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Chesapeake Bay Water Resources
Using Earth Observations to Assess Spatial and Social Disparities in Water Quality Trends Shaping Fishing and Swimming Access in the Chesapeake Bay

DEVELOP Technical Report
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Nisuka Williams (Project Lead, Analytical Mechanics Associates)
Spencer Harman (Analytical Mechanics Associates)
Simone Schneider (Analytical Mechanics Associates)
Rima Wahab (Analytical Mechanics Associates)

Advisor:
Sean McCartney, NASA Goddard Space Flight Center, Science Systems & Applications, Inc. (Science Advisor)

Lead:
Isabel Lubitz (Maryland – Goddard)

1. Abstract

The Chesapeake Bay is a source of sustenance, livelihood, and recreation for many in Maryland and surrounding areas. Harmful algal blooms and hypoxic conditions in the bay threaten these estuarine communities that rely on them. With support from our partners, Ocean Conservancy and Blacks of the Chesapeake Foundation, we investigated chlorophyll-a and turbidity trends in Anne Arundel and Dorchester Counties and focused specifically on how social vulnerability and water quality at recreational public access sites relate to one another to support outreach and public advocacy initiatives. This project utilized Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) and Sentinel-3 Ocean and Land Colour Instrument (OLCI) imagery to analyze water quality trends and identify areas with high social vulnerability. While we were not able to tease out larger trends in chlorophyll-a persistence across the entire Chesapeake Bay, we did identify certain recreational access sites in our study area that experienced sustained chlorophyll-a levels surpassing the Maryland Department of Natural Resources' threshold for significant harmful algal blooms. We also found no significant difference between the linear distance to recreation sites at low, medium, and high socially vulnerable groups; however, we did identify block groups experiencing high social vulnerability and low proximity to recreation sites. In most cases, we found that in situ monitoring sites were not within an acceptable distance to assess chlorophyll-a and turbidity values and validate satellite data at every recreation site. Despite these limitations, this project demonstrated some feasibility in using Earth observations to assess chlorophyll-a and turbidity levels in Chesapeake Bay.

Key Terms

chlorophyll-a, turbidity, harmful algal blooms, environmental justice, Chesapeake Bay

2. Introduction

2.1 Background

The Chesapeake Bay is the largest marine estuary in the United States, boasting 11,684 miles of shoreline (Chesapeake Bay Foundation, n.d.). With more than 18 million people currently residing in the bay watershed, there are limited direct physical access points to recreational activities along the shoreline. Many residents cannot recreate at the nearest stretch of shoreline due to private land restrictions, unsafe water conditions, or lack of awareness about open waterways (National Park Service, 2013)

Over the past two centuries, the Chesapeake Bay underwent major land use changes (Curtin et al., 2001) including expansion of urban developed areas (Jantz et al., 2005). This change in land use has contributed to an increase in nitrogen and phosphorus inputs to the watershed primarily from anthropogenic sources. Nutrient loading contributes to the increase of turbidity and harmful algal blooms which are indicators of poor water quality (Brush et al., 2020). Prior research shows that spectral imagery and remote sensing methods are useful in identifying levels of chlorophyll-a and turbidity in estuarine ecosystems. Yang et al. (2022) provides an extensive review of the application of remote sensing in water quality and summarizes retrieval algorithms for several specific water quality variables, including chlorophyll-a concentrations in the water. Additionally, data collected from satellites as well as ships, aircraft, and in situ data monitoring provide a way to validate Earth observation data and track seasons of wet/dry and high/low flow (Acker et al., 2005). Accounting for this climate variability is also important for understanding temporal trends of in-water phytoplankton biomass (Harding et al., 2014).

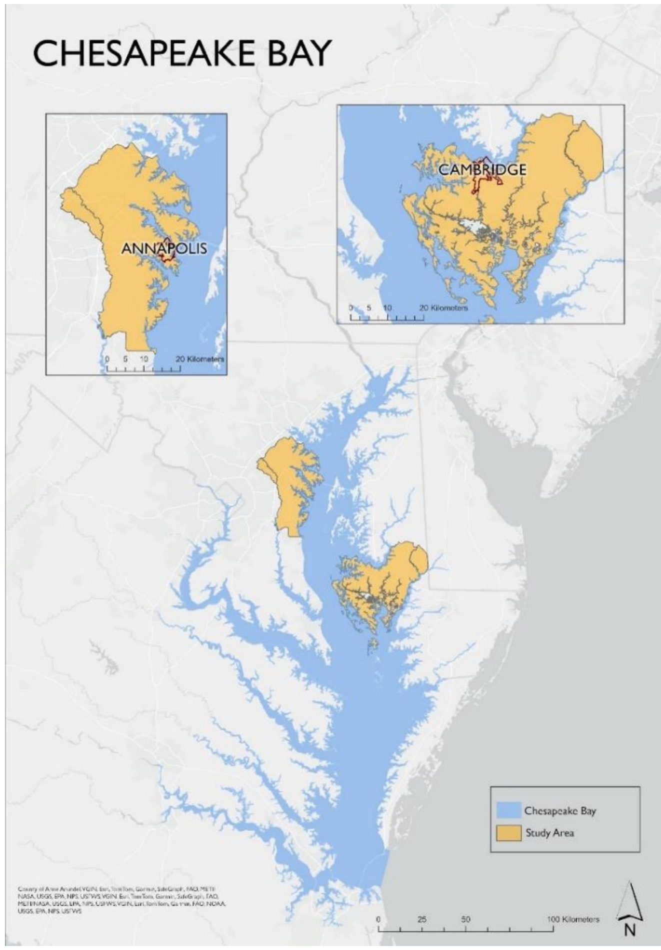
Research also highlights concerns regarding water pollution and social vulnerability. In a meta-analysis, Canfield (2024) found that research into water issues tended to focus freshwater rather than marine ecosystems. Additionally, a large-scale study found that socially vulnerable communities lacked in situ monitoring stations (Kovalenko et al., 2024). Our study aimed to address this concern by demonstrating the feasibility of employing Earth observation data to examine marine water quality at large scales in lieu of in situ data.

2.2 Project Partners & Objectives

For this project, we partnered with Ocean Conservancy and their local partner, Blacks of the Chesapeake Foundation. Ocean Conservancy works closely with local community partners to identify relevant environmental challenges. Our other local partner, Blacks of the Chesapeake Foundation, is a land, water, and cultural preservation organization that works to ensure access to green and blue spaces, such as public parks and beaches, in the Chesapeake Bay region. Both of our partners are primarily concerned with how water quality is affecting their communities' access to swimming and fishing. Information on where poor water quality is occurring allows them to further identify anthropogenic drivers of poor water quality and allocate resources toward protecting the Chesapeake Bay. Additionally, the partners are interested in seeing which communities have access points to their waterways because underserved communities in the bay have a documented lack of access to blue and green space. By examining these access points and seeing where poor water quality is occurring, our partners can effectively allocate resources for outreach and stewardship efforts.

To assist our partners in their efforts, this feasibility study explored remote sensing and sociodemographic data to address environmental concerns for communities surrounding Chesapeake Bay. Using satellite-based chlorophyll-a and turbidity products, we evaluated spatial and temporal trends in water quality in the bay. We also identified communities with high social vulnerability and low access to recreational fishing and swimming locations. Blacks of the Chesapeake Foundation plans to utilize the map end-products as outreach and communication tools to raise awareness about environmental issues in the bay and empower younger generations to pursue scientific careers in support of environmental management applications.

The study area for this project was composed of two counties in Maryland surrounding the Chesapeake Bay: Anne Arundel and Dorchester (Figure 1). Anne Arundel county is predominantly urban and includes the city of Annapolis, contrasting the more rural setting of Dorchester County that includes the city of Cambridge and the Blackwater National Wildlife Refuge. Only two percent of the Chesapeake Bay's coastline is accessible to the public (Leggett et al., 2024). Within the study area, Anne Arundel County has 817 km of shoreline and Dorchester County has 2,476 km of shoreline (Maryland Geological Survey, n.d.). We analyzed the months of May to October from 2020 to 2024 because there is a higher occurrence of harmful algal blooms in warmer months and our study period focused on recent years due to its higher relevance to our partners and the recent occurrences of harmful algal blooms in the Chesapeake Bay (Harding, 2019).



