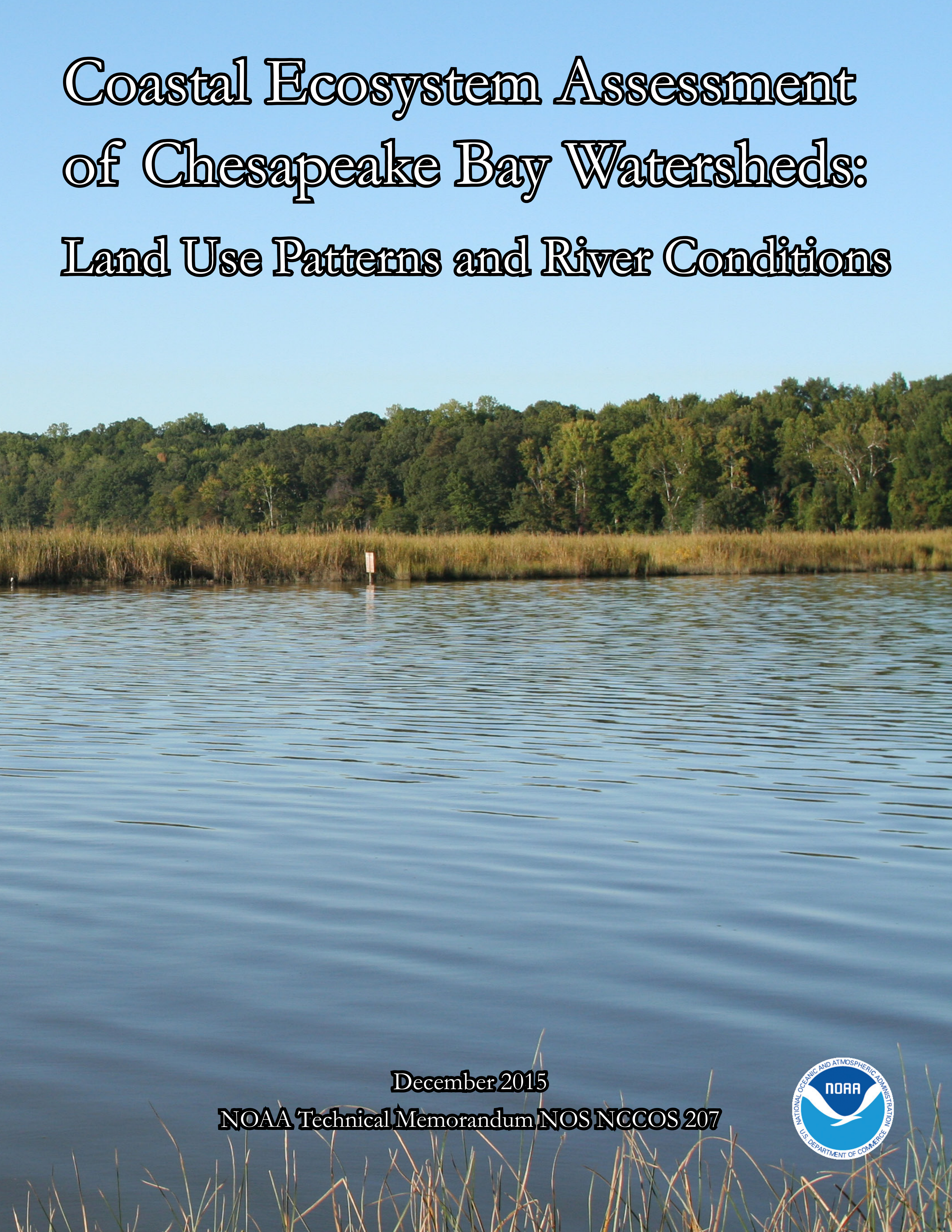
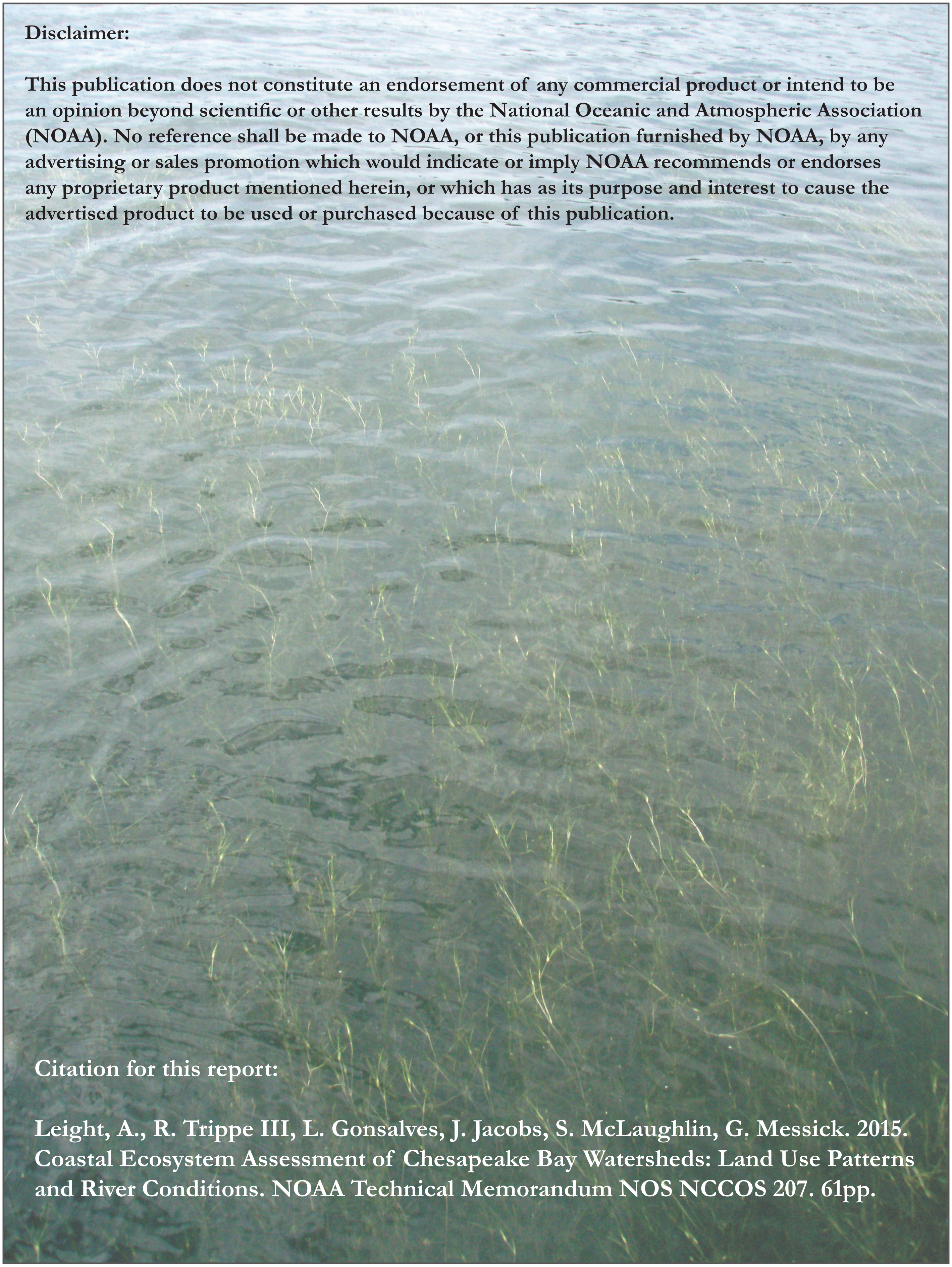
# Coastal Ecosystem Assessment of Chesapeake Bay Watersheds:

## Land Use Patterns and River Conditions



December 2015

NOAA Technical Memorandum NOS NCCOS 207



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**Citation for this report:**

**Leight, A., R. Trippe III, L. Gonsalves, J. Jacobs, S. McLaughlin, G. Messick. 2015. Coastal Ecosystem Assessment of Chesapeake Bay Watersheds: Land Use Patterns and River Conditions. NOAA Technical Memorandum NOS NCCOS 207. 61pp.**

# Coastal Ecosystem Assessment of Chesapeake Bay Watersheds: Land Use Patterns and River Conditions

Leight, A.[1], R.Trippe III[2], L. Gonsalves [1], J. Jacobs [1],
S. McLaughlin [1], G. Messick [1]

[1]NOAA, National Ocean Service
National Centers for Coastal Ocean Science

[2]JHT, Inc.

NOAA Technical Memorandum NOS NCCOS 207

December 2015

| United States Department of Commerce | National Oceanic and Atmospheric Administration | National Ocean Service |
|---|---|---|
| Penny Pritzker<br>Secretary | Kathryn Sullivan<br>Under Secretary and Administrator | Russell Callender<br>Acting Assistant Administrator |

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**Image TC1 (previous page):** Aerial view of the Sassafras River. Image courtesy of Jane Thomas, Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/).

**Image ES1 (above):** The two Chesapeake Bay, William Preston Lane, Jr. Memorial Bridge spans emerge from fog and low-hanging clouds. Image courtesy of Kendrick Brennan, Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/).

In coastal and estuarine regions, land use can have a profound impact on aquatic ecosystem health. In the Chesapeake Bay watershed, agriculture and urbanization have transformed major portions of the landscape, though some areas of undeveloped land remain. This document assesses the health of six Bay tributaries with different land use profiles via a suite of water quality and biological condition variables. Linkages are then explored between these scored variables and land use in the various watersheds.

This investigation began in 2007 with three mesohaline (moderate salinity) rivers in the upper Chesapeake Bay, each dominated by a unique land use pattern. The Corsica, Magothy, and Rhode Rivers were chosen to represent systems dominated by agricultural, residential, and mixed-use lands, respectively. Assessment of these three rivers continued annually through 2011. From 2010 to 2012, three additional oligohaline (low salinity) rivers were studied. These three--the Sassafras, Middle, and Nanjemoy Rivers--represented the effects of predominantly agricultural, urban, and forested lands, respectively.

The health of each riverine ecosystem was assessed using a suite of observations focused on water quality and aquatic organism health. Standard water quality metrics such as dissolved nutrient concentrations, water clarity, and indicator bacteria loads were measured. Organismal health measurements included metrics of blue crab health, fish abundance, dominant fish species, fish parasites, fish disease, and the abundance of submerged aquatic vegetation (SAV).

Analysis of these indicators and their relationship to land use revealed patterns which provide insight into the trade-offs between land development and aquatic ecosystem health. This information will assist managers when balancing the practical requirements of a growing human population against the integrity of the Chesapeake Bay ecosystem.

All rivers showed some signs of stress. For example, relative to established criteria or management goals, most rivers contained excess nutrients (primarily phosphorus), degraded water clarity and excessive chlorophyll *a* concentrations. Poor water clarity pervaded even the forested and mixed-use watersheds. Another common sign of degradation was low fish diversity in all but the Rhode River, with white perch predominant among the species caught.

Despite the general finding of stress for all rivers, the stressors present varied by river. Excessive nutrients and the related effects of poor water quality and reduced benthic vegetation were detected for the two rivers surrounded by agriculturally-dominated watersheds, the Corsica and Sassafras. Nitrogen levels were particularly high in these two rivers. The agricultural systems also supported relatively high numbers of fish, but the health of the fish, as measured by disease prevalence and parasite loads, was much worse in the Corsica and slightly worse in the Sassafras than that of fish from the other rivers. Crab health was mixed, with high prevalence of host response detected for the agricultural systems, but relatively low parasite incidence.

Although results for the two rivers surrounded by large amounts of forested land (the Nanjemoy and Rhode Rivers) showed some signs of stress, such as excessive nutrients and poor water clarity, there were signs of health as well. For example, the Nanjemoy River had the highest numbers of fish and the lowest incidence of fish disease. The Rhode River contained the most diverse fish populations.

In addition to land use, salinity regime also grouped rivers together for certain measurements. Crab parasites, fish abundance, fish health and submerged aquatic vegetation scores aligned particularly well among rivers of similar salinities.

Differences were detected between rivers related to land use that provide information to support decisions regarding the control of runoff from land into the Bay. Nutrients and suspended sediments were important stressors in the rivers examined, supporting current Bay-wide restoration efforts emphasizing reductions of these compounds. Preservation of habitat to support diverse and healthy fish populations, especially in spawning areas, was also supported. Our findings also suggest a need to develop better indicators to assess the impact of crab health on population sizes and the implications for managing harvest. Unexpectedly, stressors in the forested and mixed-use rivers indicated that conditions there were less pristine than predicted, and that these areas also require management to improve conditions.

**Image ES2:** Land uses in the Chesapeake Bay watershed include forest (left), agriculture (middle), and residential development (right)--all part of a dynamic and inter-related ecosystem.

*"There is but one entrance by sea into this country, and that is at the mouth of a very goodly bay…All along the shores rest plenty of pines and firs…Within is a country that may have the prerogative over the most pleasant places known…Heaven and earth never agreed better to frame a place for man's habitation."*

Captain John Smith wrote these inspired lines during his exploration of the Chesapeake Bay in 1608 [1]. The delicate balance of what was then a "most pleasant" pristine ecosystem is at risk today due to human development on a scale Smith likely never imagined. The waters of the Bay have become clouded, tree lines have been cut back, algae and bacteria have flourished, and many animal populations have dwindled.

## A Growing Problem

Currently, 17 million people live in the Chesapeake Bay watershed, and that number is expected to reach 20 million by the year 2030 [2]. Many residents rely on the Bay and surrounding rivers for their livelihood—fish and shellfish in the Bay have supported a vibrant maritime economy since the 19th century. In 2012, Maryland commercial and recreational fisheries, and the industries they support, accounted for over $1 billion to the state economy [3]. Others make their living off of the land, with 25% of the watershed being devoted to agricultural use today [4]. Furthermore, the entire residential population requires living quarters as well as modern utilities such as paved roads and sewage systems. Population growth and the corresponding increase in exploitation of natural resources present many challenges to the balance of the Bay ecosystem.

**Image I1 (Top):** Blackwater National Wildlife Refuge. Image courtesy of Jane Thomas, Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/).

**Image I2 (Above):** Dawn on Nanjemoy Creek.

## Four Classes of Contaminants

Human land uses, such as agriculture and urban or industrial development, can impact rivers and streams by releasing four broad classes of contaminants: nutrients, sediments, chemical and bacterial pollutants. For example, land selected for farming is cleared of trees, which increases runoff, resulting in greater amounts of sediments in the adjacent water body. Fertilizers used to enhance crop production are mixed with runoff, causing the enrichment of the water body with nutrients, mainly phosphorus and nitrogen. Additionally, pesticides applied to protect crops may be flushed into adjacent waterways, where they can be toxic to the organisms that live there, including commercially important species [5].

**Image I3:** A trash removal boat in the Baltimore Harbor. Image courtesy of Caroline Wicks, Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/).

Urban impervious surfaces such as roads and sidewalks increase runoff, bringing nutrients and sediments to the bay and its tributaries. Stormwater overflows and failing septic systems increase bacterial and nutrient loads in receiving waters. Industrial activities can magnify this problem by emptying chemical contaminants into those waterways [6]. Each of these contaminants can act as a stressor to fish, crabs, shellfish and their habitats, affecting their health and disrupting the natural balance of the system.

## Why Study the Chesapeake Bay?

Given the diversity of these contaminants and the various land uses that produce them, the Chesapeake Bay is an excellent case study of the relationship between land use and the health of the adjacent water body. The many tributaries of the Bay include urbanized, agriculturally dominated, mixed-use, and forested lands. It is therefore possible to compare widely varied land usage patterns within a single estuarine watershed. The Bay is also socially and economically valuable as a popular tourist destination, thriving economic center, and ever-expanding network of urban communities. Ecosystem services such as recreational and commercial fisheries, recreational boating, and ecotourism support vibrant economic sectors [3].

**Image I4:** A NOAA scientist measures a blue crab.

## The Study

NOAA scientists at the Cooperative Oxford Laboratory (COL), in collaboration with state and academic partners, monitored a suite of physical and biological variables in six Bay tributaries from 2007 to 2012. These tributaries featured urban, agricultural, forested and mixed-use watersheds, which were monitored for water quality and living resource health. Not all variables were measured in every river every year.

**Image I5:** Placid waters like these belie the complex dynamics of ecosystem health beneath the surface.

Sampling locations were selected using a stratified random design. The rivers were segmented into branches (the smaller creeks that feed the main river) and three sections along the mainstem (Figure I1 shows an example). Water quality measurements were collected in spring, summer, and fall (between April and October) from between 8-14 stations for each river. These water quality sampling locations were randomly chosen within each river segment using mapping software (ESRI, Inc.). Fish communities were sampled by both trawl and seine nets from each of the three main river segments on a monthly basis from May to October. Fish and crabs were collected in the fall (late September or early October) throughout the mainstem of each river for health assessments. The goal of this experiment was to integrate all of these measurements into an overall ecological assessment of the health of each tributary. Rivers with different predominant land use characteristics were expected to demonstrate different levels of ecosystem health.

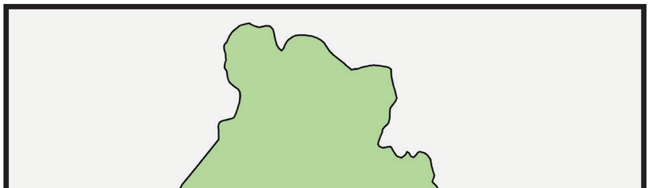



**Figure I1:** Example map of a river split into sampling segments.

## Results and Synthesis

The COL published a NOAA Technical Memorandum in 2014 entitled "Coastal Ecosystem Assessment of Chesapeake Bay Watersheds-A Story of Three Rivers" [7]. That document integrated the results of sampling from 2007-2009 in the Corsica, Magothy, and Rhode Rivers. This document expands on the previous publication by providing data from the same three rivers in 2010 and 2011, as well as from three additional rivers--the Middle, Nanjemoy, and Sassafras--from 2010 to 2012.

Results are presented for each of the variables as a summary graph of the measured values and a red-to-green color code for how these values compared to an index (see Results Template section). Wherever possible, the index used to evaluate condition was based on established criteria for the Chesapeake Bay or similar estuarine waters. For some variables, particularly those for crab and fish condition, no established criteria existed and the assessment of condition is presented as relative to the other data collected for this study.

## How to Use This Document

Each variable measured is described in a two or three page layout with standardized formatting. The Results Template section of the document describes the format used to assess and summarize each measured variable. Search the Table of Contents for variables of interest. Brief summaries of important trends for the variables are included at the end of each section. Finally, see the Synthesis section for conclusions from the assessment.

## The Road Ahead

The goals of this assessment are to characterize the conditions in the rivers studied, compare and contrast conditions across rivers, and to add evidence to the potential impacts of land use and human activities on estuarine health. The intent is to help guide community planners, local governments, industry, and other decision makers faced with increasing demands to make significant changes to the landscape. Additionally, several management implications of our findings are aimed at supporting the integrity of the Chesapeake Bay ecosystem. Finally, this ecological assessment of the United States' largest estuary is serving as a template for a similar assessment in the Choptank River as a component of the Choptank Habitat Focus Area, part of NOAA's Habitat Blueprint Program, and will help to refine similar approaches in other estuaries in the future.

**Image I7:** Birds perch on a pound net in the early morning on the Corsica River.

# Corsica River

**Image W1:** Aerial view of the Corsica River. Image courtesy of Jane Thomas, Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/).

## Overview

The Corsica River runs from headwaters near Centreville, Maryland and empties into the Chester River (Figure W1). Centreville, situated with easy access to bay shipping, became a market center not long after it was founded in 1782 [8]. Nevertheless, the area never became densely populated and remains a rural watershed, with a population density ranging from 100-1,000 people per square mile, according to the 2010 US Census [9].

The watershed is dominated by farmland, as can be seen in Image W1. As of 2003, over 60% of the river's estimated historical wetland area had been drained and filled to support expanded agricultural production [10].

