WGS 1984 Web Mercator Auxiliary Sphere
GCS: GCS WGS 1984
Projection: Mercator Auxiliary Sphere

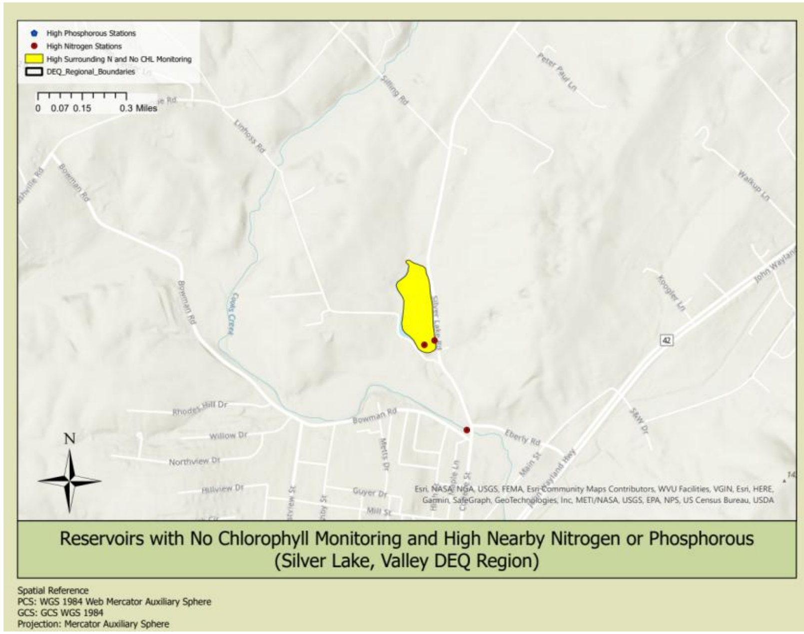
Map 4.


High Phosphorous Stations
High Nitrogen Stations
DEQ_Regional_Boundaries
0 15 30 60 Miles
Baltimore
Washington
Annapolis
Maryland
Charleston
Richmond
Lynchburg
Virginia Beach
Johnson City
Esri, CGIAR, USGS, VGIN, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NPS
High Median Total Phosphorous and Total Nitrogen Monitoring Stations (2010-2020)
Spatial Reference
PCS: WGS 1984 Web Mercator Auxiliary Sphere
GCS: GCS WGS 1984
Projection: Mercator Auxiliary Sphere

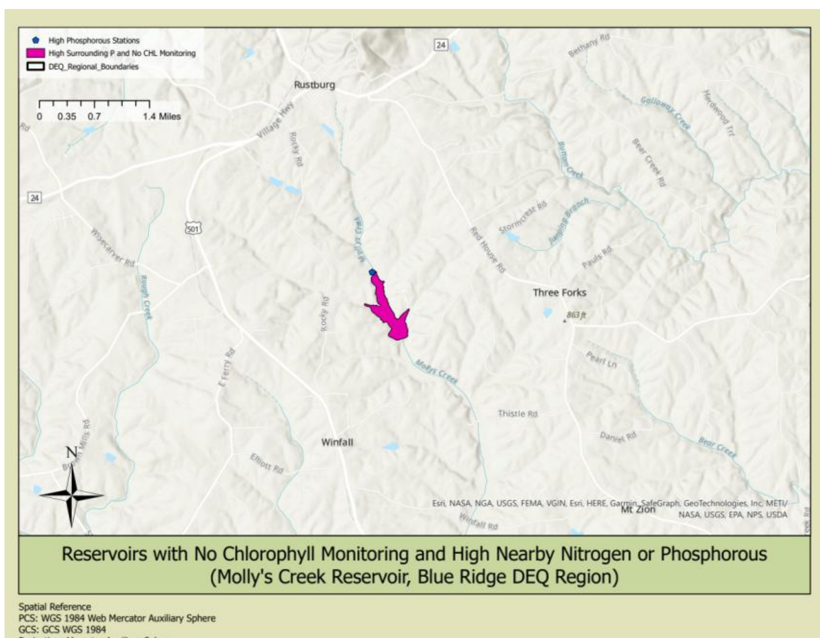
Map 5.