[Basemap Credits: County of Anne Arundel, VGIN, Esri, TomTom, Garmin, SafeGraph, METI/NASA, USGS, EPA, NPS, USFWS, FAO, NOAA]

Figure 1. Map of the study area including Dorchester County and its county seat of Cambridge on the east side of the bay, and Anne Arundel County and its county seat of Annapolis on the west side of the bay.

3. Methodology

We leveraged Earth observations from the European Space Agency's Sentinel-3 Ocean and Land Colour Instrument (OLCI) and the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite as well as ancillary datasets to do the following: create a time series analysis of chlorophyll-a and Kd(490) to evaluate harmful algal blooms and turbidity in the Chesapeake Bay, produce maps showing high chlorophyll-a persistence over our study period, and calculate a social vulnerability index (SVI) and bivariate map showing SVI and block groups with low public swimming and fishing access. We used the diffuse attenuation coefficient, Kd(490), as it shows how well visible blue and green light is attenuated within the water column, indicating the turbidity of the water column (Wang, et. al., 2009).

3.1 Data Acquisition

3.1.1 Earth Observation Data

We acquired Sentinel-3A and B OLCI Level 2 chlorophyll-a and Kd(490) datasets from the Ocean Biology Distributed Active Archive Center (OB.DAAC) with cloud and land masking already performed. We chose Sentinel-3 OLCI for its 300 meter spatial resolution, which allowed us to analyze water quality at a relatively fine spatial scale, and for OB.DAAC's pre-made chlorophyll-a and MODIS was chosen to explore the feasibility of assessing chlorophyll-a levels at a 1km resolution. We compared data from Aqua MODIS to Sentinel-3 OLCI (Table 1).

Table 1

Summary of the Earth observation data products employed in the study

Platform & Sensor	Parameter	Date Range	Temporal Resolution	Spatial Resolution	Source
Sentinel-3A/B OLCI	Kd(490)	*2020 – 2024 (May – October)	2 days	300 m	NASA Ocean Color
Sentinel-3A/B OLCI	chlorophyll-a	*2020 – 2024 (May – October)	2 days	300 m	NASA Ocean Color
Aqua MODIS	chlorophyll-a	2024 (May – October)	Daily	1000 m	NASA Ocean Color

*For the year 2024, we used data for the months of May through August. This allowed us to use the months for which all 30 or 31 days were available since this project began in mid-September of 2024.

3.1.2 Ancillary Data

We incorporated ancillary datasets such as recreational public access site locations from Chesapeake Progress and sociodemographic data from the US Environmental Protection Agency (EPA) to support our analysis (Table 2). For our social vulnerability analysis, we collected sociodemographic data from the EPA's EJScreen tool (US EPA, 2024). Their data comes from the US Census Bureau's American Community Survey 2018 – 2022 5-year estimates (American Community Survey, 2023). We downloaded the state level geodatabase at the block group level, which organizes the data into shapefiles from 2022 Census TIGER/Line data. (US Census Bureau, 2022). Variables used to calculate the SVI include people of color, low income, unemployment rate, limited English speaking household, less than high school education, under age 5, over age 64, and disability status. These are all variables used by the EJScreen tool as socioeconomic indicators of higher environmental burden and vulnerable populations.

Table 2

Summary of the Ancillary Data Employed in the Study

Ancillary Data	Source
In Situ chlorophyll-a monitoring data	Chesapeake Bay Data Hub
Sociodemographic variables	EPA's EJScreen tool
Recreation Public Access Sites	Chesapeake Progress
Maryland Point Source Discharges dataset	State of Maryland ArcGIS online
Chesapeake Bay Land Use map	Chesapeake Bay Land Use and Land Cover Database 2022 Edition

To evaluate water quality at the recreation sites in our study area, we obtained tabular data on public access locations for fishing and swimming sites in Anne Arundel and Dorchester counties from the Chesapeake Progress website. Additional ancillary data included the Maryland Point Source Discharges GIS dataset that we downloaded from the state of Maryland's GIS Data Catalogue. This dataset was developed and published in 2013 by the Maryland Department of the Environment and represents regulated facility outfalls. We also employed a high resolution 1-meter land use dataset from the US Geological Survey to support data analysis.

To further analyze water quality at select case study locations, we identified areas of importance to our partners to incorporate valuable local knowledge into the analysis. The Blacks of the Chesapeake Foundation identified the following four sites for case study locations: Bodkin Point and Jonas and Catharine Anne Green Park in Anne Arundel County, and Long Wharf in Cambridge and Crapo in Dorchester County. From these areas of interest, we found the nearest public access sites (Table 3).

Table 3
Distance between monitoring sites and public recreation access

Partner Area of Interest	**Monitoring Site**	**Feasible Public Access**	**Distance Between In Situ Monitoring Site and Feasible Public Access (Meters)**
Bodkin Point	BWB.BWB-PATMH-22	Downs Memorial Park	1418
Jonas and Catherine Anne Green Park	WT7.1	Jonas Green State Park	2150
Long Wharf	ET5.2	Long Wharf	998
Crapo, Blackwater	XCH3277	Crapo Boat Ramp	13500

3.2 Data Processing

3.2.1 Earth Observation Bi-weekly Composites (Chlorophyll-a & Turbidity) Processing

We uploaded Sentinel-3 Level 2 OLCI data into SeaDAS 9.0.1, reprojected the files into the WGS 1984 geographic coordinate system, and converted them into NetCDF-BEAM format. The Level 2 data already includes the Chlorophyll-a and Kd(490) ready products. To extract the Chlorophyll-a and Kd(490) from the downloaded data, we added the NetCDF-BEAM images to an ArcGIS Pro 3.2 project via the "Make Netcdf Into Raster" tool. We composited the raster images with the "Cell Statistics" tool—the parameters set in the tool included calculating the mean and ignoring no data values. Mean composites were decided upon in order to remain consistent with other literature that studied remote sensing applications to estuarine environments resulting in a total of 56 bi-weekly composites of chlorophyll-a and another set of 56 bi-weekly composites of Kd(490) from 2020 to 2024 for the months of May to October (May to August for 2024). We composited all of the imagery available for the months within the study period. Days 1 through 15 were used to create the first composite and days 16 through 30 or 31 were used to create the second composite, creating two composites that are representative of the first and second halves of each month.

We acquired in situ data from monitoring site ET5.2 because it had the most instances of sampling data across our entire study period. The water quality dataset provided by Data Hub Chesapeake Bay was added to ArcGIS Pro with the Add Data by X Y Point tool. Then, we input all composites previously created into the "Extract Multi Values to Points" tool which resulted in a table with chlorophyll-a values from the ET5.2 site, Sentinel-3 pixel, and MODIS pixel from May 2020 to October 2024.

3.2.2 Persistent Algal Blooms Processing

After compositing the Sentinel-3 OLCI chlorophyll-a data products, we further incorporated the 56 bi-weekly chlorophyll-a composite maps to derive the persistent algal blooms as follows: we defined the persistence of algal blooms as the cumulative per-pixel frequency of the bi-monthly chlorophyll-a abundance exceeding a set threshold over the study period. We characterized algal blooms as significant when the chlorophyll-a threshold was greater than or equal to 50 micrograms per liter in line with the monitoring approach followed by the Eyes on the Bay of Maryland Department of Natural Resources (Eyes on the Bay, n.d.).