## River Condition

The Corsica River has impaired conditions, due to high nutrient and sediment levels, according to the Maryland Department of Environment (MDE) [11]. Sampling stations along the river maintained by the Maryland Department of Natural Resources (MDDNR) indicate that water quality worsens upstream with respect to dissolved oxygen, chlorophyll *a*, and water clarity [12]. A wastewater treatment facility that once dumped directly into the river near Centreville has been redesigned to decrease nutrient and bacterial pollution and now applies all wastewater treatment plant discharge on land [10]. Nevertheless, stormwater, septic, and agricultural sources of pollution persist, and the river remains the focus of local conservation efforts. Ongoing nutrient pollution may be related in part to the slow leaching of nutrients from groundwater into the river.

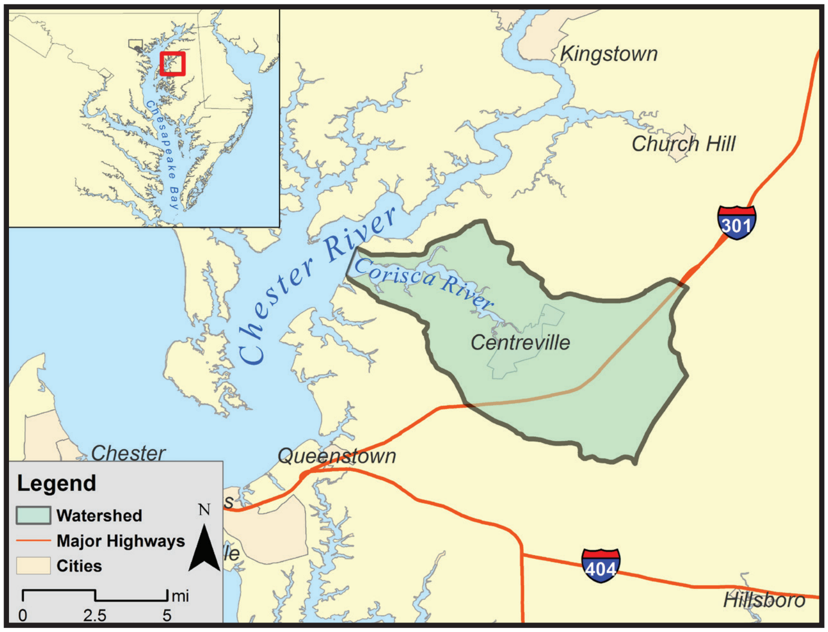



**Figure W1:** Map of the Corsica River.

## Study Justification

The Corsica River was selected for this study due to the high level of agricultural land use within its watershed. Furthermore, the similarity of its mesohaline salinity profile (generally between 5 and 18 parts salt per 1,000 parts water (ppt)) to those of the Magothy and Rhode helps limit variation among the rivers to the studied variables. Approximately 62% of the Corsica River watershed is agriculture, with a small pocket of development at the headwaters where the Town of Centreville is located [13].

# Magothy River

## Overview

**Image W2:** Aerial view of the Magothy River. Image courtesy of Ben Longstaff, Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/).

The Magothy River flows through a watershed dominated by densely-packed single family homes. The watershed is located on the western shore of Chesapeake Bay in Maryland, south of the Patapsco River and north of the Severn River in Anne Arundel County (Figure W2). Early in its history, the Magothy was coveted by its residents as a prime waterfowl hunting area [14]. However, its shores became increasingly developed, as the area offered residents a convenient location near the Bay and the economic centers of Annapolis, Washington, and Baltimore. Currently, there are over 9,000 residences with septic systems, the majority of these on the northern side of the river. Recreational boating is popular in the Magothy River, with over 30 marinas and 1,700 boat docks lining the mainstem and tributary creeks. Approximately 60% of the shoreline has been armored with rip-rap, groins, or bulk-heading. The Magothy is larger (5,600 acres) and deeper (with an average depth of about 3 m) than the other two mesohaline rivers [15].

## River Condition

The Magothy River has impaired conditions in its tributaries due to fecal bacterial pollution, with several large sewage spills having occurred there in recent history. For example, Mill Creek experienced over three million gallons of sewage and sediment spillage in December 2005 when a corroded sewer line ruptured [16]. The river is also listed with the EPA as being impaired for its level of contaminants in fish tissues, poor benthic community conditions, and excessive concentrations of sediment and nutrients in the water column [11].

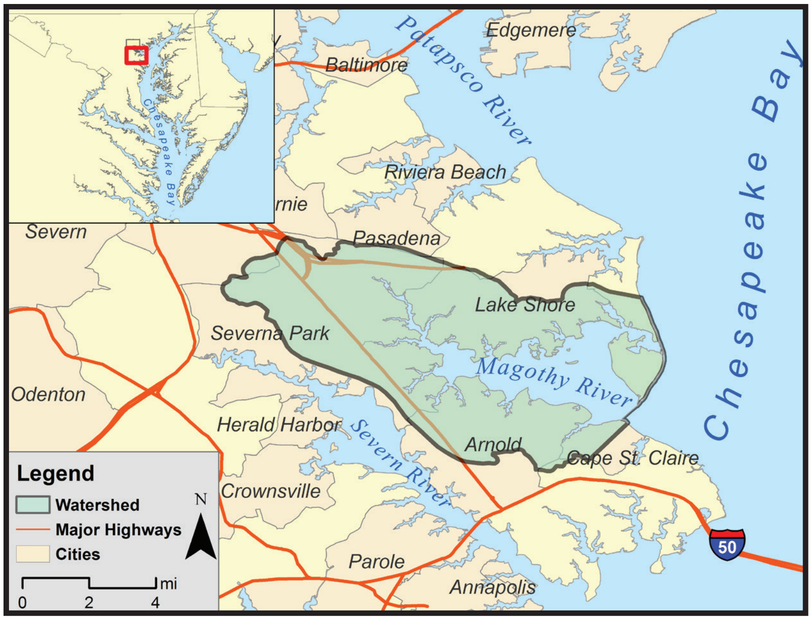



**Figure W2:** Map of the Magothy River.

## Study Justification

The Magothy River was chosen for this study due to its high level of development, extensive shoreline hardening, and numerous waste point sources. Additionally, it is similar in salinity range to the mesohaline Corsica and Rhode Rivers [17]. Approximately 55% of the Magothy River watershed is developed, with greater than 5% of the watershed classified as medium and high density development [13].

# Rhode River

**Image W3:** Trees line a bank of the Rhode River mainstem.

## Overview

The Rhode River is a tidal tributary stretching three miles through Anne Arundel County on the western shore of the Chesapeake Bay (Figure W3). The landscape of the Rhode River was once comprised of a diverse mix of forests and marshlands inhabited by a large population of beavers. The first people known to use this land, the Piscataway, hunted and fished the region for over 2,000 years. In colonial times, forested land was cleared for cash crops including tobacco, a nutrient-depleting crop that demanded the continuous clearing of large tracts of forest. In the 1800's, large farms and plantations were partitioned into smaller parcels to support more diverse crops. Wetlands were then ditched and drained to provide additional farmland. The long history of land use alterations in the Rhode River coupled with the removal of early beaver populations resulted in large amounts of sediment erosion from the upland areas and deposition in the stream valley, covering floodplains and burying historic wetlands [18].

## River Condition

Most of the Chesapeake Bay and its tidal waters are listed as being impaired and the Rhode River is no exception. The 2014 report card issued by West/Rhode Riverkeeper, Inc. reflects moderate to good scores in the Rhode River for dissolved oxygen and bacteria, a mid-level score for nutrients, poor scores for water clarity and chlorophyll *a*, and the complete absence of underwater grasses. Nearly 2,800 acres of undeveloped waterfront and near-waterfront lands on the Rhode River have been acquired by the Smithsonian Environmental Research Center since the 1960's with the goal of protecting it from future development [19].

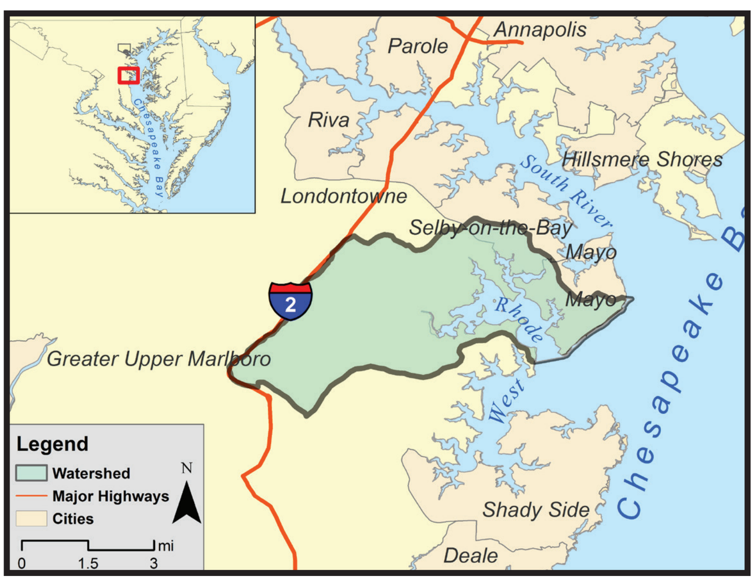



**Figure W3:** Map of the Rhode River.

## Study Justification

The Rhode River was selected for this study due to the predominance of forested land in its watershed. Furthermore, the similarity of its mesohaline salinity profile to those of the Corsica and Magothy helps limit variation among the rivers to the studied variables [17]. Approximately 51% of the Rhode River watershed is forested, with some medium and high density development along the northeastern extent of the watershed [13]. This balanced land use is reflected in the river's diverse shorelines, from tree-lined beaches to waterfront homes and marinas.

# Middle River

## Overview

The Middle River is a wide and shallow waterway which runs through a heavily developed portion of southeastern Baltimore County (Figure W4). Its watershed is mainly composed of housing developments as well as industrial and commercial centers. Early in the 20th Century, population in this area boomed, mainly due to the jobs created by large corporations such as the Glenn L. Martin Company, Eastern Rolling Mill, and Industrial Stainless Steel, Inc [20]. Currently some of the larger facilities in the area are related to aeronautic and marine industries. Despite these urbanizing forces, some pockets of forest persist throughout the watershed, and there are a few rural areas near the river's mouth [21].

**Image W4:** Aerial view of the Middle River, showing Martin State Airport. Photograph by A. Harrington, distributed under a Creative Commons BY-SA license.

## River Condition

The Middle River has impaired nutrient and sediment conditions, according to MDE [11]. In March of 2001, Versar, Inc. submitted a report to the Baltimore County Department of Environmental Protection and Resource Management, citing increased levels of sediment, nutrients and heavy metals in the Middle River due to the amount of urbanized land within the watershed. The report recommended management practices to reduce future pollution loads in the river [22]. This report was adopted by Baltimore County as the Middle River Watershed Management Plan, under the County's Watershed Management Program. Conflict has since arisen regarding the proposed development of untouched land within the watershed into residential properties [23].

## Study Justification

The Middle River was selected for this study due to the high level of development within its watershed. Furthermore, the similarity of its oligohaline salinity profile (generally below 5 ppt) to those of the Nanjemoy and Sassafras helps limit variation among the rivers to the studied variables [17]. Approximately 71% of the Middle River watershed is developed, with greater than 23% of the watershed classified as medium and high density development [13].


**Figure W4:** Map of the Middle River.

# Sassafras River

**Image W5:** Aerial view of the Sassafras River. Image courtesy of Jane Thomas, Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/).

## Overview

The Sassafras River is a 97-square-mile watershed that originates in Delaware and flows west into Maryland, forming the northern boundary of Kent County (Figure W5). The watershed is primarily devoted to agricultural land use, with pockets of urban development and marinas. It is sparsely populated, with three municipalities totaling under 1,500 people. The Sassafras is also home to several threatened or endangered species, including the Puritan Tiger Beetle and Eastern Tiger Salamander [24].

## River Condition

Several pressing ecological issues currently affect the Sassafras. The river does not meet Federal water quality criteria for nutrients, sediment, PCBs, and organismal health [11]. MDE found that phosphorus was the most elevated nutrient in the river, and calculated that the river could withstand no more than 13,875 pounds of additional phosphorus per year and remain relatively unimpaired [25]. The phosphorus load in the Sassafras is currently estimated at over 20,000 pounds per year [24]. Aggressive vegetation like the water chestnut and various species of algae have outcompeted native species, such as water lilies. Algal blooms, including harmful algal blooms (HABs), block light from entering the water, increase eutrophication (excessive nutrients) in the water body when they decompose, and can even be harmful to humans [24]. Farms, lawns, leaking septic systems and other non point-sources of runoff have eroded the banks of the river into their characteristic cliffs of exposed clay, contributing to the eutrophication of the river. A major defined source of pollution is the Conowingo Dam. When this dam on the Susquehanna River is opened, outflow is caught in the mouth of the Sassafras and moves upriver for days, carrying litter and its attendant pollutants, including sediments [24].


**Figure W5:** Map of the Sassafras River.

## Study Justification

The Sassafras River was included in this study because of its similar salinity to the oligohaline Nanjemoy and Middle Rivers [17]. Furthermore, the river is an excellent example of an agriculturally dominated watershed. Approximately 66% of the watershed is devoted to agricultural use. Another 17% is forested, while the remaining fifth is a mixture of wetland and developed land [13].

# Nanjemoy Creek

## Overview

The Nanjemoy Creek is a mostly forested watershed [26] 13.1 miles in length [27] which empties into the Potomac River about 25 miles south of Washington DC (Figure W6). Narrow, long tributary creeks wind through the hilly watershed and end in a relatively wide and shallow creek mouth. Of the watersheds' nearly 50,000 acres, roughly 150 landowners account for over 75% (about 25,000 acres) of the unprotected land [26]. The Nature Conservancy works to preserve the remaining area, which is mostly forested, with the initial goal of maintaining a breeding ground for great blue herons, but now with the goal of sheltering a fully functional forest ecosystem [26]. The watershed is also home to the Nanjemoy Creek Environmental Education Center, which focuses on teaching local students about environmental science [28].

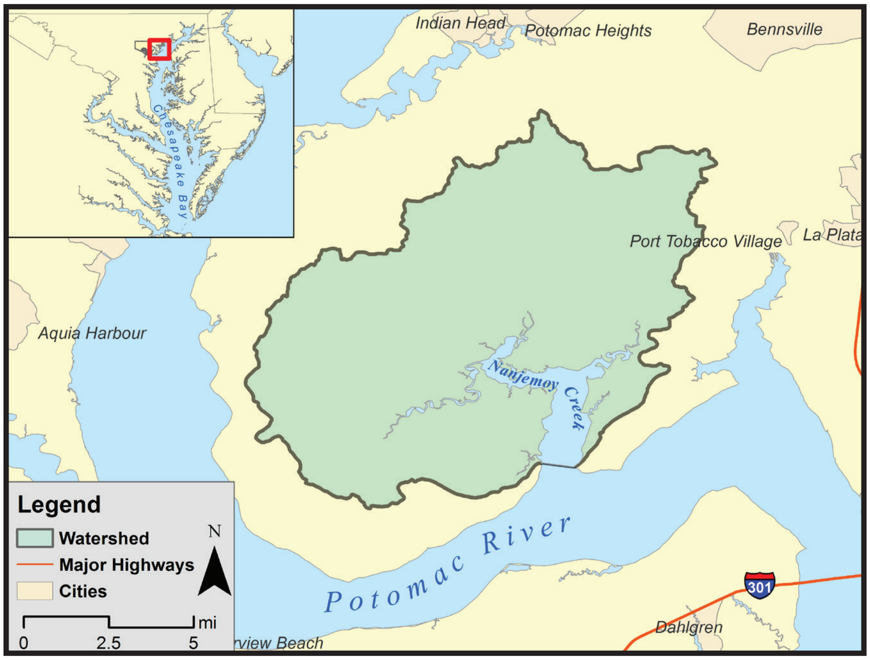



**Figure W6:** Map of Nanjemoy Creek.

## River Condition

According to a 2013 document prepared by the Chesapeake Bay Foundation, only 2% of the Nanjemoy watershed has been converted to impervious surfaces. The document cites this as a major reason for the Creek's good water quality and low polluted runoff loads [29]. Nevertheless, MDE has listed the Nanjemoy waterway as impaired due to such pollutants as nutrients and suspended sediments [11].

**Image W6:** Sunrise on the Nanjemoy.

## Study Justification

The Nanjemoy was included in the current study due to the low level of development, predominance of forested lands, and emphasis on preservation in the watershed. In addition, its salinity profile is closely matched to those of the oligohaline Middle and Sassafras Rivers [17].

# A Comparison of the Rivers Studied

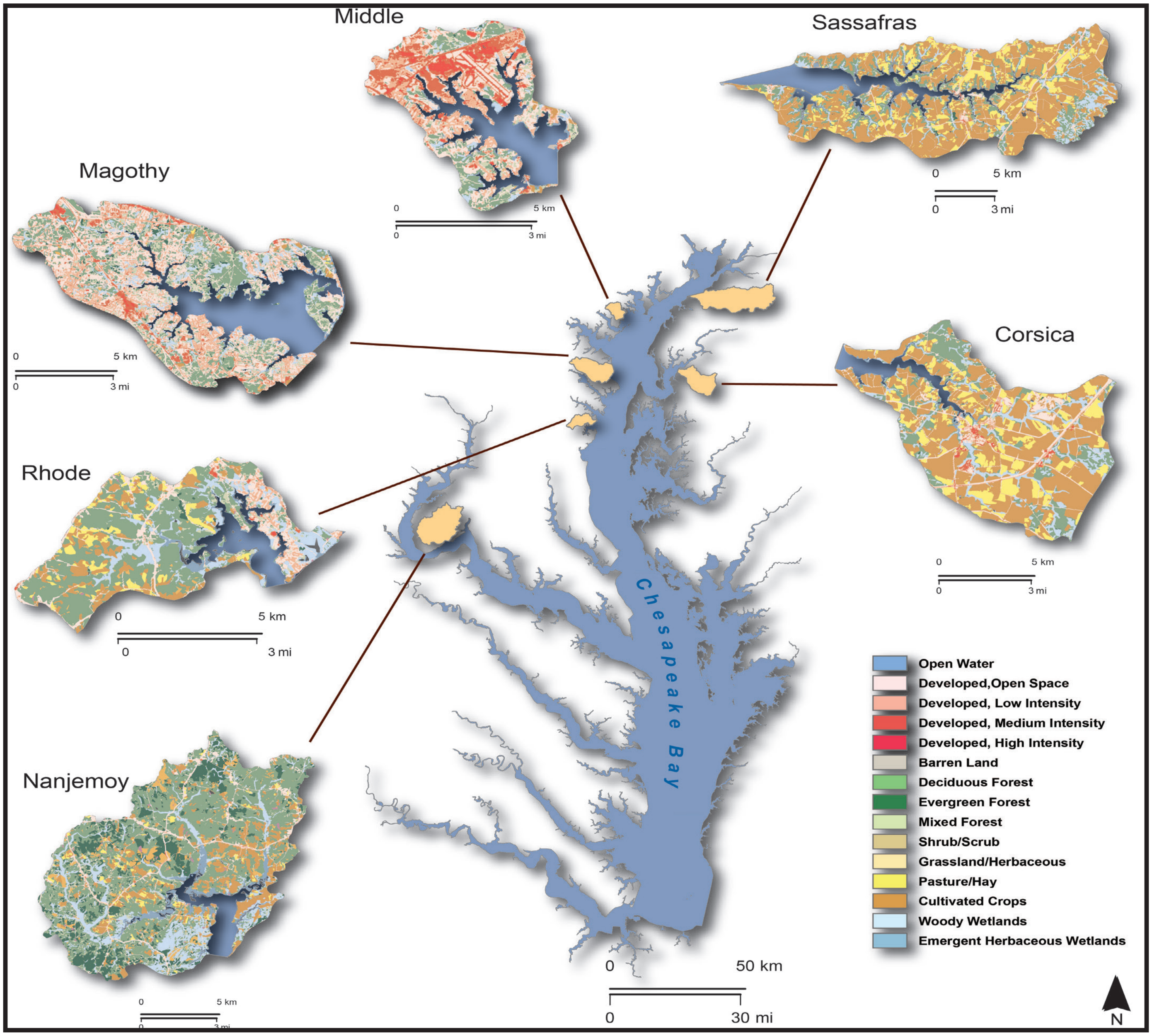



**Figure W7**. The six watersheds, color coded by land cover types, by location in the Chesapeake Bay. The main variables used in selecting the watersheds for this study were land cover classifications and salinity regime. Scale bars are included with each watershed projection in order to judge relative size. The largest watershed was that of the low salinity Sassafras which, along with the brackish water Corsica River watershed, consists primarily of agricultural lands and is located on the Eastern Shore (i.e. east of the Chesapeake Bay). The Middle and Magothy Rivers, study sites which were chosen due to their high levels of commercial and residential development, reside along the heavily developed Washington and Baltimore corridor. The smallest watershed was the Rhode. Along with the Nanjemoy watershed, it is located in the more rural and undeveloped lands on the Western Shore in southern Maryland [13].

| Watershed Facts | | | | | | |
|---|---|---|---|---|---|---|
| **River** | **Corsica** | **Sassafras** | **Magothy** | **Middle** | **Rhode** | **Nanjemoy** |
| Primary Land Use | Agricultural | | Urban | | Forested/Mixed Use | |
| Average Depth (m) | 1.978 | 2.81 | 2.90 | 1.57 | 1.59 | 0.97 |
| 303d Impairments* | PCB<br>FC<br>TSS<br>N<br>P | PCB<br>FC<br>TSS<br>N<br>P | BIBI<br>PCB<br>FC<br>TSS<br>N<br>P | PCB<br>TSS<br>N<br>P | FC<br>N<br>P | BIBI<br>TSS<br>N<br>P |
| Hardened Shoreline (%) | 15 | 9 | 60 | 51 | 25 | 4 |
| Watershed Area Except River (acres) | 23,900 | 53,700 | 20,900 | 6,100 | 8,700 | 46,700 |
| River Area (acres) | 1,400 | 8,300 | 5,600 | 2,400 | 1,200 | 2,700 |
| River:Watershed Ratio | 1:17 | 1:6 | 1:4 | 1:3 | 1:7 | 1:17 |

**Table W1:** This table provides details and comparisons of the six rivers examined in this study with regards to known impairments [11], differences in shoreline habitats, average depths, river areas, and watershed areas [15]. All six rivers contain excessive nutrients, as assessed by the MDDNR and the MDE [11].