High Phosphorous Stations
High Nitrogen Stations
High Surrounding N and No CHL Monitoring
DEQ_Regional_Boundaries
0 0.75 1.5 3 Miles
Washington
Fractionville
Abingdon
Hilander Park
Drowning Ford
Painter Spring
N
Esri, NASA, NGA, USGS, FEMA, VGIN, Esri, HERE, Garmin, SafeGraph, METI/NASA, USGS, EPA, NPS, USDA
Reservoirs with No Chlorophyll Monitoring and High Nearby Nitrogen or Phosphorous
(South Holston Reservoir, Southwest DEQ Region)
Spatial Reference
PCS: WGS 1984 Web Mercator Auxiliary Sphere
GCS: GCS WGS 1984
Projection: Mercator Auxiliary Sphere

Map 6.


High Phosphorous Stations
High Nitrogen Stations
High Surrounding N and No CHL Monitoring
DEQ_Regional_Boundaries
0 0.07 0.15 0.3 Miles
N
Reservoirs with No Chlorophyll Monitoring and High Nearby Nitrogen or Phosphorous
(Silver Lake, Valley DEQ Region)
Spatial Reference
PCS: WGS 1984 Web Mercator Auxiliary Sphere
GCS: GCS WGS 1984
Projection: Mercator Auxiliary Sphere

Map 7.


High Phosphorous Stations
High Surrounding P and No CHL Monitoring
DEQ_Regional_Boundaries
0 0.35 0.7 1.4 Miles
Rustburg
Three Forks
Winfall
N
Reservoirs with No Chlorophyll Monitoring and High Nearby Nitrogen or Phosphorous
(Molly's Creek Reservoir, Blue Ridge DEQ Region)
Spatial Reference
PCS: WGS 1984 Web Mercator Auxiliary Sphere
GCS: GCS WGS 1984
Projection: Mercator Auxiliary Sphere

Appendix C. Figures

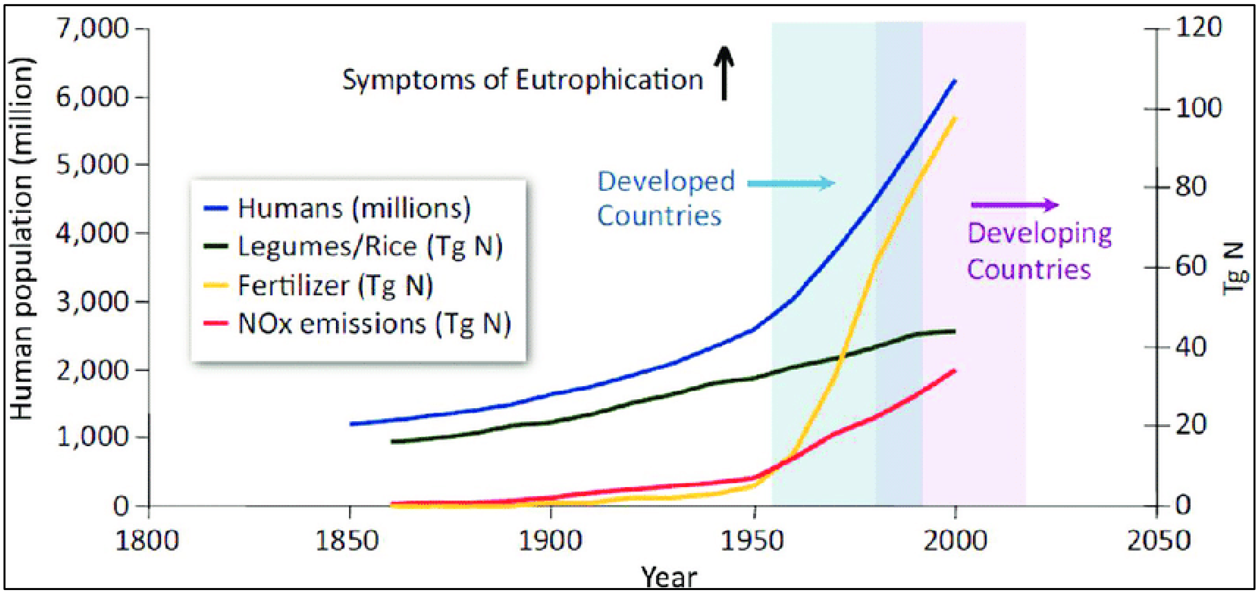


Figure 1: Period in which the symptoms of eutrophication and hypoxia/anoxia began in developed countries and the more recent evolution of these symptoms in developing countries (Ngatia et. al, 2019).