3.2.3 SVI Processing

We clipped the EJScreen Tool shapefiles with socioeconomic variable data to our study area within ArcGIS Pro 3.2 and deleted all block groups not within the state of Maryland. We then exported the attribute table to Microsoft Excel version 2308 and calculated percentile ranks for each variable. To keep our final SVI range between 0 and 1, we divided the added percentile ranks by the total number of socioeconomic variables; in our case, this number is 8 (Equation 1). This output gives a final SVI score for each block group. Next, we joined the final SVI field from Microsoft Excel to our geometry in ArcGIS Pro. Our SVI is relative to all block groups in Maryland; however, we only wanted to display our study areas. Thus, we deleted all block groups that were not in Dorchester or Anne Arundel counties.

$$\mathrm{SVI} = \frac{\text{Variable Percentile Rank}_{1+2+\ldots n}}{n} \tag{1}$$

3.3.4 Recreational Access Points Processing

Access to recreational blue space for each block group is represented as a function of its linear distance to its closest public fishing or swimming site. To calculate this, we imported public access locations for fishing and swimming into ArcGIS Pro 3.2 and converted them into a vector with points. Next, we imported our EPA EJScreen block group data and used the "Feature to Point" tool to calculate a centroid for each block group and create a point feature class of each centroid which we called "bivariate centroid". To calculate the distance from each block group's centroid to its nearest access point, we used the "Near" tool to add the distance to the "bivariate centroid" attribute table. To join each block group's distance calculation to our original block group shapefile, we used the "Join Fields" tool.

To evaluate chlorophyll-a persistence at the recreational access sites, we created a 900-meter buffer around each access point in both study area counties. We selected this buffer size to account for the point geolocational errors of select recreation access sites that may be located as a centroid of adjacent coastal parks and at a distance from the water body. In addition, we found that this buffer size may compensate for the occasional lack of data in the chlorophyll-a composites at the land-water interface due to cloud masking; thus, allowing adjacent water pixels to be considered.

3.3 Data Analysis

3.3.1 Time Series and Case Studies (2020 – 2024)

To investigate trends in water quality, we extracted chlorophyll-a and Kd(490) levels at the pixel level and compared to in situ data. Then, we plotted the values of chlorophyll-a over the course of our study period in order to create a time series graph. We established a linear trend line on the graph for satellite and in situ data.

3.3.2 Persistent Algal Blooms at Access Sites

To calculate persistence, we classified all bi-monthly chlorophyll-a composites into binary maps; a pixel value of 1 indicates that chlorophyll-a observations exceeded the threshold while pixel values of 0 fell below the threshold. We then summed the value for each pixel in the resulting binary maps across the time series and divided by the total number of occurrences (Equation 2). We also excluded NoData values from the calculations. The persistent output is an index that ranges from 0 to 1, where 1 indicates 100% persistence of significant algal blooms over the study period. We then visualized the resulting persistence map using the natural breaks classification in ArcGIS Pro 3.2 to highlight areas of high, medium, and low persistence. Furthermore, to quantify persistence at every access site, we extracted the mean and maximum values from the persistence map using a 900-meter buffer per site.

$$\text{Persistence} = \frac{\sum_{i=1}^{n} X_i}{n} \tag{2}$$

3.3.3 SVI and Distance to Recreational Access Site Bivariate Maps and Statistical Difference

To visually analyze our social vulnerability data, we represented each block group's SVI score from low to high on a map using three categories of natural breaks (low was classified using SVI values 0 – 0.36, medium using SVI values of 0.37 – 0.52, and high using SVI values of 0.53 – 0.79; Figure A1). To visually analyze each block group's fishing and swimming access, we represented the linear distance of each block group to its closest public recreation access site using three categories of natural breaks (low is classified as 0.02 – 4.74 kilometers, medium is classified as 4.74 – 10.58 kilometers, and high is classified as 10.58 – 19.45 kilometers; Figure A2). Next, we identified areas of both high social vulnerability and high distance to public fishing and swimming sites through the creation of a bivariate choropleth map in ArcGIS Pro (Figure A3). To examine the relationship between socially vulnerable block groups and their linear distance to the nearest recreational access site, we created boxplots in RStudio 4.3.2. We plotted SVI on the x-axis in the three natural break groupings by distance to recreational access site on the y-axis. To test if there was a significant difference between our natural breaks groupings, we ran an ANOVA test in RStudio.

4. Results

4.1 Analysis of Results

To analyze water quality in our study area, we investigated all public access sites in Anne Arundel and Dorchester counties. Unfortunately, many of the public access sites lacked consistently sampled, in situ chlorophyll-a and turbidity data. Out of the 72 public access sites in Anne Arundel and Dorchester Counties, we were only able to compare in situ and remotely sensed data for 13 access sites in Anne Arundel County and 17 in Dorchester County. All 30 available sites were analyzed for satellite-based chlorophyll-a persistence data. In addition, using our social vulnerability index and distance to recreation access site data, we created a bivariate map to identify communities experiencing this coupled phenomenon. Lastly, due to partner interest in Annapolis and Cambridge, we focused our time series comparing water quality data from in situ monitoring and remotely sensed data.

4.1.1 Time Series Case Studies

We compared data captured by the ET5.2 monitoring station, Sentinel-3 OLCI, and Aqua MODIS over a 4-year period (Table B1) and plotted them (Figure 2). The red line represents in situ data taken at monitoring site ET5.2 located 998 meters from a public access site in the Long Wharf area in Cambridge. The in situ data are consistently lower than satellite data as shown in blue and yellow for Sentinel-3 OLCI and Aqua MODIS, respectively. Visually, there is a similarity between in situ data and Sentinel-3 data from 2021 to 2023. Over the course of five years, the trend for Sentinel-3 data shows a decline in chlorophyll-a levels. In situ data for 2024 was not available at this monitoring site at the time this research was conducted, but the trend also signals a decline in chlorophyll-a levels.

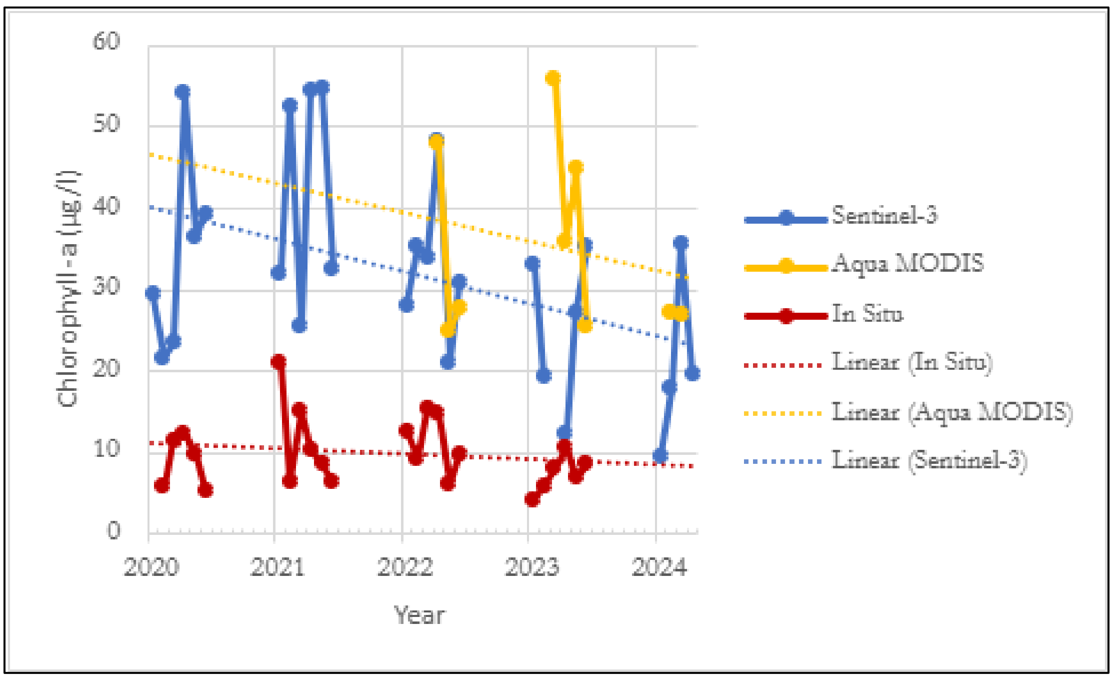


Figure 2. Variations in chlorophyll-a at a Cambridge Site

We used Aqua MODIS data to cross-reference the Sentinel-3 OCLI data with additional Earth observation data. In 2022, for example, chlorophyll-a readings from Sentinel-3 OCLI range from 21.1 to 48.3 micrograms per liter, while Aqua MODIS readings range from 25.1 to 47.9 micrograms per liter (Table B1). Though there is some discrepancy, the graph signals a visual distinction between in situ and satellite readings rather than a distinction between all three data sources.