*BIBI = Benthic Index of Biotic Integrity; PCB = Polychlorinated Biphenyls; FC = Fecal Coliforms; TSS = Total Suspended Solids; N = Nitrogen; P = Phosphorus.

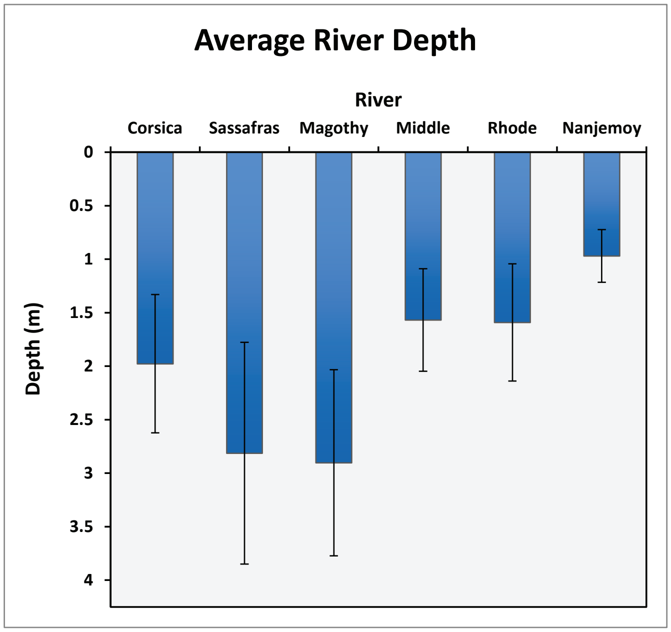



**Figure W8:** This graph shows the average depth of the rivers studied. The error bars represent 95% confidence limits.

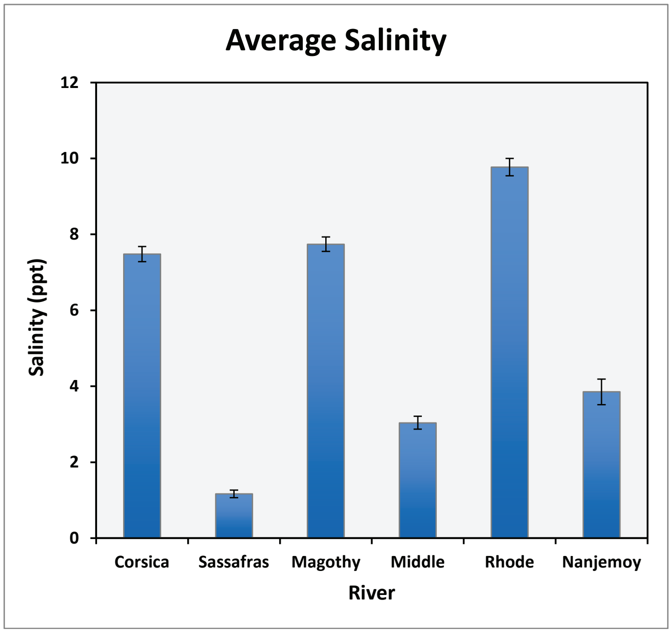



**Figure W9:** This graph shows the average salinity of the rivers studied. The error bars represent 95% confidence limits.

# A Climatological Note

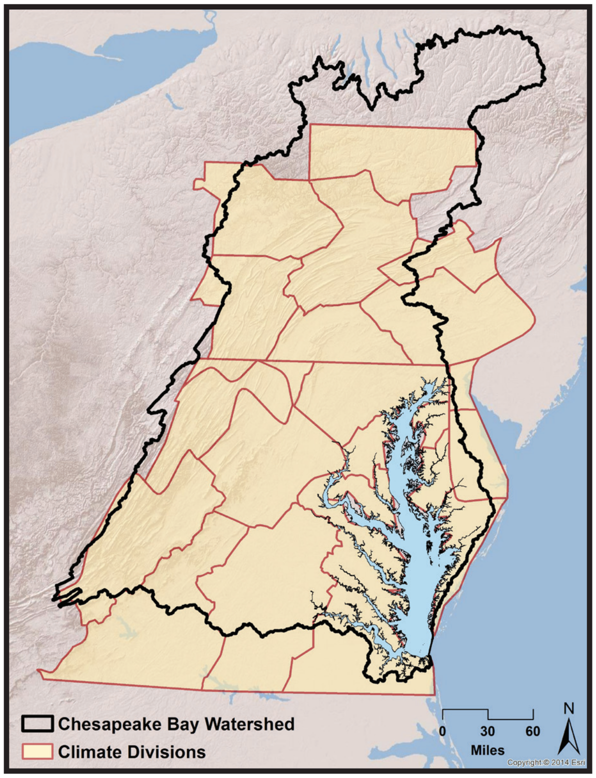


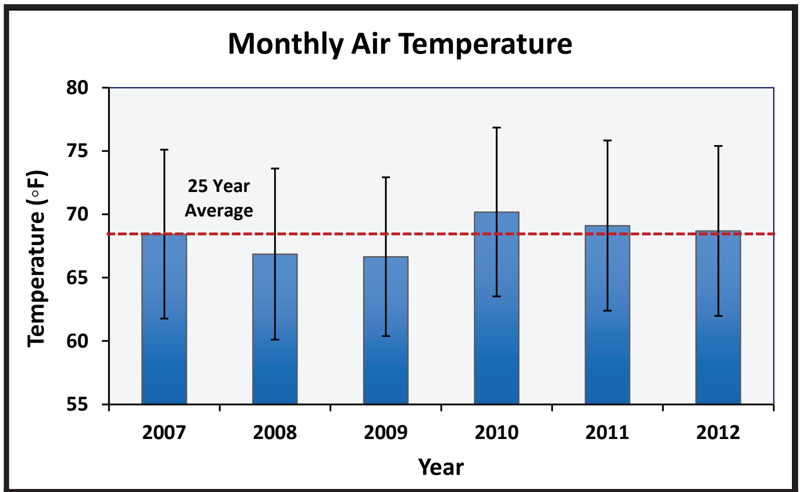

**Figure W10:** This map shows the climate divisions surrounding the Chesapeake Bay used for climate data in this study.

Climate data was collected from the National Climatic Data Center [35] using Climate Division information from the Chesapeake Bay region (Figure W10). This data is quality assured and presented by geographic area as monthly averages (air temperature) or totals (precipitation).

For the years of this study, precipitation ranged from a fairly dry year in 2007 to an unusually wet year in 2011 (Figure W11). The extreme precipitation events in 2011, reflected in the large error bars that year, occurred in August and was related to Hurricane Irene.

Average annual temperatures also showed some interannual varibility, though not with a consistent trend over the six years and not with the same pattern as precipitation.

Climate can have a distinct impact on conditions in coastal waters. Changes in air temperature and precipitation have been linked to changes in nutrient levels [30], dissolved oxygen levels in bottom waters [31], zooplankton populations [32], fish populations [33], and fecal bacteria in surface waters [34]. Some of these relationships, such as with striped bass population size, consist of multi-decadal cycles, which are much longer than the scope of the six watersheds study. Other components of the estuarine ecosystem, such as nutrient loads and water clarity, are influenced by annual climate variability and within-year timing of precipitation and air temperature changes. In order to provide contextual climate information for the six watersheds study, air temperature and precipitation values in the Chesapeake Bay are presented (Figure W11).



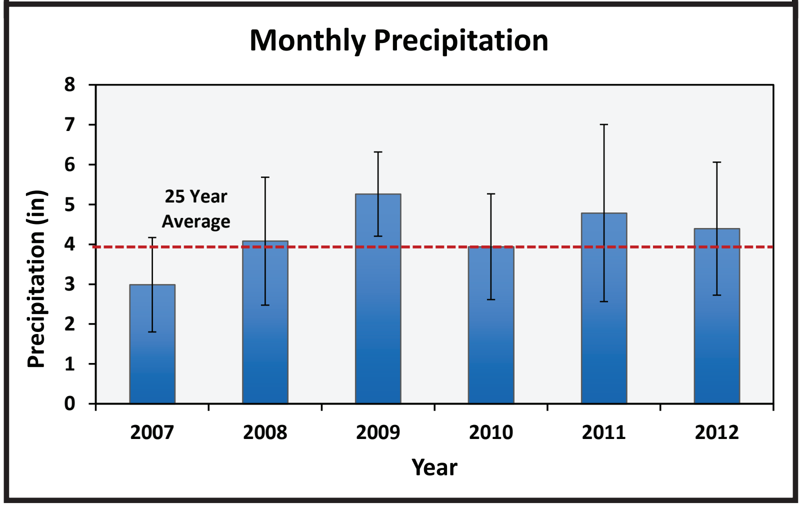




**Figure W11:** These graphs show average monthly temperature (top) and precipitation (bottom) for the six years of this study. Error bars represent 95% confidence limits.

**This section describes the presentation of results throughout the document and how to read the figures that will be displayed for each of the variables investigated for this assessment.**

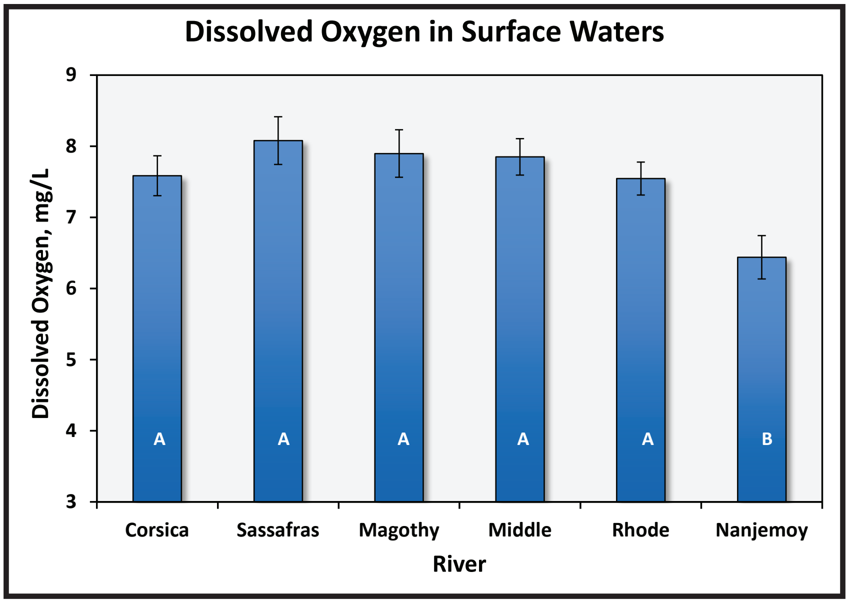



**Figure RT1:** Bar charts of this type compare assessment variables between rivers, in their original units. If two bars do not share any of the same white letters, then they are significantly different. The error bars display 95% confidence limits, which provide a relative estimate of differences between average conditions for the six rivers, but not an absolute measure of significance. An Analysis of Variance (ANOVA) test was performed for each variable, often after transforming the data, in order to assess differences between rivers.

| **Dissolved Oxygen Criteria** | | |
|---|---|---|
| Habitat | Criteria (mg/L) | Time of Year |
| Open Water | ≥5.0 | Year-Round |
| Deep Water | ≥3.0<br>≥5.0 | Jun. 1 - Sep. 30<br>Oct. 1 - May 31 |
| Deep Channel | ≥3.0<br>≥5.0 | Jun. 1 - Sep. 30<br>Oct. 1 - May 31 |

**Figure RT2:** Tables like the one above explain how measured values were translated into scores for the variable assessed. In this example, dissolved oxygen criteria are differentiated by river habitat and time of year. All measurements meeting or exceeding these criteria were scored a 5, while measurements below were scored a 1. The scoring methodology and relevant literature references are further described in the text accompanying each variable.

| Score Equivalence for Total Nitrogen | | | |
|---|---|---|---|
| Score | 1 | 3 | 5 |
| Criteria (uM) | ≥92 | ≥46 and <92 | <46 |

**Figure RT3:** In a variation of the table in Figure RT2, the table above shows how nitrogen was scored. The score calculations were not broken down by any sub-criteria here; rather, the scoring criteria was the same for all measurements. Measurements in each category were thus assigned the corresponding score.

| River | Abbr | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|
| Corsica | C | | | | | | |
| Sassafras | S | | | | | | |
| Magothy | Ma | | | | | | |
| Middle | Mi | | | | | | |
| Rhode | R | | | | | | |
| Nanjemoy | N | | | | | | |

**Figure RT4:** The table above is a heat map representing the scores for each river by year. The colors are chosen from the color bar in Figure RT5, based on the corresponding score.

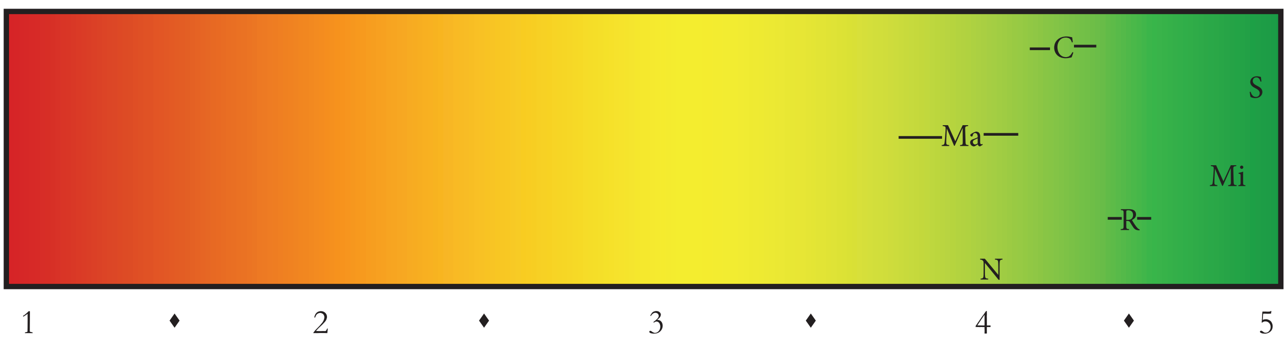



**Figure RT5:** The spectrum above represents the variable score (from 1 as poor condition to 5 as good condition). The initials of each river are overlaid on the spectrum representing the average score over all years. The error bars represent one standard deviation from the mean. If the standard deviation is very small no bars appear.

## Findings

- Bullet points here summarize the results shown in bar charts, heat map and red-to-green scoring spectrum.

**Image WQ1:** Boats on the Chesapeake Bay. Image courtesy of Jane Hawkey, Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/).

The term 'water quality' generally refers to the set of physical, chemical, and biological conditions of a water body that affect its ability to support particular uses [36]. Often, water quality is assessed with respect to human needs, such as drinking water and recreational activities like swimming. In this study, we assessed the condition of the water in six rivers relative to established criteria and to published goals that represent conditions necessary to support healthy communities of organisms. Focusing on a few factors, including concentrations of dissolved oxygen, nitrogen, phosphorus, chlorophyll *a*, fecal indicator bacteria, and measurements of water clarity, this assessment sought to provide an accurate indicator of water quality in the six rivers that were investigated.

In addition to the variables listed above, water temperature and salinity were measured every half meter in depth at each sampling station. These two variables may be informative on their own, are necessary for calculating several of the indicators, such as dissolved oxygen conditions, and add contextual information for comparison of the rivers. Average salinity conditions were presented in the Watersheds section (Figure W9). Water temperatures did not differ substantially among the rivers, averaging between 23 and 25 °C.

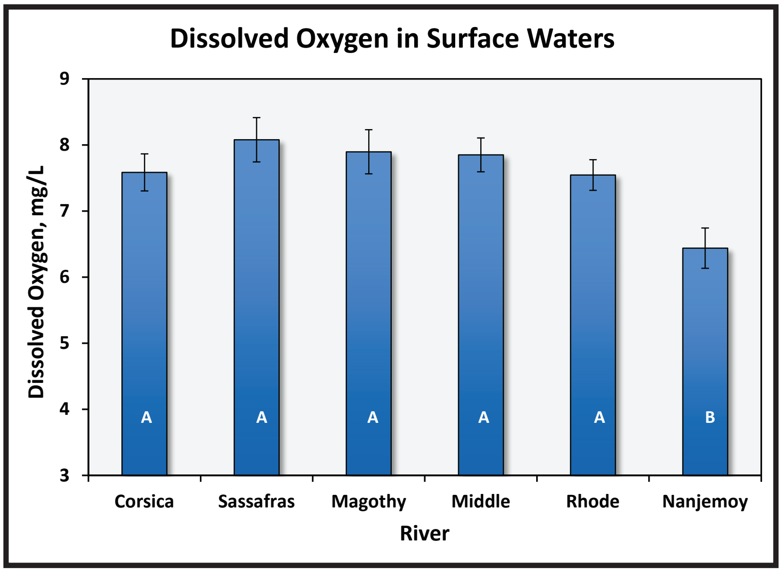
Many factors influence water quality, from hurricanes to wastewater effluent. General trends in water quality may also be associated with land use practices, such as eutrophication (i.e. excess nutrients) in agricultural areas and decreased water clarity in areas of sediment runoff [37-39]. One goal of this study was to look for trends in these water quality parameters in relation to the various potential drivers in each river.

# Dissolved Oxygen

## Background

In natural water bodies, oxygen is diffused from the overlying atmosphere and mixed into the water column by wind and waves. Oxygen is also produced by plants and some bacteria and is a requirement of most aquatic organisms. Therefore, dissolved oxygen levels play perhaps the most significant role in determining what species can survive in a given body of water [40].

Dissolved oxygen may become depleted in bottom waters when the water column exhibits stratification (strong horizontal layering), excess nutrients, or both [40]. In large estuaries such as the Chesapeake Bay, stratification of the water column occurs in the mainstem and lower portions of some tributaries in late spring through late summer as water temperatures increase and storm frequencies decrease. Most water quality assessments, including the USGS National Water Quality Assessment Program [41] and Chesapeake Bay Report Card [42], account for seasonal variation in dissolved oxygen concentrations.