4.1.2 Chlorophyll-a Persistence

Visualizing the persistence map using the natural clustering of the data reveals that low persistence areas experienced significant algal blooms less than 15% of the time across the study period; medium persistence depicts areas that have experienced significant algal blooms from 15% to 47% of the time, and high depicts areas that experienced significant algal blooms more than 47% and up to 100% of the time during our study period (Figure 3). While we were not able to determine larger trends in chlorophyll-a persistence across the entire Chesapeake Bay, we did notice that certain recreational access sites in our study area experienced sustained chlorophyll-a levels surpassing the Maryland Department of Natural Resources' threshold for significant harmful algal blooms. For example, we found that the area within the buffer around Long Wharf access site in the city of Cambridge in Dorchester county experienced a maximum persistent chlorophyll-a level at 0.32 meaning that 32 percent of the chlorophyll-a observations in that area between 2020 and 2024 are at or above the Maryland Department of Natural Resources' threshold for significant algal blooms (Figure B1). We also examined the locations of the wastewater treatment sites in our study area and observed that waters around the wastewater treatment plant had experienced significant algal blooms ranging from 33 percent to 80 percent of the times. However, there might be quantification errors due to spectral mixing of the Sentinel-3 OLCI pixels at the land-water interface. The wastewater treatment plant in Cambridge is located about 2 kilometers away from the Long Wharf access site.

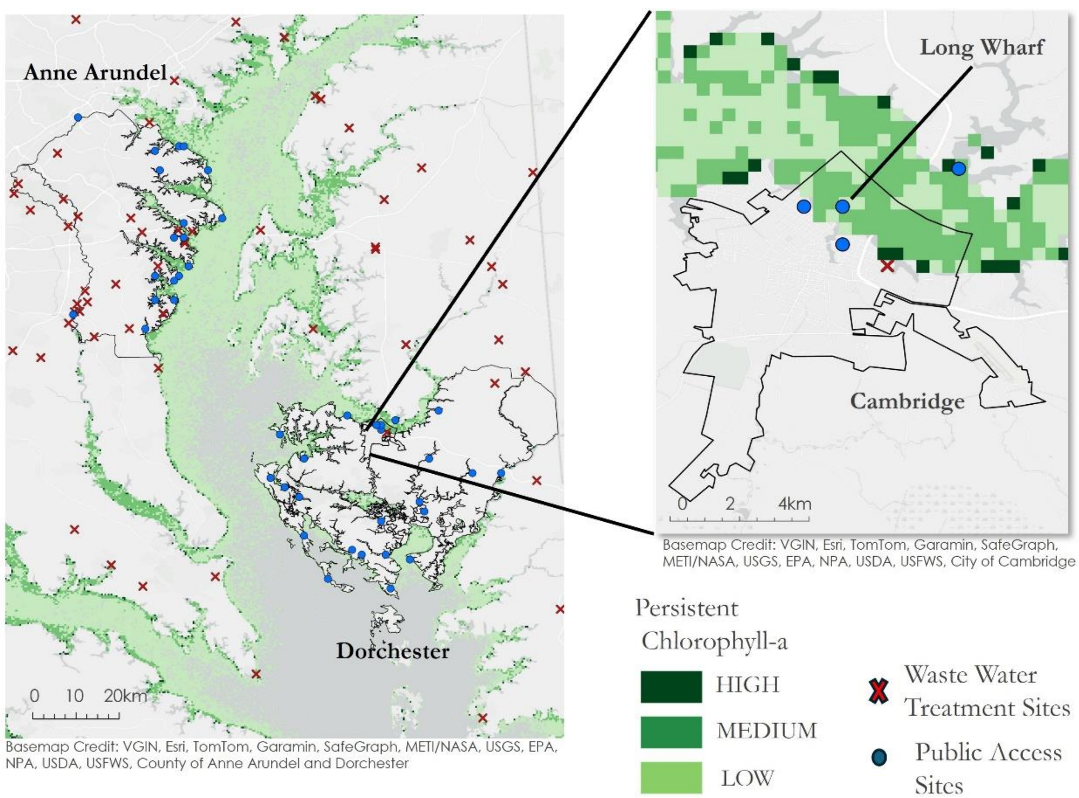


Figure 3. Chlorophyll-a Persistence in the Chesapeake Bay and the distribution of Wastewater Treatment Sites along the Bay, and the location of Access points in Anne Arundel and Dorchester Counties. The inset map highlights persistence along Long Wharf access site in Cambridge and the nearby Wastewater Treatment Plant.

In Dorchester County, we examined mean and maximum persistence data for the 17 fishing and swimming access sites (Figure B1). Average persistence results ranged from the lowest at Tyler Cove Boat Ramp (0.04) to the highest at Kirwins Wharf (0.5), noting Toddville Boat Ramp site (0.4) and the Choptank River Fishing Pier (0.34). Kirwins Wharf access site is a fishing and boating site while Toddville Boat Ramp is a fishing site, and both access sites are surrounded by tidal wetlands (US Geological Survey data, 2022). The Choptank River Fishing Pier is only utilized as a fishing site and is surrounded by cropland (US Geological Survey data, 2022).

In Anne Arundel County, we calculated the mean and maximum persistence of 13 access sites (Figure B2). Persistence results ranged from the highest average at Jack Creek Park (0.48) to the lowest at Downs Memorial Park (0.08). Jack Creek Park is a fishing and swimming site and is surrounded by tidal wetland forest (US Geological Survey data, 2022). We suspect the high persistence values may be a result of the spectral mixing of the Sentinel-3 OLCI pixel at the land-water interface. In addition, our partners highlighted an interest in the Jonas Green State Park as a fishing and boat access site off the city of Annapolis where we noted an average persistence value of 0.2.

4.1.3 Social Vulnerability and Distance to Recreational Access Site

In Anne Arundel, the areas with the highest SVI score are north of South Gate, Pumphrey, Fox Chapel, Maryland City, and Southern Annapolis as seen in dark blue (Figure A1). Specifically, in Annapolis, block groups by its northern inlet along the US Naval Academy are low in social vulnerability, while block groups around its southwest boundaries are higher in social vulnerability. Dorchester in comparison has a higher average SVI score at 0.55 than Anne Arundel at 0.41 (Figure A2). Dorchester County's most vulnerable areas are block groups on its east side in areas such as Linkwood, Hurlock, as well as Church Creek a seen in dark blue (Figure A2). The city of Cambridge specifically has its highest SVI in its northwestern section near our study area site of Long Wharf (Figure A2).

In Anne Arundel, the average distance to the centroid of a block group is 6.79 kilometers. As expected, areas in Anne Arundel that are further from the shoreline have further distances to an access site. However, block groups near Ferndale and Pumphrey, just south of Baltimore, are close to waterways, but have a notably high distance to public access sites compared to other block groups closer to the shoreline (Figure A1). Annapolis specifically has two public fishing sites and block groups here are considered low linear distance to public access sites. In Dorchester, the average distance from the centroid of a block group is 4.36 kilometers. As expected, the highest distance to a fishing or swimming access site is in block groups furthest inland. However, the Church Creek area notably has a further distance to an access site despite being a coastal block group (Figure A2). Cambridge specifically has three public fishing sites and block groups in this area are not considered to be high in linear distance to an access site.

To better understand the relationship between SVI and public access to recreation, we plotted SVI against linear distance to public access sites (Figure A3). Block groups with low social vulnerability and short linear distances to public access sites show up as lighter colors on the bivariate map, while high social vulnerability and further distances show up as darker colors on the bivariate map. In Anne Arundel, the areas highest in both SVI and distance to access sites are Maryland City and a couple block groups directly east of Fort Meade. Pumphrey and South Gate are also areas of note that are high in SVI and relatively far from access sites. In Dorchester, the block group that covers El Dorado, Brookview, and Millpond Acres is highest in both SVI and recreation access distance. Areas near Hurlock are also notably high in SVI and moderately high in distance to public recreation. Additionally, our ANOVA test p-value was greater than 0.05, indicating that there is not sufficient evidence to say that there is a statistically significant difference between the average of our SVI groupings' distance to recreation access sites (Figure A4).

4.2 Errors and Uncertainties

First, the spatial resolution of Aqua MODIS at 500m and Sentinel-3 OLCI at 300m; pixel size made it challenging to track changes over a small spatial scale, especially in coastal areas where land and water pixels mix. We chose to use these data because they had larger swaths than Sentinel-2 Multispectral Imager (MSI) and included level 2 bands for chlorophyll-a and Kd(490). In addition, we introduced uncertainty into the time series analysis by using 15 day mean composites. Averaging 15 days' worth of imagery into one mean composite mutes what was happening day to day but allowed us to draw trends from a larger scale of five years. With respect to validating monitoring data with recreation site, there was a lack of colocation between the monitoring sites and recreation sites, with an average of 17km separating each site. There were very few cases where the sites were near each other, limiting our ability to draw conclusions using in situ data at areas we were interested in. Additionally, the recreation and monitoring site data was unconfirmed to be up to date, leading to some uncertainty.

As in situ measurements and reflectance values are plotted on the charts, it is important to note that the data point for the monitoring station represents the measurement taken at one moment in the entire month. The data point for Sentinel-3 OLCI represents the average of several values taken for the entire month. For example, in Table B1 for May 2020, the in situ data point was collected on May 12. The corresponding data point for Sentinel-3 OLCI is the average of 20 measurements from May 1 to May 31. The lack of consistent in situ measurements for popular areas as well as the lack of monitoring sites around areas like Crapo Boat Landing in the Blackwater Wildlife Refuge provide justification for Earth observations to supplement water quality analysis. If we had adequate time and financial resources, we would redo the study and collect in situ measurements at popular recreation access sites for inclusion in the comparative analysis with satellite measurements.

Few limitations and uncertainties contributed to the chlorophyll-a persistence results along the bay and particularly at access sites. First, we utilized bi-weekly mean composites that could have possibly underestimated certain spikes in blooms. An alternative approach would be to test weekly compositing or testing results using the median rule instead of mean. Another method would be to avoid compositing and threshold the daily satellite data to create the persistence map. Second, we implemented a threshold of 50 micrograms per liter that is also employed by Maryland Department of Natural Resources' Eyes on the Bay to characterize significant blooms. While Eyes on the Bay notes that algal blooms can be harmful with concentrations at or exceeding 10 micrograms per liter, identifying the optimal threshold to characterize significant blooms remains a challenge, particularly within the context of our study to address blooms at the land-water interface to impact management decisions at recreation access points along the Bay. And third, we observed few high persistence values up to one (100 percent) particularly in areas adjacent to the land. Some of these values appear to be resulting from the spectral mixing due to Sentinel-3 OLCI's 300m pixel resolution at the land-water interface. A suggested solution would be to investigate higher resolution satellite data such as Sentinel-2 MSI.

When examining social vulnerability, our output SVI scores are contingent on the input variables. Other variables to consider are gender, proximity to hazardous waste facilities, access to a car, housing type, health care coverage, among others. These variables were not used due to partner interest or constraints to accessible data at the block-group level but are also key variables to consider when creating a vulnerability index. Additionally, social vulnerability indices are typically used to identify populations at a higher risk of exposure to a hazard. While harmful algal blooms are considered a hazard, they do not pose imminent threat to populations inland.

Additionally, our proxy for a block group's access to blue space was the linear distance of its centroid to its nearest public access site. Using a centroid to represent a block group raises uncertainty because: 1) the accuracy of the distance calculation will vary depending on where you are looking within that block group, and 2) block groups vary in size, meaning larger ones whose outskirts fall close to an access point may not reflect it due to their centroid being further away. Additionally, the linear distance does not account for the true travelled distance it would take along a path to reach a public access site. This is especially true for Dorchester, a more rural county with notably less roads running through the Blackwater National Wildlife Refuge. Lastly, our access calculations do not consider individual access to public transportation or cars, variables that act as a hindrance or enhancer to blue space access. Overall, our method to quantify access is functional within the time constraint of this project, but not a comprehensive method to examine barriers to access, particularly through qualitative analysis.

5. Conclusions

5.1 Interpretation of Results

At the monitoring site near Cambridge, there has been a downward trend in chlorophyll-a over the past 5 years according to both in situ and satellite data (Figure 2). Note that this trend occurred at one monitoring station. There is also a lack of satellite data at public access points due to the resolution of Sentinel-3 OLCI. Points too close to land (swimming and fishing sites) tend to have sparse pixel data compared to points that are further out from the coastline. This is also true of Aqua MODIS data; 1000m pixel sizes were too large to resolve chlorophyll-a within inland tributaries, limiting us to public access points closer to the greater Chesapeake Bay. Based on results from Sentinel-3 OLCI, the chlorophyll-a concentrations ranged from 9.4 micrograms per liter to 54.5 micrograms per liter. A threshold of 50 micrograms per liter characterizes a significant algal bloom by the Maryland Department of Natural Resources. With both in situ and remote sensing data, the last five years show a downward trend in chlorophyll-a levels for this area.

A lack of monitoring site observations and in proximity to recreation sites limited our ability to validate our remotely sensed turbidity data. On average the distance between a turbidity monitoring site and a recreation site was 17km. This distance was too large to connect the two site's water quality and ultimately led to us excluding the turbidity data from analysis. Initially, we had wanted to compare turbidity and chlorophyll-a over time in our case study areas; however, there was a large disparity in the availability of in situ data. Even though the average distance between recreation site and monitoring points were similar values, chlorophyll-a was monitored nearly 26,000 times over the past 5 years.

While we were not able to quantify larger trends in chlorophyll-a persistence across the entire Chesapeake Bay, we did notice that certain recreational access sites in our study area experienced sustained chlorophyll-a levels surpassing the Maryland DNR's threshold for significant harmful algal blooms. As for our SVI and distance to recreational access sites, we find no significant difference between socially vulnerable populations and distance to recreational sites. However, our main purpose was to identify socially vulnerable communities and ones experiencing less access to public recreation sites so that we may further support Blacks of the Chesapeake's education efforts. We visually assessed these communities in our bivariate maps and conclude that Eldorado in Dorchester and Maryland City and the Brooklyn Park/Pumphrey area in Anne Arundel are the neighborhoods in our study area that experience coupled high SVI and high distance to recreation access sites.

5.2 Feasibility & Partner Implementation

Through this project we conclude that remote sensing data are beneficial to communities where there is a lack of resources to monitor the water quality. We were able to utilize satellite Earth observations to analyze trends in chlorophyll-a and turbidity in the Chesapeake Bay during our study period. Compared to Aqua MODIS, we found that Sentinel-3 OLCI was the more optimal satellite to use within the scope of the project as it provided datasets for chlorophyll-a and KD 490 at 300-meter resolution. Aqua MODIS also provided chlorophyll-a data products, but at a lower resolution of 500 meters and was not deemed feasible within the scope of the project.