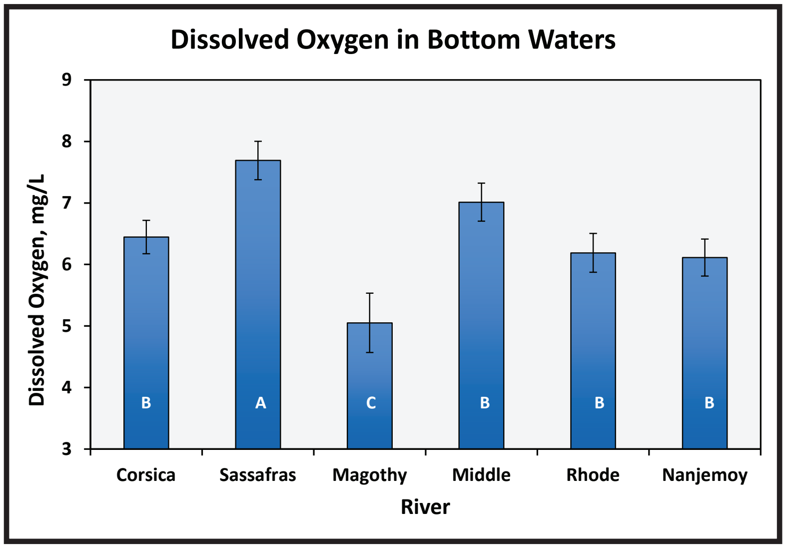




**Figure WQ1:** Average dissolved oxygen concentrations in surface (top) and bottom (bottom) waters for each river studied.

## Methods

Average dissolved oxygen levels (mg/L), for both surface and bottom waters, are shown in Figure WQ1. The US EPA has suggested levels of dissolved oxygen sufficient to support aquatic life in each sub-habitat, for each season, within the Chesapeake Bay [43]. These sub-habitats and their associated seasonal dissolved oxygen criteria are presented in Figure WQ2.

For this assessment, dissolved oxygen levels were measured at 0.5 meter depth increments at each station. Levels were measured as concentrations in milligrams of oxygen per liter of water (mg/L). Stratified waters, if present, were calculated as described by the Chesapeake Bay Program [44], and the appropriate EPA dissolved oxygen criteria were applied to evaluate condition.

If a measurement exceeded the criteria it was scored as a 5; if not, it was scored as a 1. Scores at the stations were averaged for each river by year (Figure WQ3) and then averaged for each river for all years sampled (Figure WQ4). Data were analyzed with respect to river, year, and depth.

| Dissolved Oxygen Criteria | | |
|---|---|---|
| Habitat | Criteria (mg/L) | Time of Year |
| Open Water | ≥5.0 | Year-Round |
| Deep Water | ≥3.0<br>≥5.0 | Jun. 1 - Sep. 30<br>Oct. 1 - May 31 |
| Deep Channel | ≥3.0<br>≥5.0 | Jun. 1 - Sep. 30<br>Oct. 1 - May 31 |

**Figure WQ2:** Threshold criteria for dissolved oxygen by estuarine sub-habitat and time of year.

## Results

| River | Abbr | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|
| Corsica | C | | | | | | |
| Sassafras | S | | | | | | |
| Magothy | Ma | | | | | | |
| Middle | Mi | | | | | | |
| Rhode | R | | | | | | |
| Nanjemoy | N | | | | | | |

**Figure WQ3:** Heat map of dissolved oxygen scores by river and year.

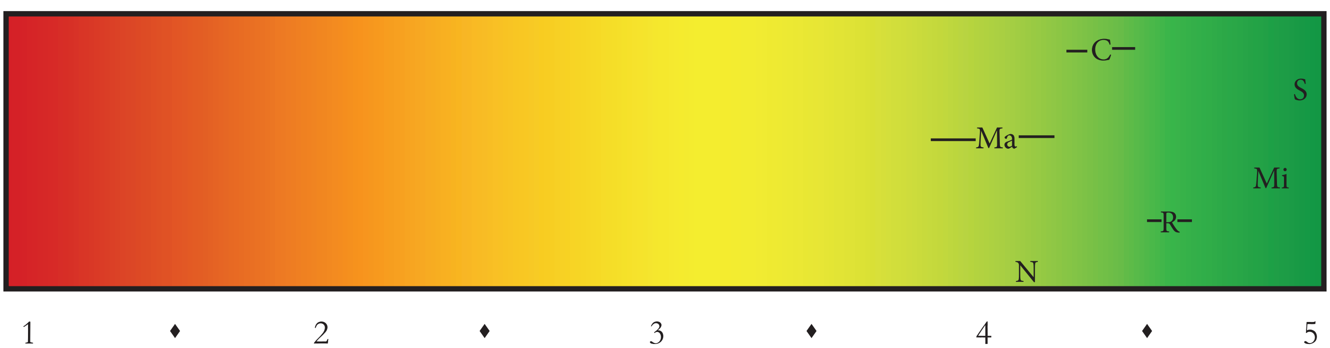



**Figure WQ4:** Overall dissolved oxygen scores for each river. Error bars represent one standard deviation from the mean of all annual scores.

### Dissolved Oxygen Findings

- Dissolved oxygen was generally sufficient to support natural resources in all six rivers, which is in agreement with the Chesapeake Bay Report Card [42].
- The Magothy and Nanjemoy had lower dissolved oxygen measurements than the other rivers, though their scores were still acceptable.
- Dissolved oxygen concentrations in bottom waters of the Magothy were lower than all other rivers and insufficient to support benthic organisms at times.
- Interannual variability and trends were minimal.

# Nitrogen

## Background

Nitrogen is an essential nutrient for all organisms. It enters aquatic systems primarily through atmospheric deposition, stormwater runoff and groundwater flows. However, if nitrogen concentrations become excessive (and sufficient amounts of phosphorus are also present, a process called eutrophication), estuarine plants and bacteria grow at stimulated rates, which can lead to overproduction. For example, in the Chesapeake Bay, high nitrogen concentrations often cause phytoplankton blooms in surface waters during spring and summer [45,46].

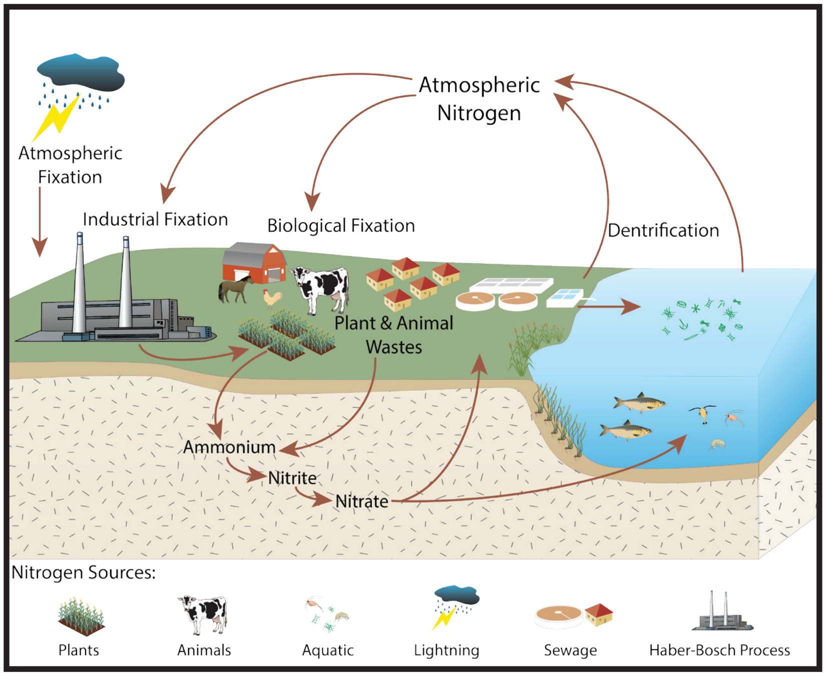



**Image WQ2:** This graphic demonstrates nitrogen cycling through a riverine ecosystem and the associated watershed. Image courtesy of Catherine Ward, Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/).

Overproduction causes problems for an estuarine ecosystem. When phytoplankton blooms die, they sink to the bottom and are consumed by bacteria. These bacteria use up dissolved oxygen, leading to low oxygen concentrations in bottom waters. These conditions are exacerbated by stratification of waters that often occur in areas of the Bay during hot summer months. In this way, concentration of nutrients such as nitrogen in the water are important indicators of water quality and habitat condition [46].

## Methods

Water samples for nitrogen analysis were collected just below the surface using acid-washed 500 mL plastic bottles. In order to compare nitrogen concentration in the samples with established water quality criteria [47], inorganic and organic nitrogen compounds, in both dissolved and particulate forms, were measured using analytical instruments [48] and combined to establish a total nitrogen concentration. Average concentrations are shown in Figure WQ5. Total nitrogen values were then compared to an established threshold (46 µM) for the health of seagrass beds [47], and a value double that level (92 µM) reflective of extreme concentrations (Figure WQ6).

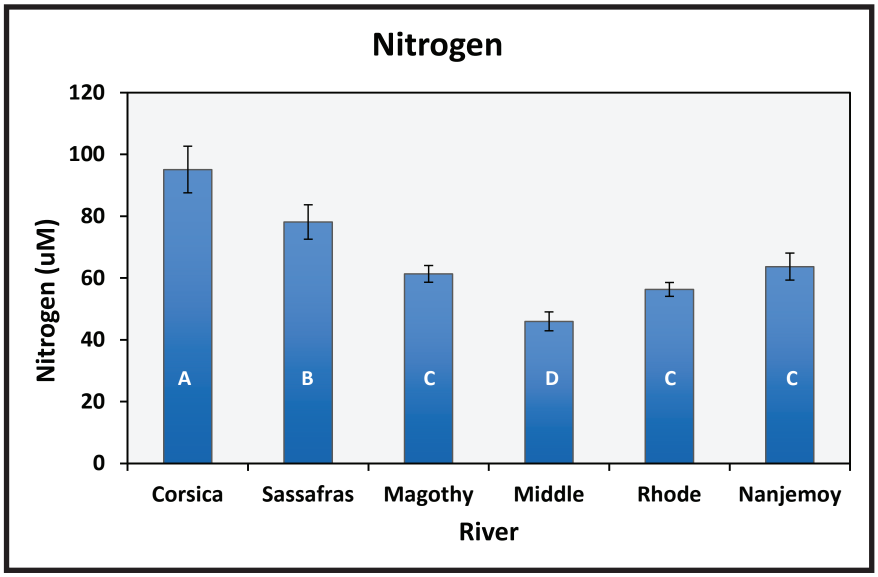



**Figure WQ5:** Average nitrogen concentrations for each of the studied rivers.

| Score Criteria for Total Nitrogen | | | |
|---|---|---|---|
| Score | 1 | 3 | 5 |
| Criteria (µM) | ≥92 | ≥46 and <92 | <46 |

**Figure WQ6:** This table classifies the threshold levels of nitrogen for each score.

## Results

| River | Abbr | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|
| Corsica | C | | | | | | |
| Sassafras | S | | | | | | |
| Magothy | Ma | | | | | | |
| Middle | Mi | | | | | | |
| Rhode | R | | | | | | |
| Nanjemoy | N | | | | | | |

**Figure WQ7:** Heat map of nitrogen scores by river and year.

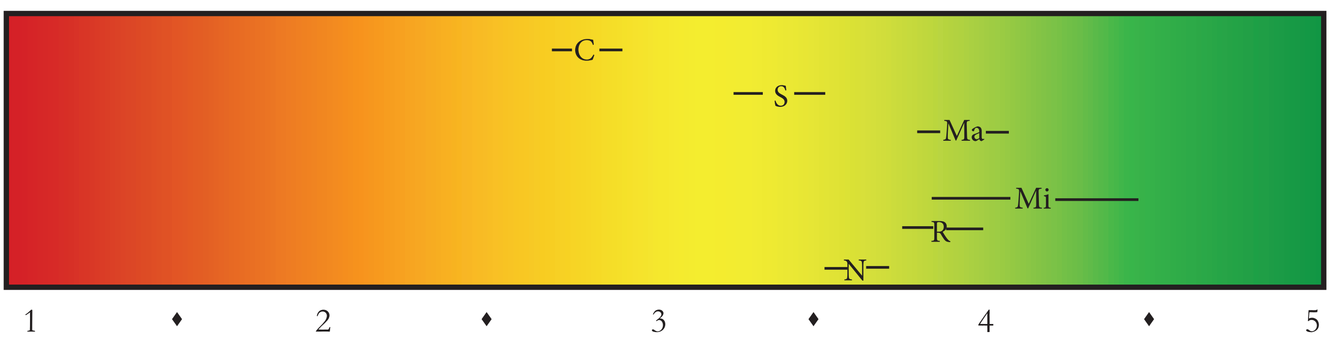



**Figure WQ8:** Overall nitrogen scores for each river. Error bars represent one standard deviation from the mean of all annual scores.

### Nitrogen Findings

- Concentrations of nitrogen were statistically highest in the agricultural Corsica, followed by the agricultural Sassafras, and lowest in the urban Middle River (Figure WQ5).
- Similarly, nitrogen scores were also worse in the two agriculturally dominated rivers, especially the Corsica, and best in the more heavily developed rivers, Middle and Magothy (Figure WQ8).
- No significant chronological patterns were observed. Varying rainfall totals did not seem to affect annual nitrogen levels at the spatial scale of this study.

# Phosphorus

## Background

In addition to nitrogen, all organisms depend on external sources of phosphorus. Although phosphorus compounds occur naturally in most aquatic systems, many estuaries suffer from excessive phosphorus input due to human activities, via agricultural application, wastewater treatment and urban runoff. Erosion and overground runoff are responsible for more than half of the phosphorus transported into Chesapeake Bay [46,49].

Overloading a water body with phosphorus causes problems similar to the effects of nitrogen pollution. Both nutrients are consumed by algae which can then grow into "blooms" that cover the surface of the water body, preventing sunlight from reaching other aquatic vegetation. Furthermore, when the algae dies, it sinks to the bottom where it is consumed by bacteria, which use dissolved oxygen in bottom waters, causing hypoxia (low oxygen) and anoxia (no oxygen). These poor conditions can be dangerous and even lethal to fish and shellfish [46].


**Image WQ3:** A NOAA scientist collects a water sample for chlorophyll *a* and nutrient analysis.

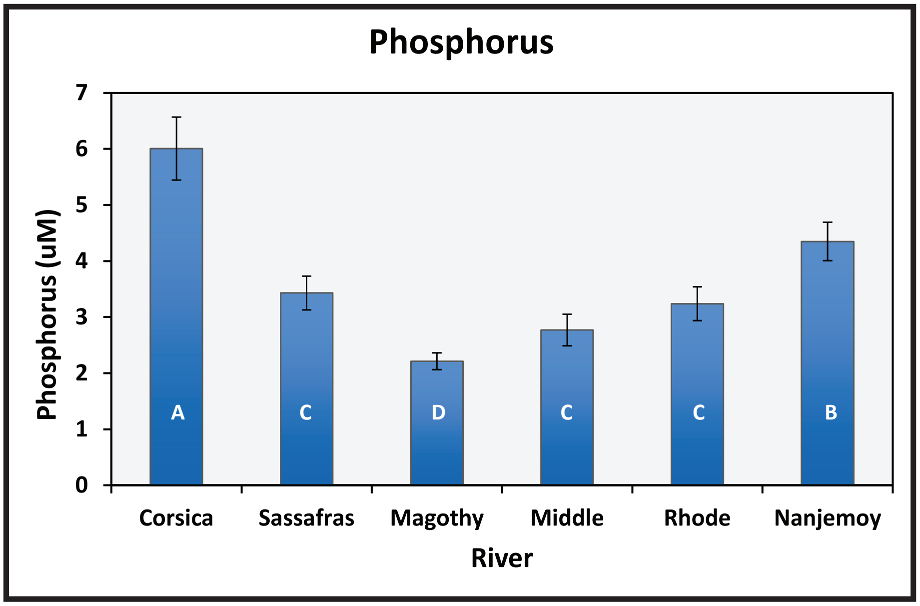



**Figure WQ9:** Average phosphorus concentration in each studied river.

## Methods

Water samples for phosphorus analysis were collected from just below the surface using acid-washed 500 mL plastic bottles. Total phosphorus, consisting of both dissolved and particulate forms, were measured using analytical instruments [48]. Average concentrations are shown in Figure WQ9. Total phosphorus values were then compared to an established threshold (1.2 μM) for the health of seagrass beds [47], and a value double that level (2.4 μM) reflective of extreme concentrations (Figure WQ10).

| Score Criteria for Total Phosphorus | | | |
|---|---|---|---|
| Score | 1 | 3 | 5 |
| Criteria (µM) | ≥2.4 | ≥1.2 and <2.4 | <1.2 |

**Figure WQ10:** Threshold levels of phosphorus and their corresponding scores.

## Results


**Figure WQ11:** Heat map of phosphorus scores by river and year.

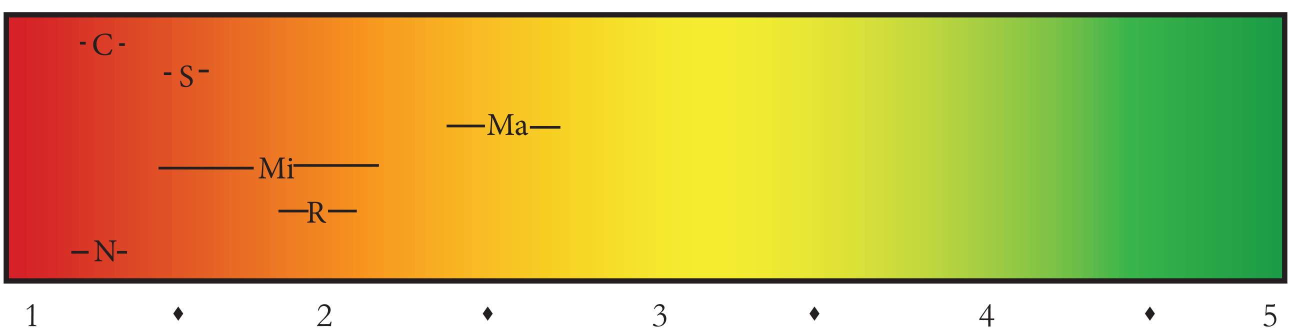



**Figure WQ12:** Overall phosphorus scores for each river. The error bars represent one standard deviation.

### Phosphorus Findings

- Concentrations of phosphorus were highest in the agricultural Corsica, followed by the forested Nanjemoy (Figure WQ9)
- The urban Middle and forested Nanjemoy Rivers had surprisingly high phosphorus concentrations.
- Low index scores were found for all rivers, with Magothy scoring the highest (Figure WQ12).
- As with nitrogen, the agricultural rivers scored poorly relative to most other rivers.
- Scores degraded over time in the Sassafras, Magothy and Middle Rivers (Figure WQ11).

# Secchi Depth

**Image WQ4:** A NOAA scientist watches until the black and white segments on the secchi disk are indistinguishable under water (left) and then reads the depth at that point (right).

## Background

Many organisms, such as plants and photosynthetic bacteria, use sunlight as their source of energy. Water clarity, which is a function of the depth that light of various wavelengths can penetrate into a water body, is therefore an important indicator of the water quality and overall condition of an aquatic ecosystem [50]. Water clarity is affected by many variables, but is primarily related to the amount of suspended material in the water. This material can be living organisms (e.g. phytoplankton), organic debris, or inorganic particles [50-51].

## Methods

Water clarity was estimated by Secchi depth measurements. The Secchi disk is a small flat disk with alternating black and white painted quadrants (Image WQ4), and is used widely to assess water clarity. The disk is lowered into the water until the pattern on the disk is no longer visible. This measurement is called Secchi depth and provides an estimate of turbidity. Because readings are affected by sun angle, cloud cover and other lighting factors, care must be taken to minimize sampling biases. Average Secchi depths in the six rivers are presented in Figure WQ13. Individual measurements were then compared to the published thresholds of 0.65 m (oligohaline waters) and 1.63 m (mesohaline waters) for phytoplankton health in Chesapeake Bay [52] (Figure WQ14).