Our partners at Blacks of the Chesapeake and Ocean Conservancy proposed this project because they were interested in how vulnerable communities are experiencing impaired water and how that was affecting their access to recreation in Chesapeake Bay. They expressed interest in communicating some of the trends we noticed with local fishermen and aquaculture farmers, to spread the word on harmful algal blooms and their toxic effects. Additionally, based on our SVI and access maps, our partners can direct resources and speak to community leaders about access in Anne Arundel and Dorchester Counties and actively focus on the most affected communities that lack access to recreation sites and are being the most exposed to impaired water quality. Lastly, our partners can use our maps and products for outreach and youth empowerment. They will focus on uplifting youth by educating them about environmental issues such as water quality and access issues in the bay and fostering a passion in them to become the next generation of environmental stewards.

6. Acknowledgements

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7. Glossary

ANOVA – A test that determines if there is a statistically significant difference between the means of more than two groups
Anthropogenic – Resulting from or produced by humans
Chlorophyll-a – Green pigment found in algae, among other plants, and can be used as an indicator of harmful algal blooms in aquatic systems
Earth Observations – Satellites and sensors that collect information about the Earth's physical, chemical, and biological systems over space and time
Environmental Justice – The idea that all people deserve protection from environmental and health hazards
EPA – Environmental Protection Agency
ESA- European Space Agency
Harmful Algal Blooms – Overwhelming growth of algae or cyanobacteria in water producing toxic effects
Kd(490) – Diffuse attenuation coefficient at 490 nm, representing the rate at which light is attenuated with depth, and often used as a proxy for water turbidity
MODIS – Moderate Resolution Imaging Spectroradiometer
OLCI – Ocean Land and Color Instrument
SVI- Social Vulnerability Index
Temporal Resolution – The time elapsed between consecutive images of the same location on Earth taken by a satellite sensor, also known as the revisit period
Turbidity – Measure of how light reflects off suspended particles in water such as sediment or plankton in a body of water