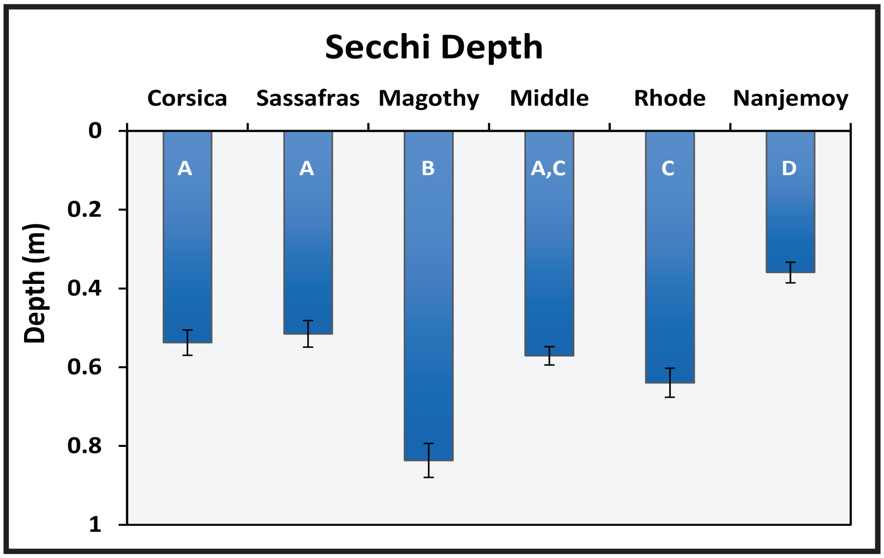



**Figure WQ13:** Average Secchi depth for each of the studied rivers.

| Score Criteria for Secchi Depth | | | |
|---|---|---|---|
| | Score | | |
| Habitat | 1 | 3 | 5 |
| Oligohaline (salinity <5.0 ppt) | ≤0.325 m | >0.325 m and ≤0.65 m | >0.65 m |
| Mesohaline (salinity >5.0 and <18 ppt) | ≤0.815 m | >0.815 m and ≤ 1.63 m | >1.63 m |

**Figure WQ14:** Secchi depth scoring criteria by salinity profile.

## Results

| River | Abbr | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|
| Corsica | C | | | | | | |
| Sassafras | S | | | | | | |
| Magothy | Ma | | | | | | |
| Middle | Mi | | | | | | |
| Rhode | R | | | | | | |
| Nanjemoy | N | | | | | | |

**Figure WQ15:** Heat map of scores by river and year.

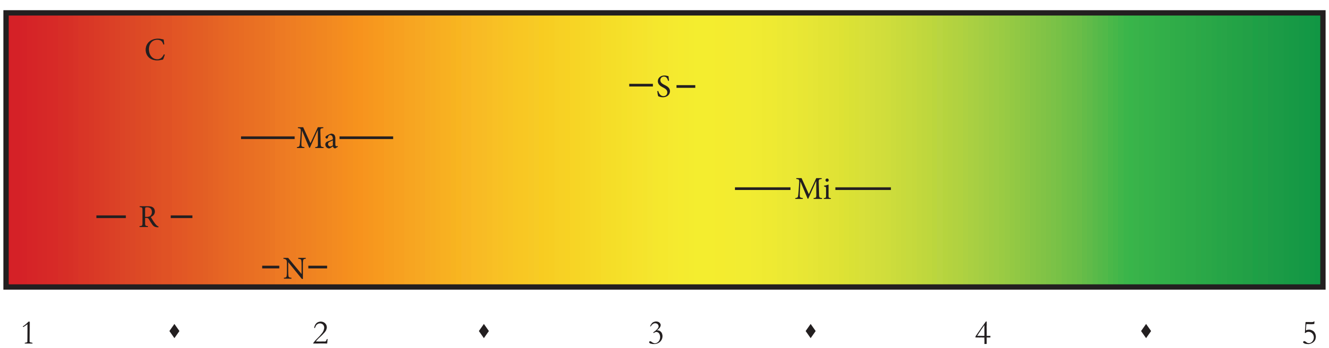



**Figure WQ16:** Overall scores for each river. Error bars represent one standard deviation.

### Secchi Depth Findings

- The forested Nanjemoy unexpectedly had the worst average water clarity (Figure WQ13), perhaps because it is a shallow river with fine benthic sediments and has a very large watershed relative to river size.
- The Magothy had deepest Secchi readings, though the scoring criteria still indicated poor water clarity (Figure WQ16).
- Except for the Nanjemoy, the oligohaline rivers (Sassafras and Middle) scored better than the mesohaline rivers (Rhode, Magothy, and Rhode), partly due to the salinity-dependence of the scoring criteria.

# Chlorophyll *a*

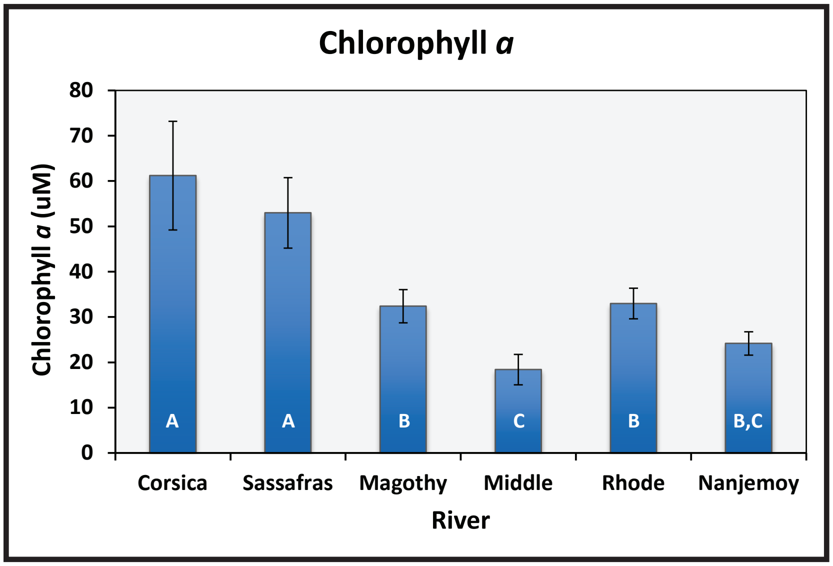



**Figure WQ17:** Average concentrations of total chlorophyll *a* in the rivers studied.

## Background

The pigment chlorophyll *a* plays a critical role for most photosynthetic organisms: it captures light, which supplies necessary energy for plants and some bacteria to produce organic molecules. Chlorophyll *a* concentrations can be measured to attain an estimate of the density of photosynthetic organisms in natural waters. The presence of low to moderate levels of chlorophyll *a* suggests a healthy habitat where primary producers, in balance with consumers, are creating organic matter from inorganic molecules and producing oxygen as a waste product. However, high levels of chlorophyll *a* indicate the presence of excess nutrients, favorable temperatures, and the necessary salinity conditions to support the growth of dense phytoplankton populations [53].

Habitat loss, reduced growth rates, or disturbances in trophic structure may result in system imbalances with high levels of chlorophyll *a* present, as phytoplankton growth outpaces phytoplankton consumption by grazers such as zooplankton. Stratification of waters in warm summer months concurrent with high phytoplankton growth rates establish conditions for low dissolved oxygen in bottom waters and reduced habitat for aerobic organisms.

**Image WQ5:** Algal blooms such as this denote an imbalance in the production of photosynthetic organisms and their consumption. Image courtesy of Jane Thomas, Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/).

## Methods

Chlorophyll *a* was measured in surface water samples by filtering 50-100 mL of water through a pre-rinsed 0.7 um filter. The filters were stored on dry ice in the field and in a -80°C freezer in the lab. Chlorophyll *a* concentrations were measured from the filters using high performance liquid chromatography [48]. Average conditions for each river are presented in Figure WQ17. Individual measurements were compared to an established threshold [47] for the health of seagrass beds (15 µg/L), and a value double that level (30 µg/L) reflective of extremely high concentrations.

| Score Criteria for Chlorophyll *a* | | | |
|---|---|---|---|
| Score | 1 | 3 | 5 |
| Criteria (µg/L) | ≥30 | ≥15 and < 30 | <15 |

**Figure WQ18:** Criteria for chlorophyll *a* values (based on [46]) and their corresponding scores.

## Results

| River | Abbr | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|
| Corsica | C | | | | | | |
| Sassafras | S | | | | | | |
| Magothy | Ma | | | | | | |
| Middle | Mi | | | | | | |
| Rhode | R | | | | | | |
| Nanjemoy | N | | | | | | |

**Figure WQ19:** Heat map of chlorophyll *a* scores by river and year.

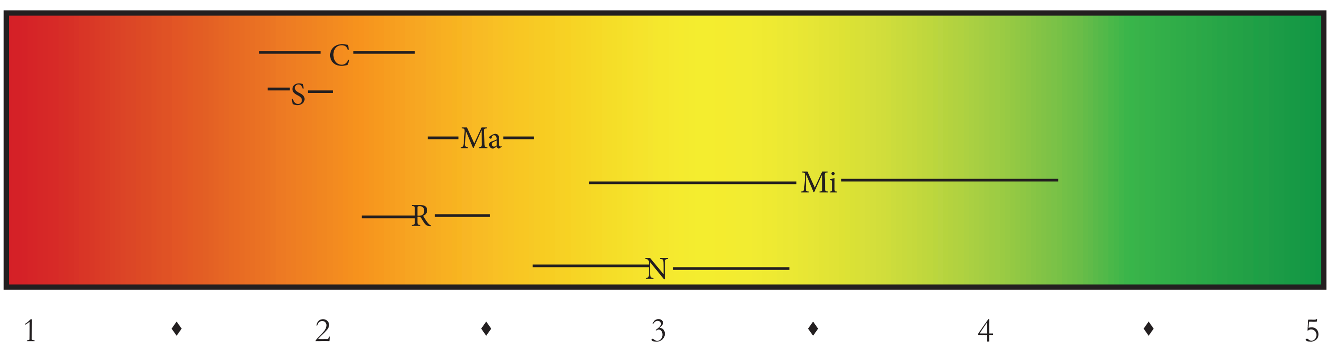



**Figure WQ20:** Overall chlorophyll *a* scores by river. Error bars represent one standard deviation.

### Chlorophyll *a* Findings

- Agricultural rivers (Corsica and Sassafras) had predictably high concentrations (Figure WQ17) and low scores (Figure WQ20) for chlorophyll *a*.
- The urban Magothy and less developed Nanjemoy and Rhode had similar chlorophyll *a* concentrations, while the urban Middle had the lowest concentrations.
- The Sassafras, despite better nutrient scores than the Corsica, scored slightly worse for chlorophyll *a*.
- The Middle and Nanjemoy had relatively low chlorophyll *a* concentrations and the best scores.
- All rivers became more degraded over the course of the study.

# Indicator Bacteria

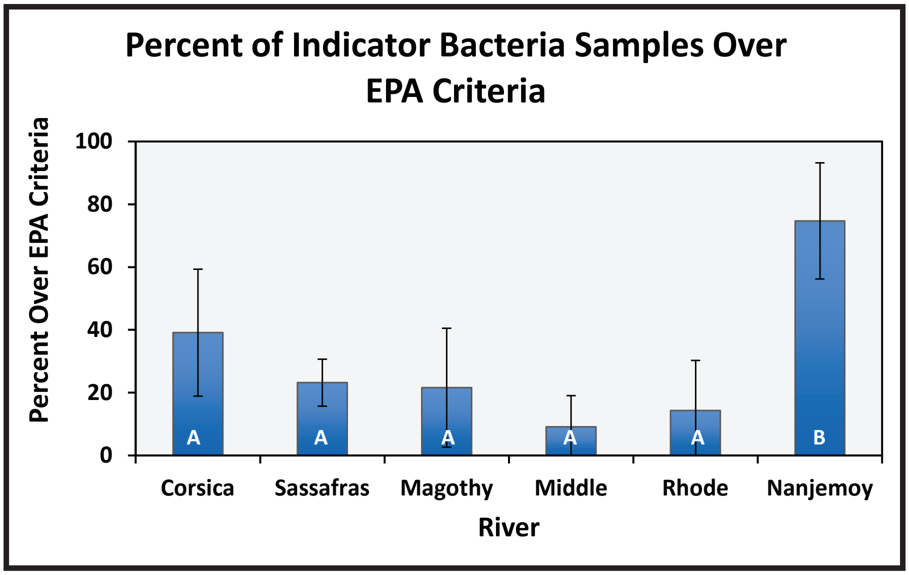



**Figure WQ21:** Percent of indicator bacteria measurements for each river that exceed the EPA criteria for a healthy river.

## Background

An important component of water quality is the presence and concentration of human pathogens. Humans may contract an illness from estuarine environments via direct contact with the polluted water or from the consumption of raw or undercooked contaminated shellfish. Monitoring water bodies for potential pathogens is infeasible due to their great diversity. However, fecal bacteria like *Enterococcus spp.* are good indicators of human pathogen levels. That is, although fecal bacteria are not usually harmful, their concentrations may correspond to risk of encountering pathogenic bacteria [54]. Therefore, fecal bacteria are often monitored in both fresh and marine waters as well as in seafood to indicate the likelihood of contracting human illness from contact with those waters or food items.

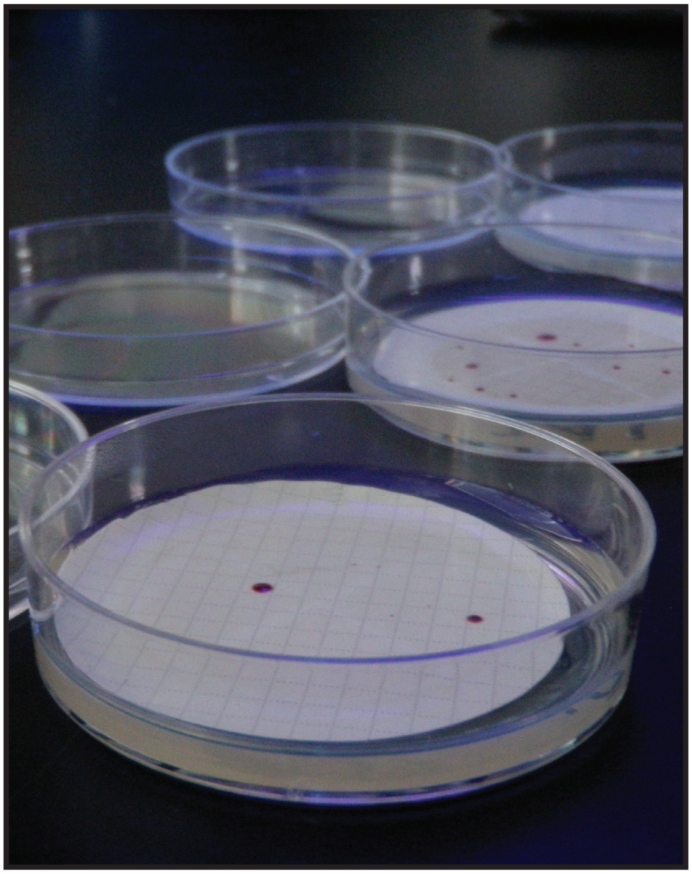


**Image WQ6:** Indicator bacteria were counted according to standard methods[54], by placing filters on growth media.

## Methods

For this study, *Enterococcus spp.* bacteria concentrations were measured in all six studied rivers. Bacteria were isolated using standard methods [55], which involve filtering sample water, incubating filters on specific culture media, counting bacteria colonies on the media, and comparing the counts to threshold criteria determined by the EPA. For marine and estuarine waters, the US EPA has established that waters with concentrations below 104 cells/100 mL are acceptable as "designated beach areas", and that waters with concentrations below 158 cells/100 mL are acceptable for "moderate" swimming use [56]. Although samples for this study were not collected at beaches, these criteria represent reasonable indicators of risk due to recreational activities in estuarine waters [24,57-61]. The "designated beach area" criterion was used as a lower threshold and the "moderate" swimming use criterion was used as an upper threshold in this study.

| Score Criteria for Indicator Bacteria | | | |
|---|---|---|---|
| Score | 1 | 3 | 5 |
| Criteria (colonies/100 mL) | ≥158 | ≥104 and < 158 | <104 |

**Figure WQ22:** Criteria for indicator bacteria colony densities [56] and their corresponding scores.

## Results

| River | Abbr | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|
| Corsica | C | | | | | | |
| Sassafras | S | | | | | | |
| Magothy | Ma | | | | | | |
| Middle | Mi | | | | | | |
| Rhode | R | | | | | | |
| Nanjemoy | N | | | | | | |

**Figure WQ23:** Heat map of scores by river and year.

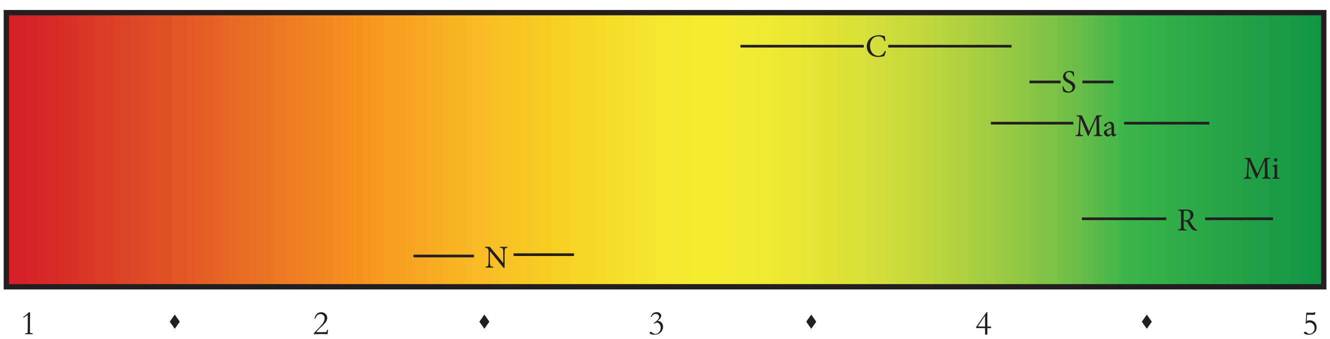



**Figure WQ24:** Overall scores by river. Error bars represent one standard deviation.

### Indicator Bacteria Findings

- There were no discernable trends in bacteria levels due to land use or climate.
- The predominantly forested Nanjemoy had the highest concentrations of indicator bacteria (Figure WQ21), corresponding to poor water clarity and high suspended sediment levels.
- The agricultural Corsica had the next highest concentrations, and is like the Nanjemoy in that it has a high land area to water area ratio.
- Scores for indicator bacteria levels in 2010 and 2011 were somewhat higher than other years for most rivers (Figure WQ23).

**Image LR1:** A NOAA scientist from the Cooperative Oxford Laboratory pulls a seine net.

Living aquatic resources are organisms that possess an ecological, commercial, or social value. In the Chesapeake Bay, many species of fish and shellfish represent important living resources as they constitute a valuable component of commercial and recreational economies. In Maryland in 2012, over 33,000 metric tons of fish and shellfish were caught commercially, and the combination of both commercial and recreational fishing generated over $1 billion [3]. The availability of these important resources in the Chesapeake Bay is predicated on the amount of healthy habitat that supports their reproduction, growth, and survival. Stressors, such as pollution and habitat loss, can induce drastic changes in the size and health of populations of living resources [62]. As discussed in the water quality chapter, these stressors may be related to land alterations and other human activities. Therefore, measuring living resource population sizes and determining the overall health of these populations allows us to evaluate the relative health of estuarine habitats in relation to land use. Assessing the health of living resources allows for a more direct measure of the combined effects of these stressors and of ecological change than do individual water quality or habitat variables.

Responses to environmental stressors by living organisms can occur at all levels of biological organization. For example, intermittent stressors can cause changes in gene expression, resulting in altered physiological conditions. If a stressor persists, the structure and function of internal organs can be affected. Often, organismal responses to environmental stressors can be observed before there are consequences on the population level, particularly if the stress impacts the reproductive success of the organisms. In this way, living resources provide an early warning of alterations to their environment. Finally, chronic or prolonged habitat degradation or stress can lead to broad scale changes in fish and shellfish populations.

In this study, living resources were used as bioindicators of estuarine health. Responses at each level of biological organization were measured in this study to create a holistic picture of the health of each river. Species studied for sub-lethal health impacts included white perch (*Morone americana*) and the blue crab (*Callinectes sapidus*). Assessments of fish populations and communities were conducted in nearshore and mid-river habitats by identifying and counting all species of fish captured in trawl and seine nets.

# Crab Host Response and Parasites

## Background

The blue crab, *Callinectes sapidus* (Image LR2), is a key component of the Chesapeake Bay ecosystem. A bottom-feeder, it preys on a wide range of invertebrates and is a major food source for many fish species [63]. Its consumption of various bivalve species may have an effect on the composition of soft-bottom communities [64]. Furthermore, the blue crab has been found to possess several quantifiable characteristics that act as indicators of environmental change.

Blue crab characteristics measured for this study fall under the two categories of host response and parasitology. Host response refers to physical signs of an organism's reaction to some stressor. Blue crab stressors include disease and abnormal environmental parameters. Host responses in *C. sapidus* include inflammation, nodule formation and tissue necrosis [63]. It is often difficult to tell what type of stressor caused a given host response. However, unlike disease and environmental parameters, parasites are often easier to see, if present in sufficient numbers. Therefore, parasitology was further studied, and parasites including ciliates, larval worms, microsporidians, gregarines and viruses were observed. Ciliates feed on bacteria, so higher numbers of ciliates on crab gills may indicate higher nutrient levels in the water, and therefore lower water quality. Furthermore, if ciliates are dense enough on crab gills they may inhibit respiration, which along with low levels of dissolved oxygen may lead to anoxia.

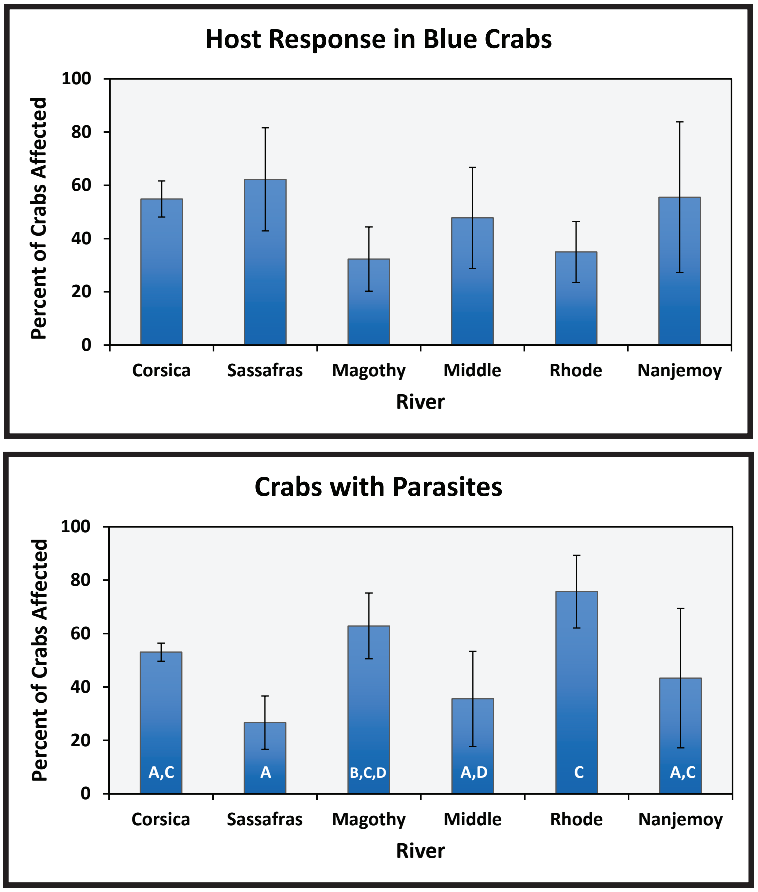



**Figure LR1:** Percent of crabs from each river showing a host response (top) and with parasites (bottom). No significant differences were detected for host response.

## Methods

Thirty or more crabs from each watershed were collected using a baited line laid along the river bottom. Crabs were then chilled to reduce mobility. Within a few hours, tissues were dissected and preserved for routine histopathological examination using light microscopy [65]. Crabs were assessed for any host responses and any parasites. Rivers were ranked by prevalence of host response and prevalence of parasites.

**Image LR2 (Right):** A NOAA scientist from the Cooperative Oxford Lab holds a blue crab prior to dissection.

| Score Criteria for Crab Host Response and Parasitology | | | | | |
|---|---|---|---|---|---|
| Score | 1 | 2 | 3 | 4 | 5 |
| Criteria (% prevalence of any host response) | 100 | 75 | 50 | 25 | 0 |
| Criteria (% prevalence of any parasite) | 100 | 75 | 50 | 25 | 0 |

**Figure LR2:** Scaling from percentage to score for crab host response and parasitology.

## Results

| River | Abbr | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|
| Corsica | C | | | | | | |
| Sassafras | S | | | | | | |
| Magothy | Ma | | | | | | |
| Middle | Mi | | | | | | |
| Rhode | R | | | | | | |
| Nanjemoy | N | | | | | | |

**Figure LR3:** Host response scores by river and year.

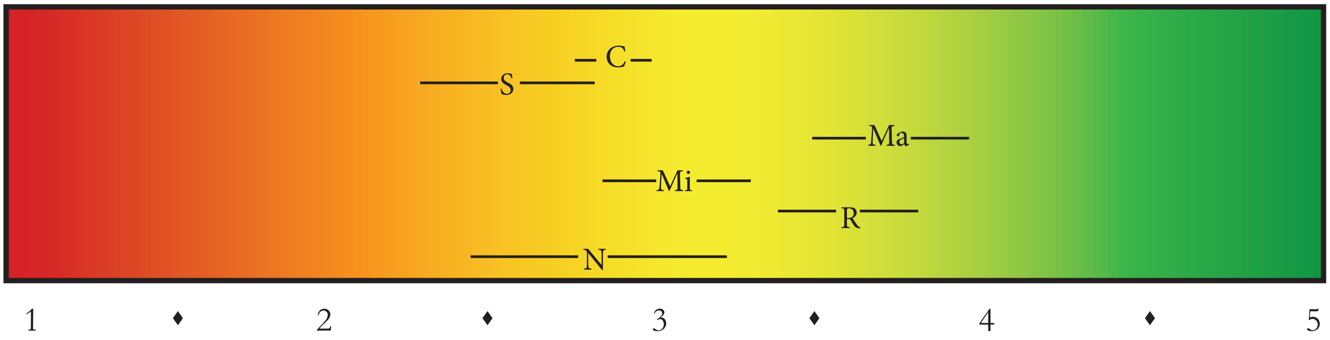



**Figure LR4:** Overall host response score for each river. Error bars represent one standard deviation.

### Crab Host Response Findings

- The percent of crabs with host response was not statistically different between any of the rivers (Figure LR1).
- However, for rivers with similar salinity ranges (Figure W5), scores for host response were poorer in agricultural rivers (Corsica and Sassafras) and better in urban rivers (Magothy and Middle) (Figure LR4), which is similar to the nutrient results.
- Host response scores were generally better than parasite scores.

## Results Continued

| River | Abbr | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|
| Corsica | C | | | | | | |
| Sassafras | S | | | | | | |
| Magothy | Ma | | | | | | |
| Middle | Mi | | | | | | |
| Rhode | R | | | | | | |
| Nanjemoy | N | | | | | | |

**Figure LR5:** Heat map of crab parasite scores by river and year.

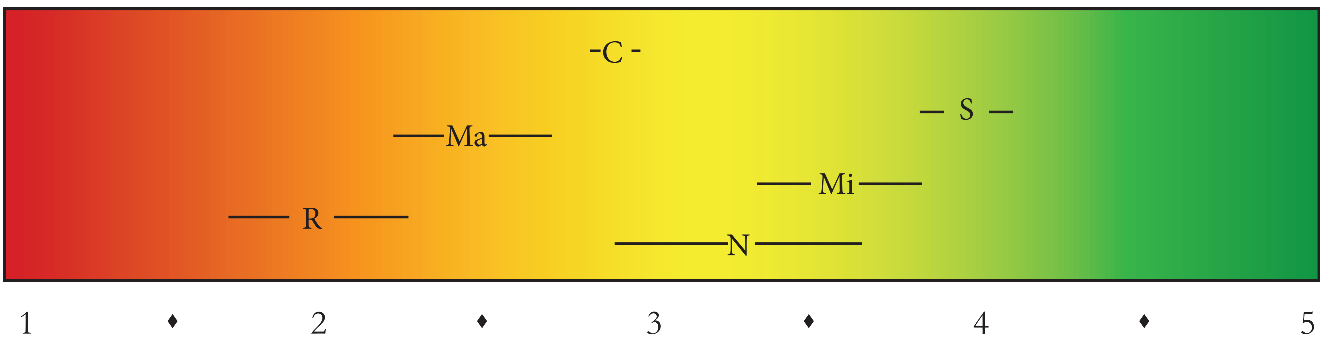



**Figure LR6:** Overall crab parasite scores by river. Error bars represent one standard deviation.

### Crab Parasite Findings

- There was higher prevalence of parasites in crabs from the higher salinity rivers (Corsica, Magothy, and Rhode) (Figure LR1).
- In contrast to host response, scores for the prevalence of crabs with parasites were best in the agricultural rivers (Corsica and Sassafras) and worst in the forested/mixed-use rivers (Rhode and Nanjemoy), within salinity group (Figure LR6).
- There was notable interannual variation in all rivers except the Corsica (Figure LR5).

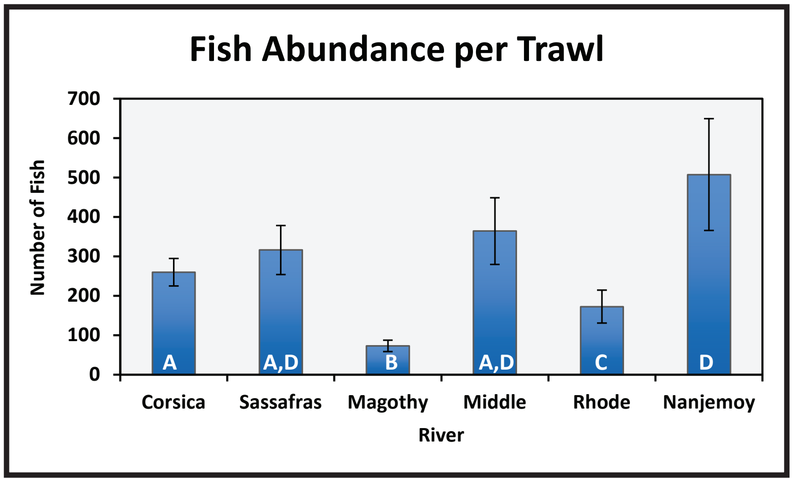
# Fish Abundance

## Background

Abundance is a measure of the relative proportions of a given group of species in a given environment [66]. The abundance and diversity of the finfish community are indicators of the overall suitability of the aquatic ecosystem to support growth. Appropriate physical habitat, acceptable water quality, proximity to spawning grounds, and sufficient food availability all play a role in determining the types and numbers of fish a water body can support [67-68].

**Image LR3:** NOAA scientists from the Cooperative Oxford Lab pull in a seine net.

Estuarine systems are highly variable in nature with annual changes in salinity structure, bay grasses, and recruitment success. Because of this variability, fish which inhabit estuarine systems tend to be tolerant to change and assessing trends in abundance should be conducted over several years to address the impact of annual cycles on recruitment. It is also necessary to characterize both fish inhabiting open water and those staying near to shore in the system.



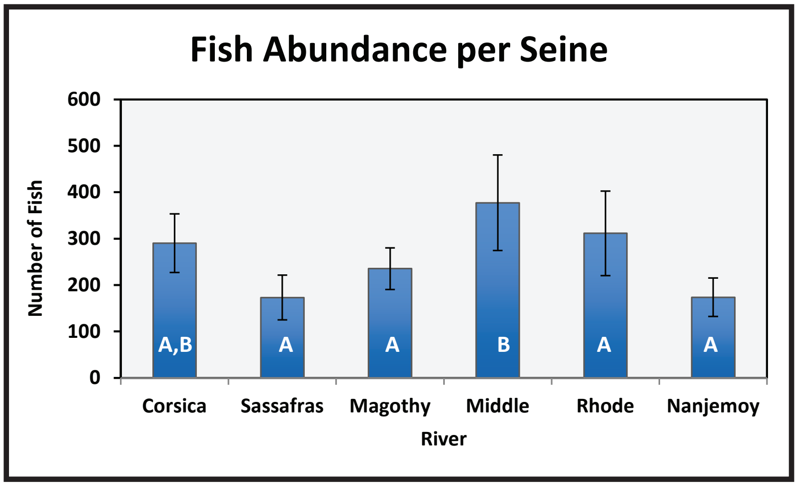




**Figure LR7:** Fish abundance in each river per trawl (top) and seine (bottom).

## Methods

A 100 foot beach seine and 16 foot otter trawl were used to sample sites throughout each river six times per year. Seines and trawls were deployed in a standardized manner and the number of individuals collected for each fish species was tallied. Because no criteria exists for fish abundance, we scored individual abundance values based on where they fell within the range of all observed values. First, all abundance values were ranked and quantiles were calculated. Samples were then scored by comparison to the quantiles, as shown in Figure LR9. Furthermore, data for fish abundance collected by seine in near shore shallow waters was separated from fish abundance collected by trawl in mid-river deep water, in order to look at differences between these habitats.

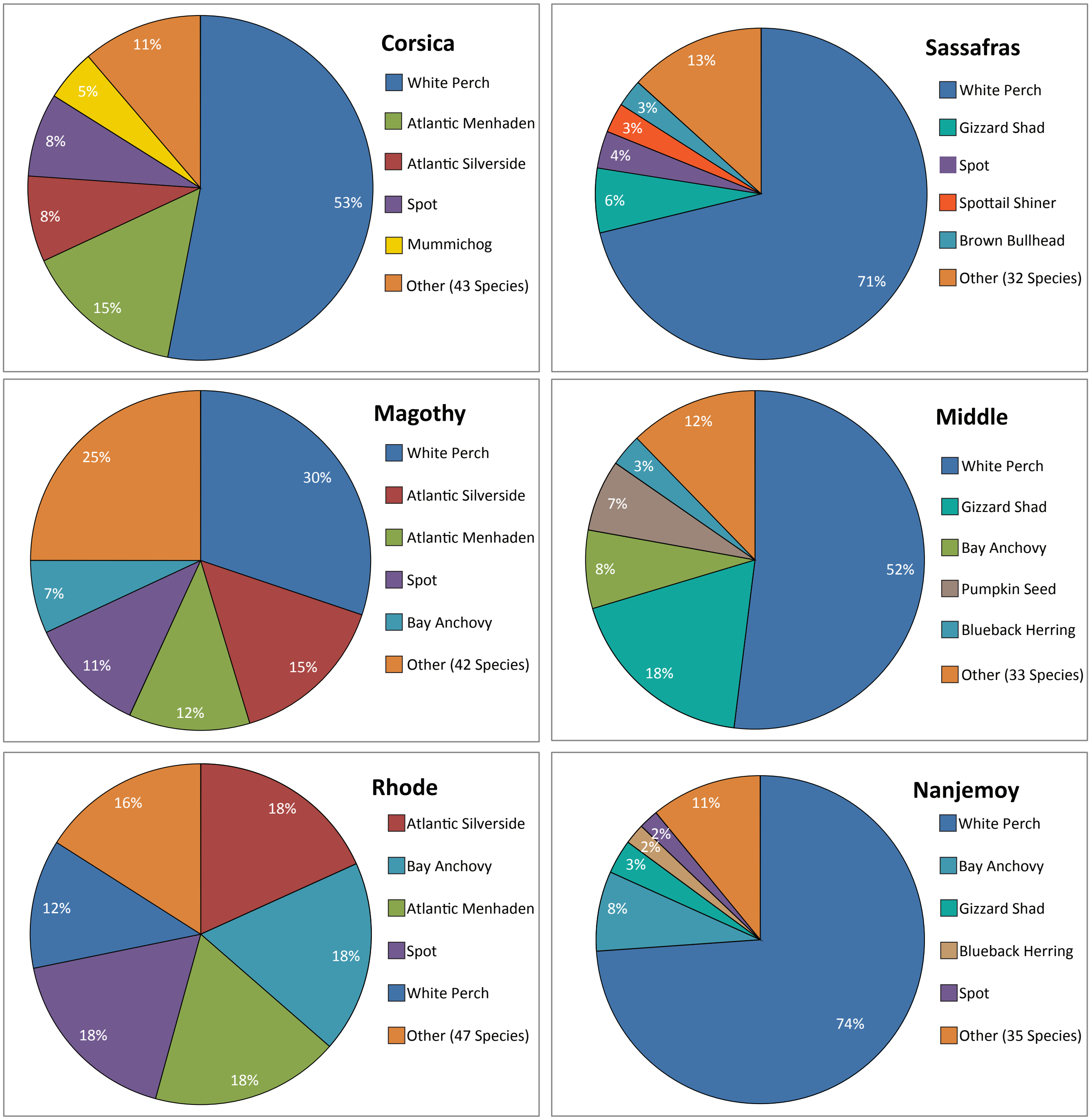



**Figure LR8:** Relative abundance of the five most abundant species in each river, in addition to the total relative abundance of all other species.

| Score Criteria for Fish Abundance | | | | | |
|---|---|---|---|---|---|
| Abundance Data Quartiles | 0-20% | 21-40% | 41-60% | 61-80% | 81-100% |
| Index Score | 1 | 2 | 3 | 4 | 5 |

**Figure LR9:** Explanation of fish abundance scoring criteria.

## Results

| River | Abbr | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|
| Corsica | C | | | | | | |
| Sassafras | S | | | | | | |
| Magothy | Ma | | | | | | |
| Middle | Mi | | | | | | |
| Rhode | R | | | | | | |
| Nanjemoy | N | | | | | | |

**Figure LR10:** Heat map of fish abundance scores from near shore (seine) by river and year.

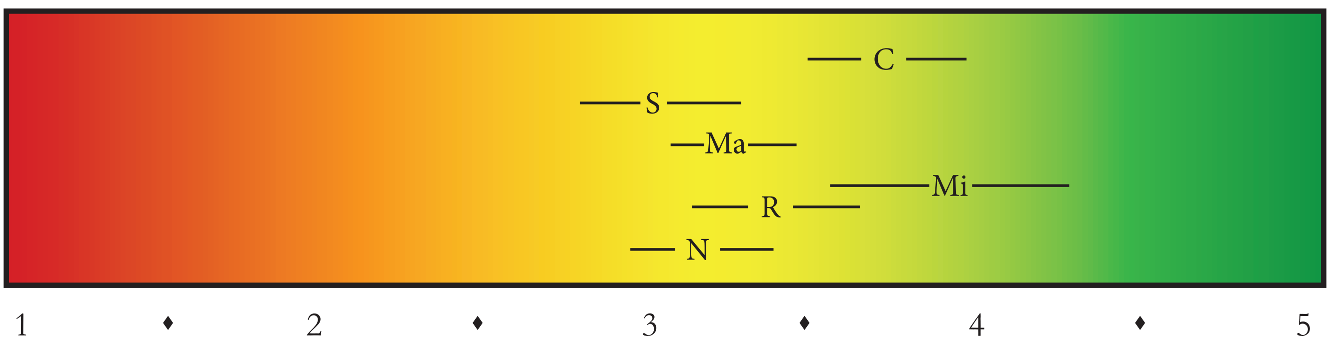



**Figure LR11:** Overall fish abundance scores from near shore (seine) by river. Error bars represent one standard deviation.

### Fish Seine Abundance Findings

- The mixed-use Rhode River had the most balanced distribution of fish species, while most other rivers were dominated by white perch (Figure LR8).
- Nearshore abundance was greatest in the urban Middle and agricultural Corsica Rivers, but overall, most systems were similar.
- No correlations were observed with water quality or watershed land use patterns.