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9. Appendices

Appendix A: *Social Vulnerability Index (SVI) Maps*

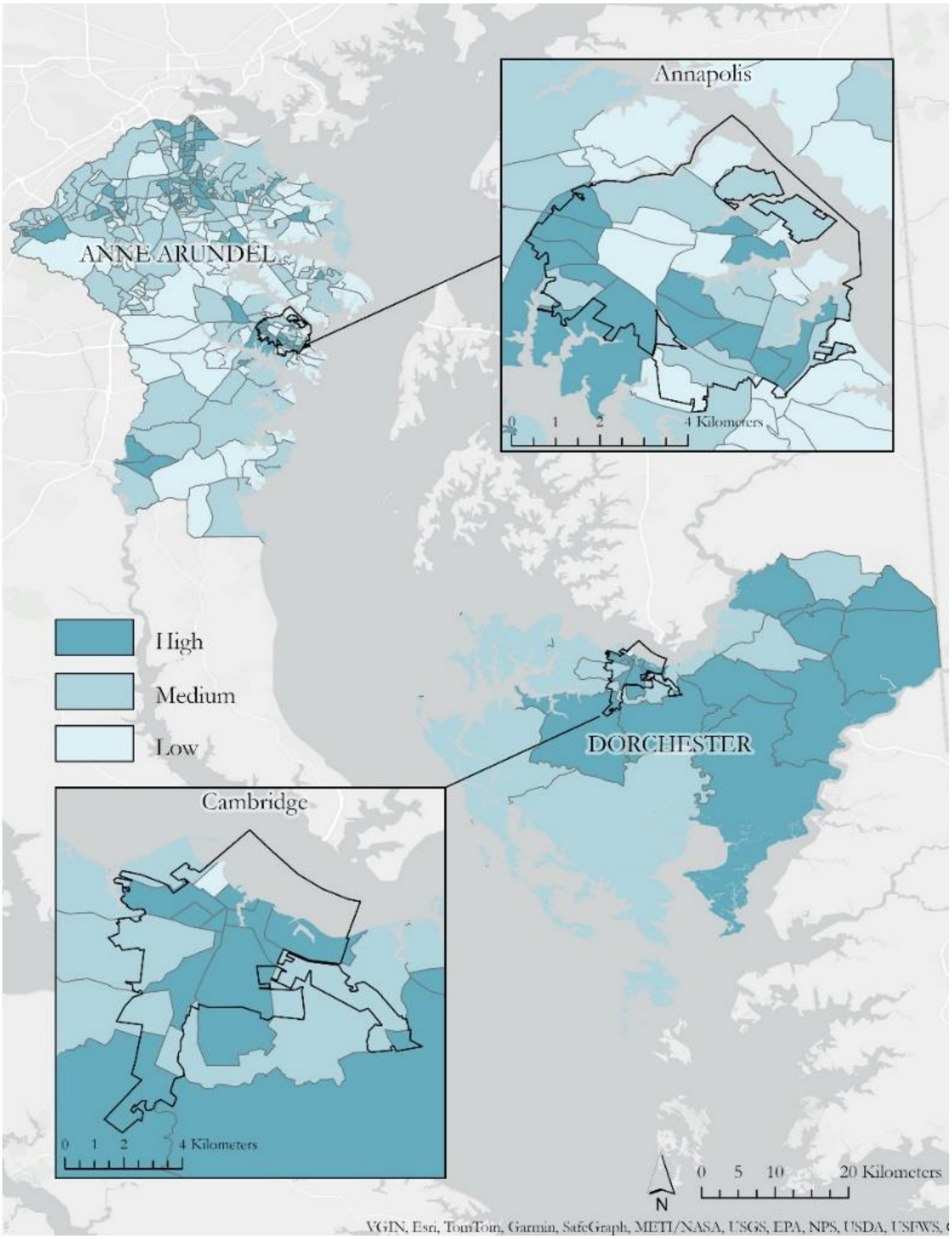

Figure A1. Social Vulnerability Map

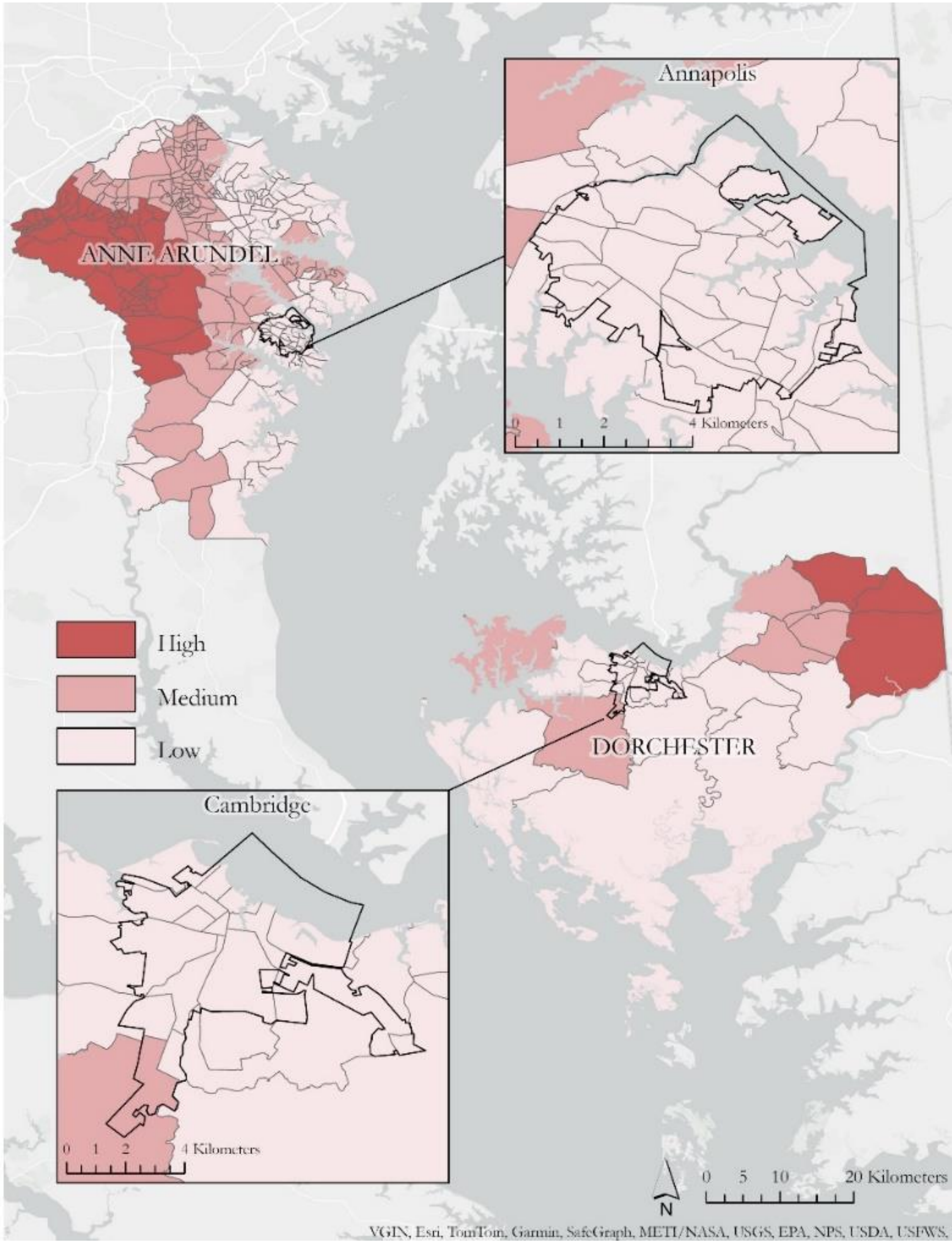

Figure A2. Distance to Recreational Swimming and Fishing Access Sites

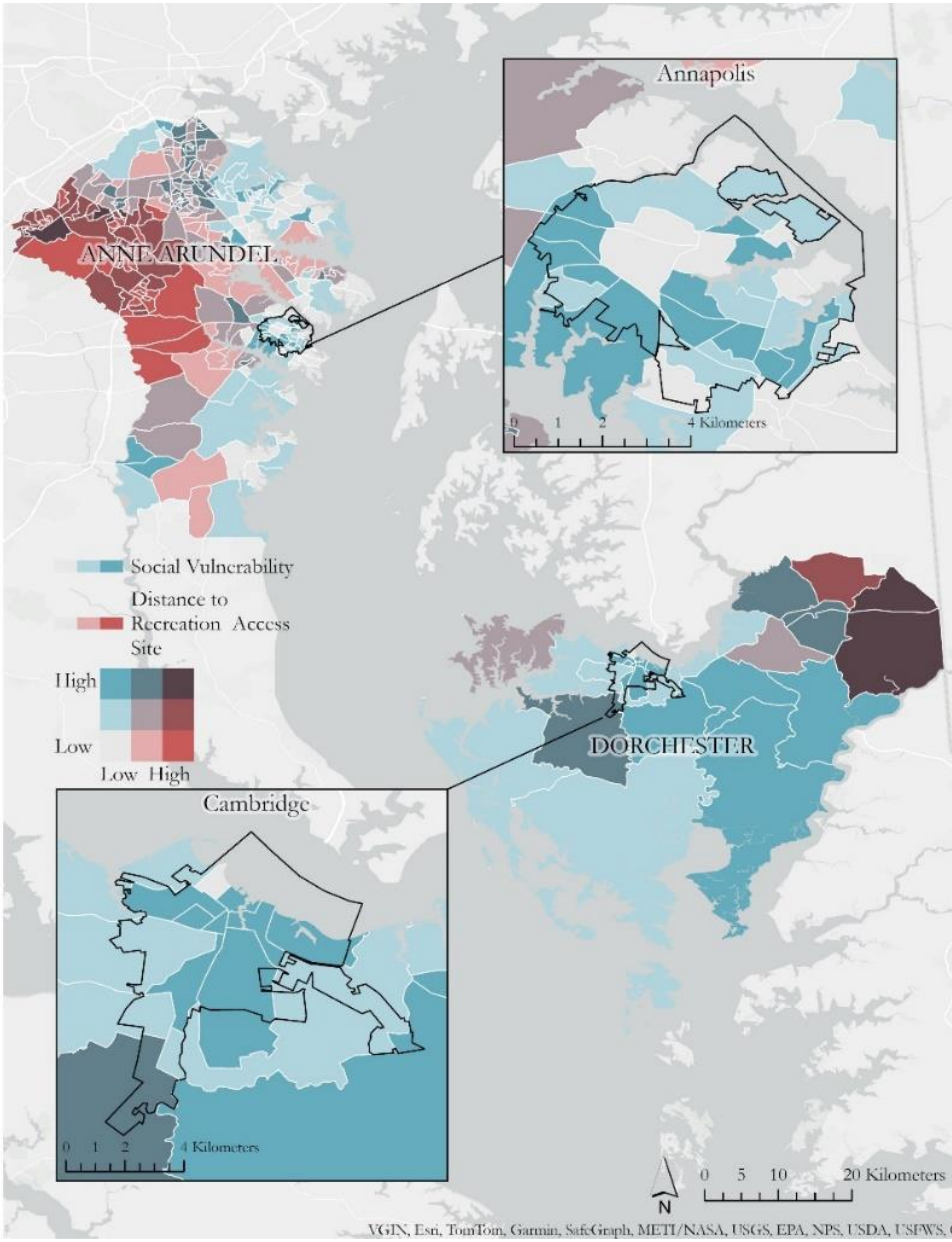

Figure A3. Bivariate SVI and Distance to Recreation Access Sites

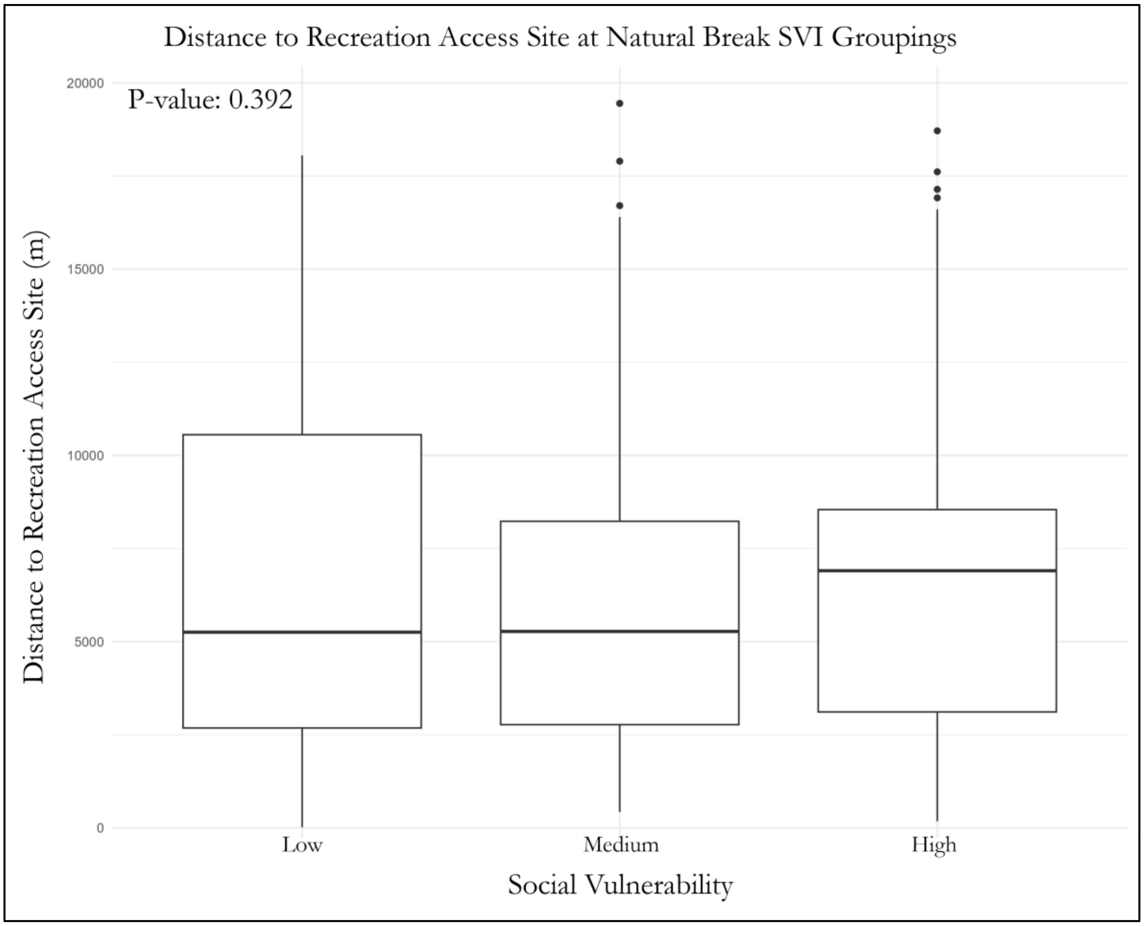

Figure A4. Boxplots showing SVI on the x-axis and distance to recreational access sites on the y-axis