## Results Continued

| River | Abbr | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|
| Corsica | C | | | | | | |
| Sassafras | S | | | | | | |
| Magothy | Ma | | | | | | |
| Middle | Mi | | | | | | |
| Rhode | R | | | | | | |
| Nanjemoy | N | | | | | | |

**Figure LR12:** Heat map of fish abundance scores from mid-river (trawl) scores by river and year.

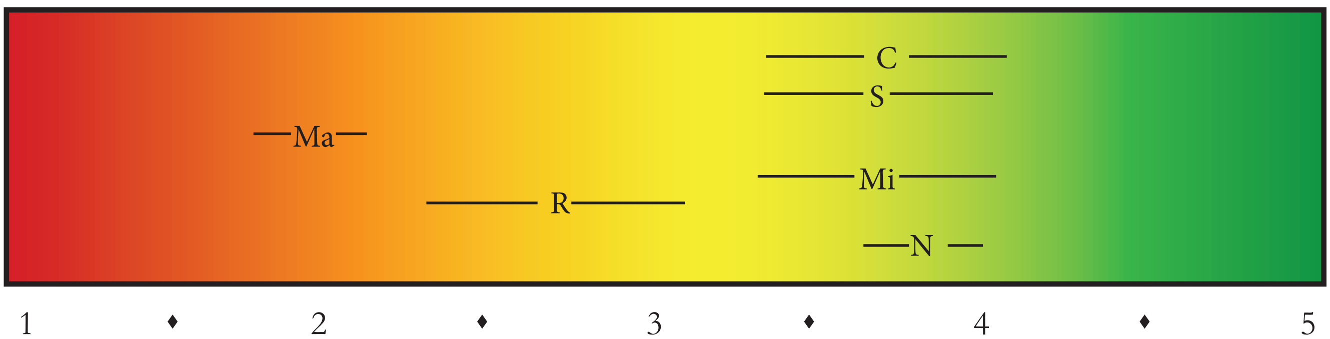



**Figure LR13:** Overall fish abundance scores from mid-river (trawl) by year. Error bars represent one standard deviation.

### Fish Trawl Abundance Findings

- There was no general trend in trawl abundance related to land use type (Figure LR7).
- The urban Magothy, with the lowest dissolved oxygen concentrations, had lowest fish abundance (Figure LR7).
- The Nanjemoy, Middle, and Corsica and Sassafras Rivers generally had higher mid-river abundance than the Magothy and Rhode (Figure LR7).
- The overall catch in all systems, except for the Rhode and Magothy, was dominated by white perch (>50%).
- The Magothy and Rhode were also slightly higher in salinity, lower in nutrients and turbidity, and more distant from major white perch spawning areas.

# Fish Body Fat Index

## Background

Fish health is often assessed by observing average condition, or overall well-being, of a population. These observations regularly use metrics of fish nutritional status. Healthy ecosystems possess adequate amounts of forage for fish populations to not only survive, but for individuals to grow and reproduce. Stressors that interrupt the ability of fish to obtain forage reduce individuals' nutritional status. In addition, some stressors may significantly alter the biochemical patterns that govern metabolism [69].

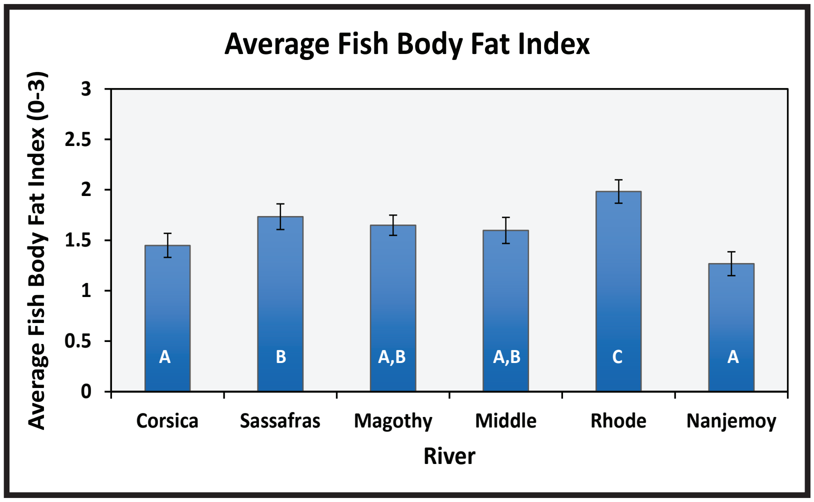



**Figure LR14:** Average fish body fat index values for each river.

In this study, fish muscle tissue moisture and the presence of body fat were examined. During periods of starvation, moisture levels in fish increase as lipid reserves are reduced. Well-fed fish accumulate fat reserves in their abdominal cavity. The presence and quantity of these reserves, as measured by the body fat index (BFI), provides a rapid method of determining relative nutritional status. The relationship between BFI and measurements of both tissue lipid and tissue moisture were verified in this study (see Figure LR15) and as well as in previous research [70]. During this assessment, BFI was examined in white perch collected in all six years while tissue moisture levels were analyzed for three years of the study to verify the efficacy of the index. This approach assumed that a majority of fish collected in rivers with healthy habitat would possess abundant fat reserves relative to rivers with poor habitat quality.

## Methods

Fat content in the body cavities of white perch was assigned a semi-quantitative score from 0 to 3 based on visual observation. Fish tissue moisture was determined by weighing samples of white perch muscle tissue before and after oven-drying the tissue. Moisture was then calculated as a percent of the total weight of the fish based on the percent of its total weight in the sample.

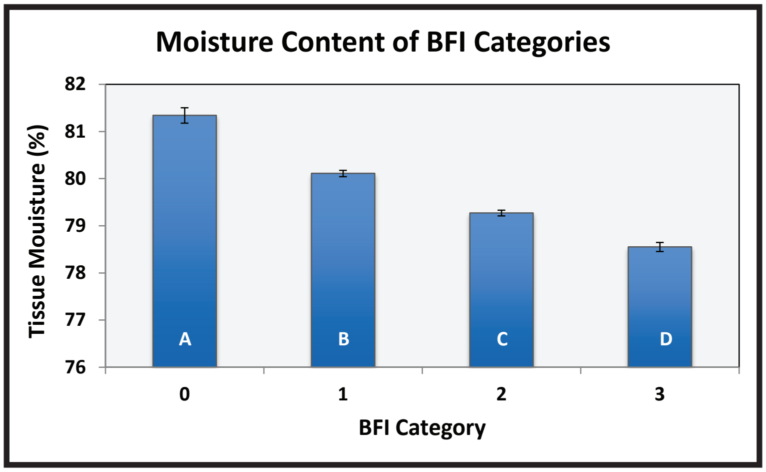



**Figure LR15:** This table shows that average moisture content for fish in each BFI category is significantly different from all the other BFI categories.

Tissue moisture and body fat were then compared using an analysis of variance, and found to correlate significantly (Figure LR15).

Body fat scores were translated to index scores from 1-5 by a scaling equation, such that a BFI score of 0 is equivalent to an index score of 1, and a BFI score of 3 is equivalent to an index score of 5 (Figure LR16).

| Score Criteria for Body Fat Index | | | |
|---|---|---|---|
| Body Fat Score | 0 | 1.5 | 3 |
| Index Score | 1 | 3 | 5 |

**Figure LR16:** Equating body fat scores to corresponding index scores.

## Results

| River | Abbr | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|
| Corsica | C | | | | | | |
| Sassafras | S | | | | | | |
| Magothy | Ma | | | | | | |
| Middle | Mi | | | | | | |
| Rhode | R | | | | | | |
| Nanjemoy | N | | | | | | |

**Figure LR17:** Heat map of body fat index scores by river and year.

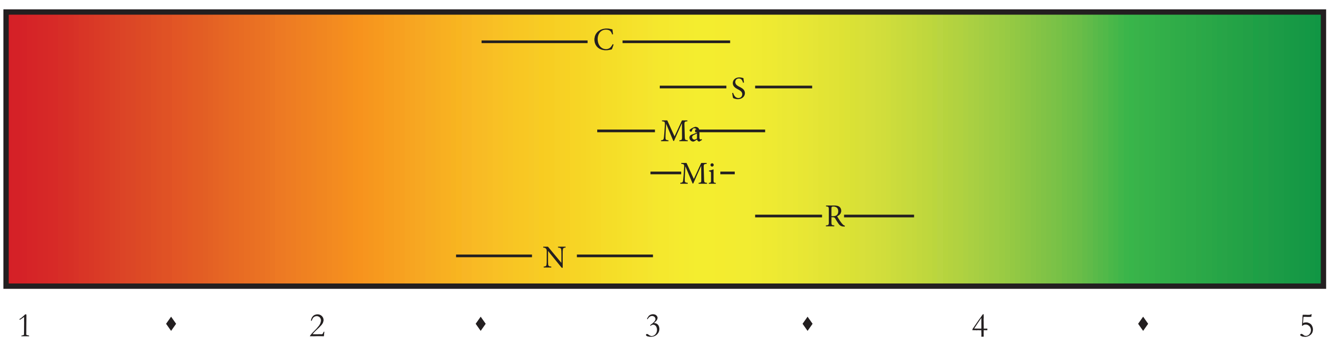



**Figure LR18:** Overall body fat index scores by river. Error bars represent one standard deviation.

### Body Fat Index Findings

- Fish from the mixed land use Rhode River had significantly more body fat than fish from all other rivers (Figure LR14).
- Differences in BFI score did not clearly separate the rivers.
- BFI scores from the rivers tended to improve over time (Figure LR17).

# External Fish Parasites

## Background

Fish parasites tend to be found on gills, intestines and skin. Research has shown that the abundance of fish parasites, particularly external parasites, are indicators of fish health in relation to river condition [71]. Environmental conditions such as poor water quality and high contaminant loads correspond to higher parasite quantities [71]. From an organismal perspective, poor fish condition and abundant intermediate parasite hosts (generally benthic macroinvertebrates) also relate to higher parasite loads.

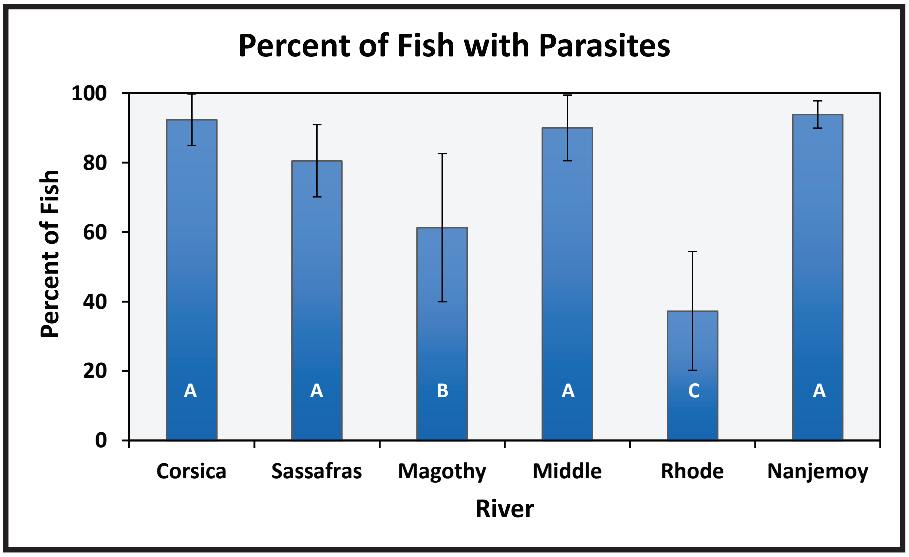



**Figure LR19:** Percent of fish with parasites from each river.

For this study, external parasites were counted on white perch, as these fish are found in each of the rivers, and they tend to spend most of their adult life within an individual river [72]. The most common parasites found on white perch in the six Chesapeake Bay rivers in this study included ciliated protozoans, encysted flatworms, and gill flukes, which were found on the gill tissues and/or the mucous which covers the skin. Less commonly, copepod and isopod parasites were found attached to the gills and fins.

**Image LR4:** Image of an isopod parasite on the gills of a white perch. Photo courtesy of M. Matsche, MDDNR.

## Methods

At least 12 white perch were collected from three different locations within each river during the fall of each year. In the field, small sections of gills and samples of the mucous scraped from the skin were taken from fish collected by various means (trawl, beach seine, hook and line). External parasites were counted. The intensity, or number of external parasites counted, was converted into a score, representing an index of external parasite burden.

| Score Criteria for External Fish Parasites | | | |
|---|---|---|---|
| Number of parasites per section | >3 | 1-3 | <1 |
| Index Score | 1 | 3 | 5 |

**Figure LR20:** Translation from parasite density to index score.

## Results

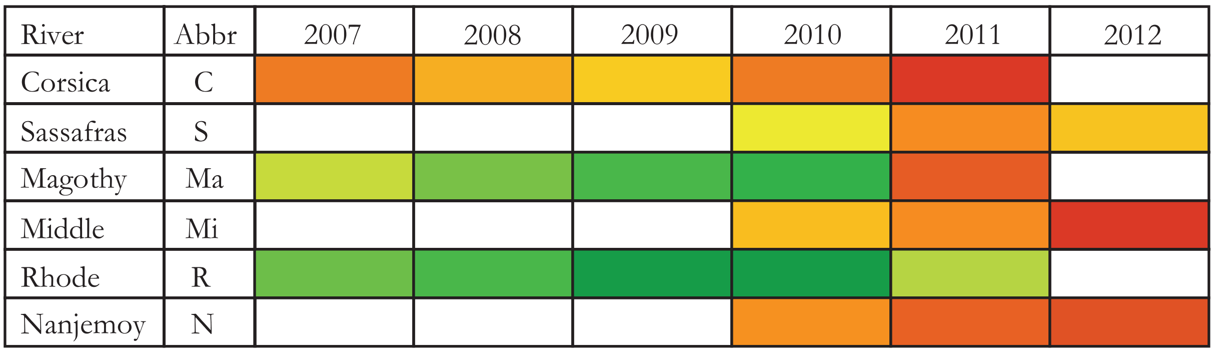



**Figure LR21:** Heat map of external fish parasite scores by river and year.

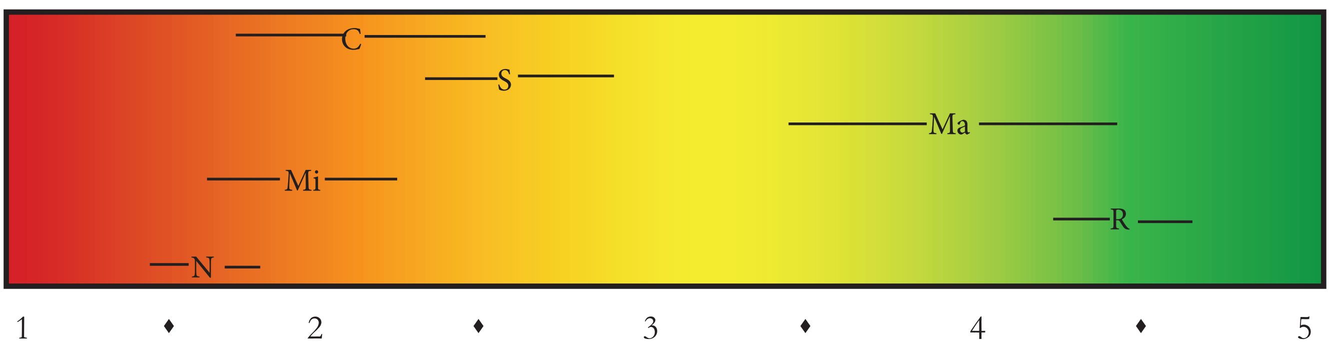



**Figure LR22:** Overall external fish parasite scores by river. Error bars represent one standard deviation.

### External Fish Parasite Findings

- Fish from the two agricultural systems (Corsica and Sassafras) consistently possessed relatively high parasite loads (Figure LR19).
- Across all rivers, fish collected in 2011 possessed higher parasite loads and corresponding low scores (Figure LR21), indicating a possible overarching ecological impact independent of land use type.
- Relative scores between the two urban systems, the Magothy and Middle, and the two forest and mixed-use systems, the Rhode and Nanjemoy, failed to demonstrate a consistent pattern of parasite abundance that could be linked to land use.

# Fish Macrophage Aggregates

## Background

Macrophage aggregates are accumulations of white blood cells involved in the capture, transport, and destruction of foreign materials, such as contaminants, heavy metals, parasites and dead cells. These cells clump together in focal centers to destroy foreign materials and reclaim useful tissues and cells. Macrophage aggregates can be detected using histological techniques, where fish tissue is stained, preserved in wax, sliced into very thin layers and examined under a microscope. The size and density of macrophage aggregates in the spleens of fish are known to be indicators of impaired water quality. By looking at nearly a thousand fish collected from many estuaries around the US, criteria have been developed to use macrophages as indicators of fish health [73]. Specifically, macrophage groupings larger than $5.0 \times 10^{-5}$ mm$^2$ are considered aggregates. If aggregates at or above this size are observed at a density below 15 per mm$^2$ of fish tissue, the system is scored as healthy. If aggregates are observed at a density above 40 per mm$^2$, the system is considered impaired. Densities between 15 and 40 per mm$^2$ indicate intermediate river health [73].

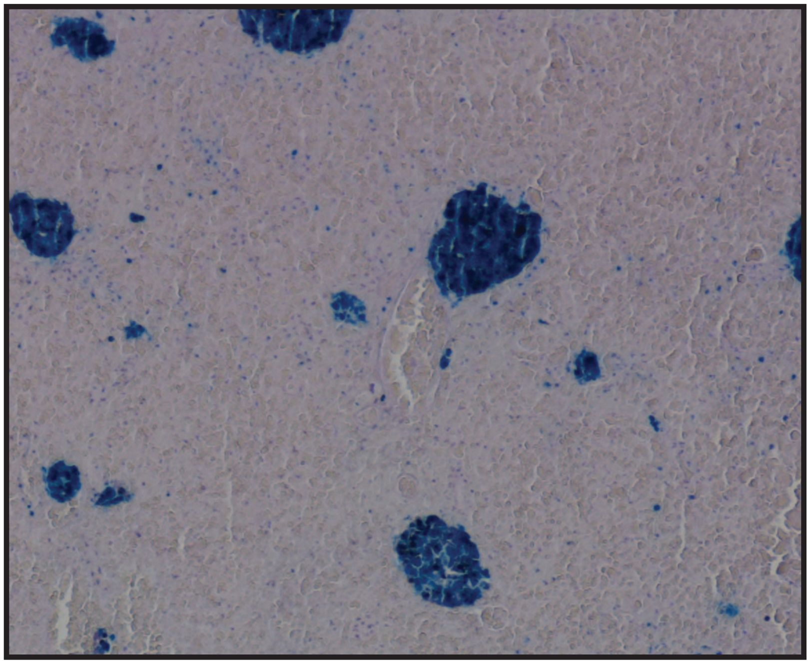


**Image LR5:** A 10x magnified image of macrophage aggregates (stained dark blue) from a white perch spleen tissue sample.

## Methods

White perch spleens were embedded in paraffin, cut to 5 microns, and stained using either Mayer's hematoxylin-eosin-phloxine or Perl's Prussian Blue [65]. The stained tissue was examined using a Nikon Coolscope, in conjunction with the freeware ImageJ program. Macrophages larger than $5.0 \times 10^{-6}$ mm$^2$ were counted from randomly selected areas on each slide. The densities of these were then calculated per mm$^2$ of fish tissue. Scores were assigned according to Figure LR24.