Appendix B: *Water Quality Data*

Table B1

Satellite and In Situ Measurements of Chlorophyll-a (µg/L)

Year	**May-20**	**Jun-20**	**Jul-20**	**Aug-20**	**Sep-20**	**Oct-20**
In Situ Station		5.8	11.5	12.3	9.7	5.4
Sentinel-3	29.4	21.7	23.4	54.1	36.5	39.3
Aqua MODIS						
Year	**May-21**	**Jun-21**	**Jul-21**	**Aug-21**	**Sep-21**	**Oct-21**
In Situ Station	21.1	6.6	15.1	10.5	8.5	6.4
Sentinel-3	32.0	52.6	25.4	54.5	54.8	32.7
Aqua MODIS						
Year	**May-22**	**Jun-22**	**Jul-22**	**Aug-22**	**Sep-22**	**Oct-22**
In Situ Station	12.7	9.3	15.3	15.0	6.2	9.7
Sentinel-3	28.1	35.4	34.1	48.3	21.1	30.8
Aqua MODIS				47.9	25.1	27.7
Year	**May-23**	**Jun-23**	**Jul-23**	**Aug-23**	**Sep-23**	**Oct-23**
In Situ Station	4.2	5.9	8.1	10.7	6.9	8.5
Sentinel-3	33.1	19.2		12.2	27.2	35.2
Aqua MODIS			55.9	35.8	44.9	25.4
Year	**May-24**	**Jun-24**	**Jul-24**	**Aug-24**	**Sep-24**	**Oct-24**
In Situ Station						
Sentinel-3	9.4	17.9	35.5	19.6		
Aqua MODIS		27.1	26.8			

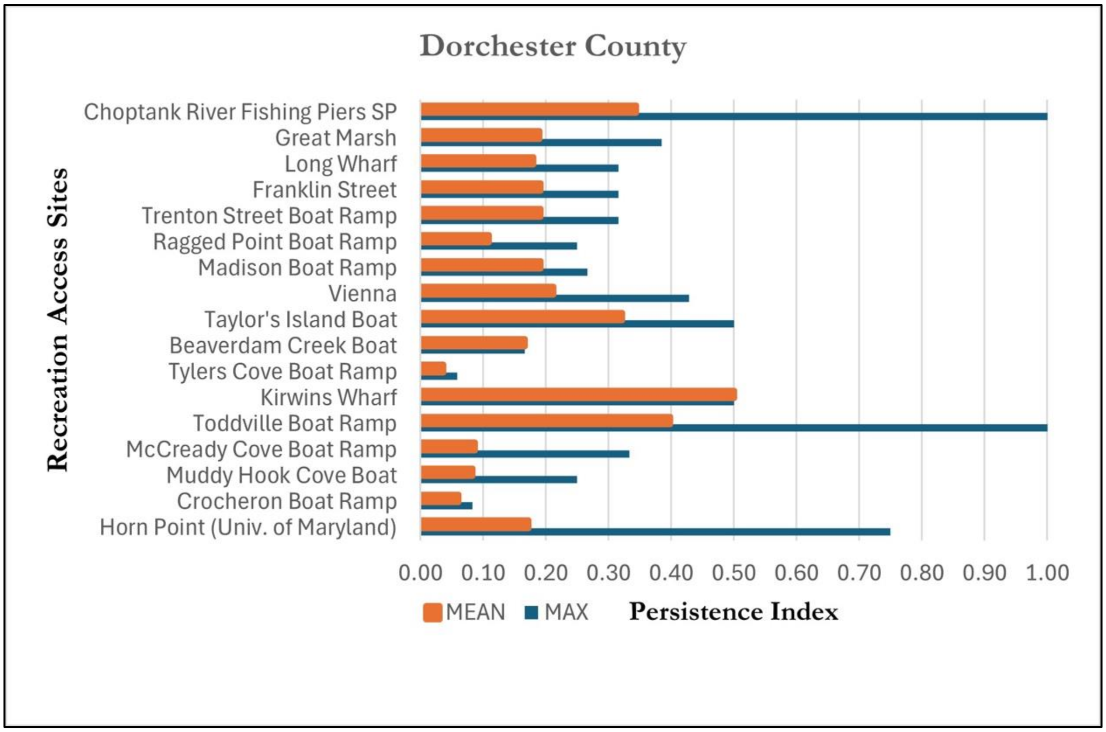

Figure B1. Mean and max persistence within the 900-meter buffer per access site in Dorchester County.

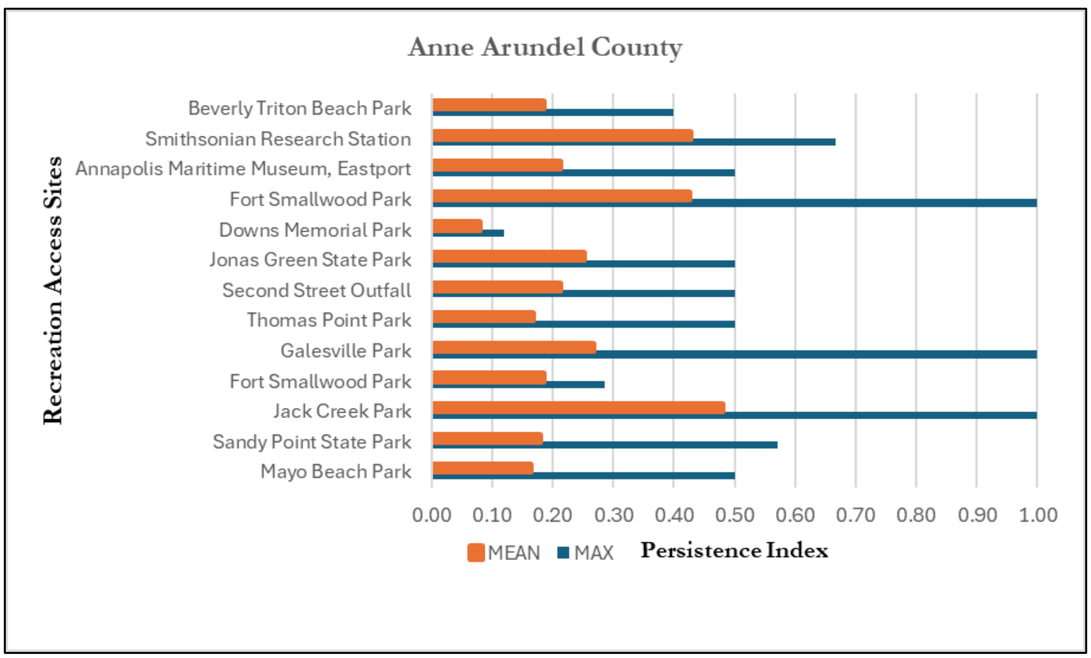

Figure B2. Mean and max persistence within the 900-meter buffer per access site in Anne Arundel County.