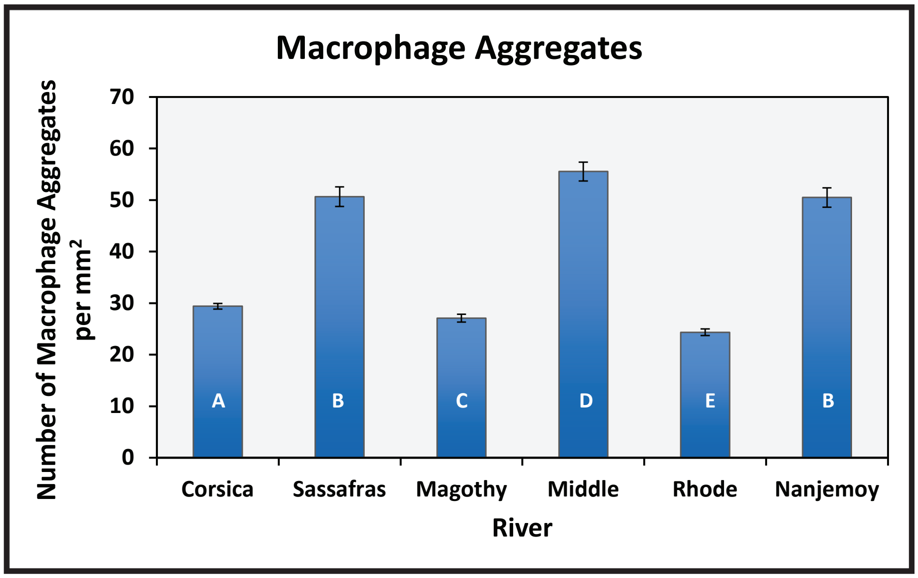



**Figure LR23:** Average macrophage aggregate densities in each river.

| Score Criteria for Macrophage Aggregates | | | |
|---|---|---|---|
| Density (Macrophage Aggregates per mm$^2$ of tissue) | >40 | 15-40 | <15 |
| Index Score | 1 | 3 | 5 |

**Figure LR24:** Macrophage aggregate density thresholds and their corresponding index scores.

## Results

| River | Abbr | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|
| Corsica | C | | | | | | |
| Sassafras | S | | | | | | |
| Magothy | Ma | | | | | | |
| Middle | Mi | | | | | | |
| Rhode | R | | | | | | |
| Nanjemoy | N | | | | | | |

**Figure LR25:** Heat map of macrophage aggregate scores by river and year.

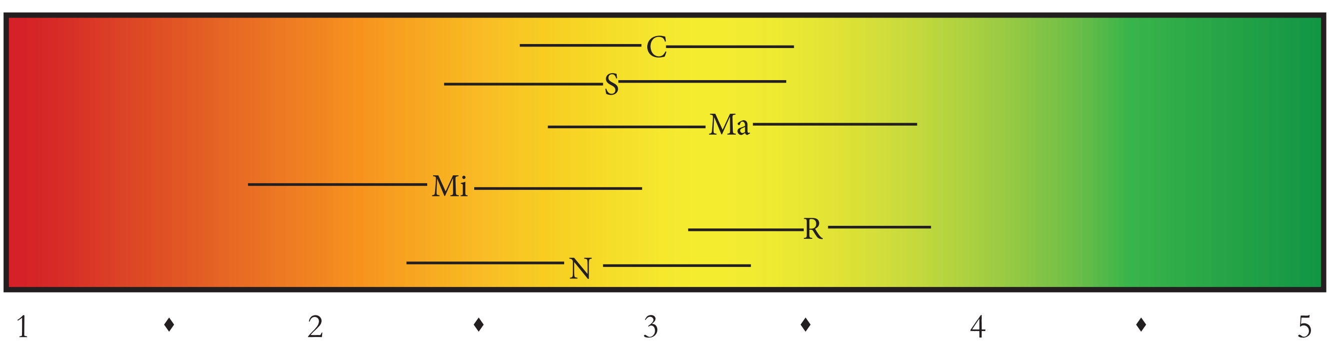



**Figure LR26:** Overall macrophage aggregate scores by river. Error bars represent one standard deviation.

### Fish Macrophage Aggregate Findings

- Lower salinity rivers (Sassafras, Middle, and Nanjemoy) had more macrophage aggregates per area of tissue than the higher salinity river (Corsica, Magothy, and Rhode) (Figure LR23).
- There was a high degree of interannual variability, particularly in the latter years of the study.
- Most systems had high levels of macrophage aggregates in 2010 and low levels in 2011 (Figure LR25).

# Fish Disease

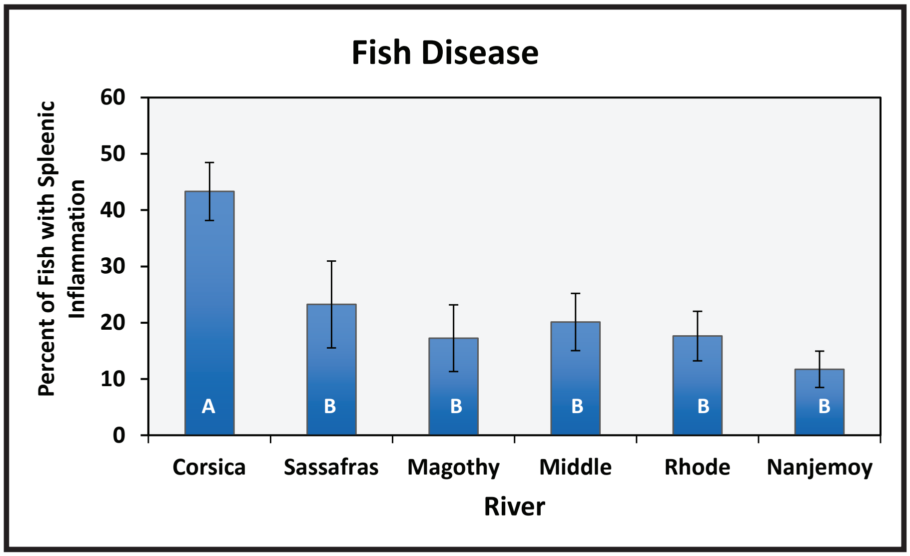



**Figure LR27:** Percent of fish with spleenic inflammation due to disease or a combination of disease and internal parasites.

## Background

Disease prevalence in fish and other aquatic organisms has been linked to river health. For disease to progress in a natural fish population, three ingredients must be present: a susceptible fish population, a viable pathogen, and environmental stress. In theory, environmental conditions that are stressful to organisms or beneficial to pathogens can lead to increased incidence of disease. Evidence for a relationship between environmental stress and fish disease has been accumulating for decades [74]. Recently a link between poor water quality and a higher incidence in disease has been developed for Chesapeake Bay fish (Mark Matsche, MD DNR, personal communication).

In this study, mycobacteriosis prevalence in white perch was analyzed as an indicator of environmental health. Mycobacteriosis is a disease caused by several species of the genus *Mycobacterium*. Immune response to mycobacterial infections include inflammation and granuloma formation in the spleen [75]. Inflammation diverts greater blood flow to the infected area to deliver disease-fighting cells, and granulomas are capsules which form around the infected area to contain it.

**Image LR6:** A NOAA scientist prepares a white perch for necropsy.

## Methods

White perch were necropsied with organs processed for histopathology, and pathological changes were noted. Mycobacteriosis presence was judged by the inflammation in the spleen (exclusive of inflammation caused solely by parasites) and the presence of acid-fast bacteria (bacteria such as Mycobacterium that have thick, waxy outer membranes). The percent of fish showing these disease conditions is shown in Figure LR27. The severity of splenic inflammation for each fish was rated as severe, moderate, or none (normal). These ratings were then converted to scores as shown in Figure LR28.

| Score Criteria for Fish Disease | | | |
|---|---|---|---|
| Degree of Tissue Inflammation | Severe | Moderate | None (Normal Tissue) |
| Index Score | 1 | 3 | 5 |

**Figure LR28:** Translation of tissue inflammation assessment to index score.

## Results

| River | Abbr | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|
| Corsica | C | | | | | | |
| Sassafras | S | | | | | | |
| Magothy | Ma | | | | | | |
| Middle | Mi | | | | | | |
| Rhode | R | | | | | | |
| Nanjemoy | N | | | | | | |

**Figure LR29:** Heat map of fish disease scores by river and year.

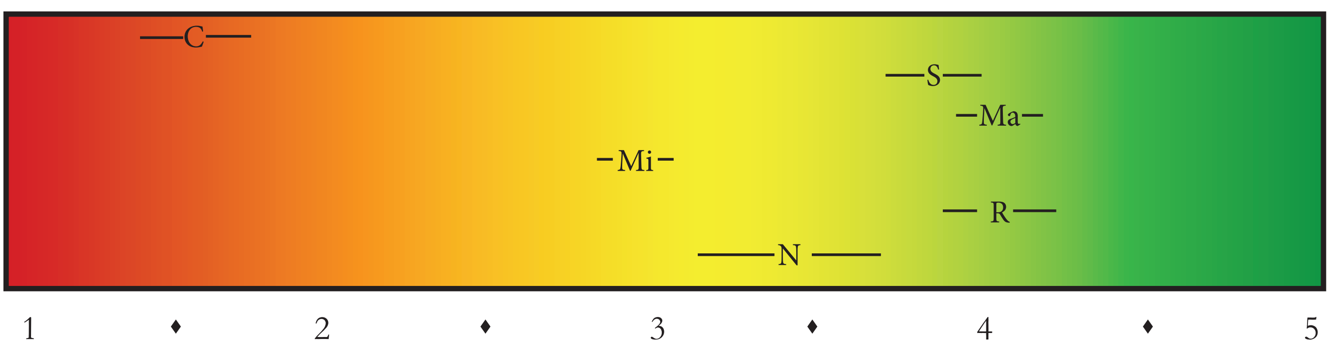



**Figure LR30:** Overall fish disease scores by river. Error bars represent one standard deviation.

### Fish Disease Findings

- Corsica River fish had much higher disease prevalence than all other systems (Figure LR27).
- Disease prevalence followed general land use categorization with agricultural systems having higher prevalence than the others (Figure LR27).
- Disease severity was also highest in the Corsica, but did not follow the same pattern as prevalence, with diseased fish in the Nanjemoy and Middle having more severe inflammation than Sassafras, Magothy, and Rhode River fish (Figure LR30).

# Submerged Aquatic Vegetation

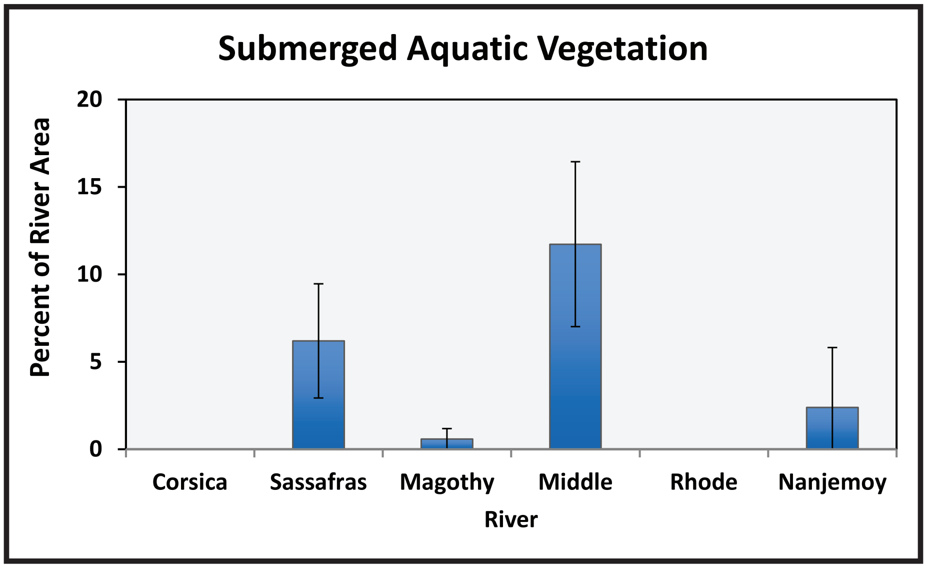



**Figure AV1:** Percent of river area covered by SAV.

## Background

Submerged aquatic vegetation (SAV) in the Chesapeake Bay includes several species of bay grasses that grow underwater in the shallow areas of the Bay and its tributaries. SAV is both an excellent indicator and mediator of Bay health. As an indicator, SAV acreage declines steeply in response to increases in pollution, but respond well to improvements in water quality. Furthermore, since SAV relies on photosynthesis and therefore requires sunlight, its ability to thrive is closely linked to water clarity. As a mediator, SAV improves water quality, including clarity, by filtering out pollutants, trapping suspended sediments, and oxygenating the water [76]. Historically, all six rivers have supported SAV beds, occasionally in greater extent than during our study, though the amount of SAV has varied considerably over time [77,78].

## Methods

Unlike the other variables in this study, data obtained from the Virginia Institute of Marine Science [77] was used to determine the area in each of the six studied rivers that was covered by SAV beds from 2007 to 2012. This area was then divided by the total area of each river to find a percent coverage for each river, each year. .

The Chesapeake Bay Program (CBP) has established a restoration goal of 185,000 total acres of SAV in the Bay. This goal was divided into several categories, depending on the salinity regime of the location [79]. The rivers in this study fell into either the low salinity (oligohaline) or moderate salinity (mesohaline) categories for CBP goals, which were 10,334 and 120,306 acres, respectively. The total oligohaline and total mesohaline surface areas of the Bay were divided by these values to come up with goal percent coverage values [80]. The mesohaline goal was 6.45% and the oligohaline goal was 4.39%. For this study, the ranges from 0 to 6.45% and 0 to 4.39% were then scaled to a score from 1 to 5, where any river in the appropriate salinity regime with greater than 6.45% or 4.39% coverage was scored a 5 (see Figure AV2).

**Image AV1:** SAV beds in the Choptank River, pictured from below (left) and above (right) the surface. Images courtesy of Ben Fertig, Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/).

| Score Criteria for Submerged Aquatic Vegetation | | | |
|---|---|---|---|
| Mesohaline River Coverage (%) | 0 | 3.23 | >6.45 |
| Oligohaline River Coverage (%) | 0 | 2.20 | >4.39 |
| Index Score | 1 | 3 | 5 |

**Figure AV2:** Scaling from percent SAV coverage to score, dependent on salinity profile.

## Results

| River | Abbr | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|
| Corsica | C | | | | | | |
| Sassafras | S | | | | | | |
| Magothy | Ma | | | | | | |
| Middle | Mi | | | | | | |
| Rhode | R | | | | | | |
| Nanjemoy | N | | | | | | |

**Figure AV3:** Heat map of SAV scores by river and year.

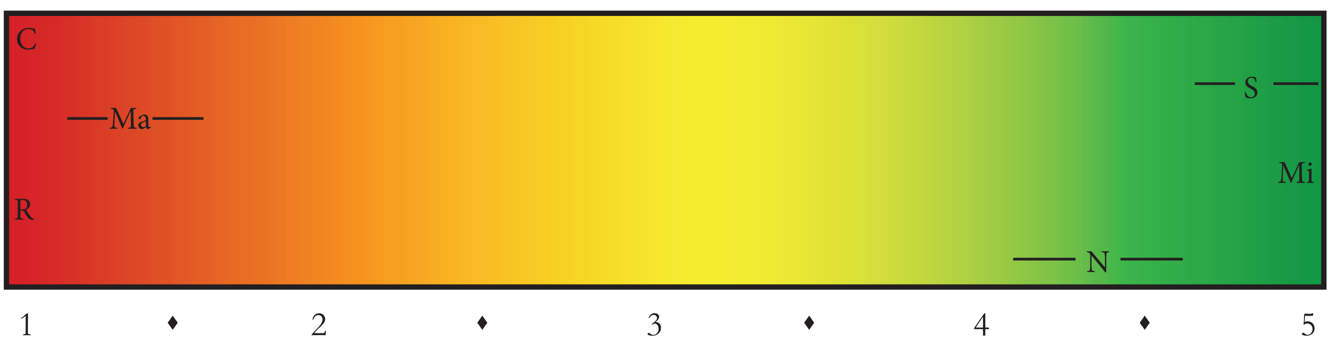



**Figure AV4:** Overall SAV scores by river. Error bars represent one standard deviation.

### Submerged Aquatic Vegetation Findings

- The rivers diverged by salinity profile, perhaps due to the success of Widegeon grass and other low salinity (oligohaline) species [42].
- The Magothy had more SAV than the other moderate (mesohaline) salinity rivers (Corsica and Rhode), corresponding to its better water clarity.
- The Nanjemoy had less SAV than the other low salinity (oligohaline) rivers (Sassafras and Middle) corresponding to its poor water clarity.

**Image S1:** Floating vegetation on the Sassafras River.

This study assessed ecological conditions in six rivers of the Chesapeake Bay watershed and related differences in those conditions to potential stressors, primarily those resulting from land use activities. The assessment uncovered a mix of expected relationships and some surprising trends. Major suspected findings include high nutrient concentrations and cloudy waters in the agricultural rivers, abundant but unhealthy fish in the agricultural rivers, and relatively balanced nutrient levels and healthier fish in the mixed-use and forested rivers. The unexpected outcomes include mixed signals in the urbanized rivers for water quality and living resources, multiple signs of poor health in the forested river, the nearly complete lack of SAV in the mesohaline rivers, and multiple instances of strong interannual variability across all studied rivers without a clear correlation to changing weather patterns.

The traditional agricultural signals of high nutrient and chlorophyll *a* concentrations were considerably stronger in the two agriculturally dominated watersheds, the Corsica and Sassafras, than the two urban systems, the Magothy and Middle. This finding suggests that controls on urban point sources of nutrients, such as wastewater treatment plants and industrial effluents, have been more effective in reducing nutrient inputs then those for nonpoint sources, such as runoff from agricultural fields. As expected for the nutrient-enriched agricultural watersheds, high chlorophyll *a* was correlated to relatively low Secchi depths and sparse SAV. This set of conditions can occur when excessive phytoplankton growth clouds the water column and prevents sunlight from penetrating to the bottom where SAV grows.

Although high nutrient and phytoplankton concentrations often lead to low dissolved oxygen in summertime, when waters become vertically stratified, dissolved oxygen concentrations in the two agricultural systems were sufficient to support living resources. In fact, open water fish abundances were as high or higher in the agriculturally dominated watersheds than in all other systems except the forest-lined Nanjemoy River. High levels of nutrients and phytoplankton in the Corsica and Sassafras appear to be consumed rapidly and help support the relatively abundant fish populations found there.

**Image S2:** A great blue heron stands beside the Tred Avon River. Image courtesy of Jane Hawkey, Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/).

Fish disease was common in white perch from both agricultural rivers. In the Corsica, 43% of fish were affected by disease, nearly twice the proportion of the next most affected river, the Sassafras. Fish disease prevalence was lower in the urbanized and mixed-use rivers and lowest in the and forested rivers. Disease severity (as measured by the stage of advancement of infections) in fish from the Corsica was also high, though the Sassafras did not show high severity. Disease prevalence and severity in the agricultural rivers may, in part, be the result of stressful competition for resources among the large open-water fish populations in those rivers; however, high abundances and good health in other rivers suggest this may not be the only factor.

Conditions in the highly urbanized Middle and Magothy rivers were mixed. Although nutrient concentrations were lower than the agricultural systems, values were still excessive compared to established criteria. Secchi depth scores were best in the Magothy and Middle when compared to the other rivers in their respective salinity groups. Dissolved oxygen in bottom waters of the Magothy was lower than all other rivers, though this trend was not severe enough to be reflected in the overall dissolved oxygen scores for that river. The Magothy also had the lowest fish abundance scores for the mid-channel habitat (trawl samples), perhaps related to the relatively low oxygen levels in the bottom waters. In contrast, the Middle River had relatively high abundances of fish in both the open water trawl samples and the nearshore seine samples. Both urbanized rivers may have been expected to show low abundance due to the effects of urban pollutants like heavy metals and PCBs. Mixed abundance scores suggest that urban pollution may not be the defining factor. The Middle River also had relatively low fish diversity, though the diversity of fish in this system, as well as the other two low salinity rivers (Nanjemoy and Sassafras), may be related in part to the high numbers of white perch and the proximity of the rivers to white perch spawning grounds. In a previous report on the first three years of this study (2007 to 2009), levels of chemical contaminants and toxic sediments were higher in the urbanized Magothy than in the Corsica and Rhode [7]. Unfortunately, benthic contaminant information was not collected from the other three rivers.

The Rhode River, which is partially forested with low to moderate urbanized areas, and the Nanjemoy, which is largely forested, had complex condition signatures as well. Both rivers tended to have lower nitrogen and chlorophyll *a* concentrations, and lower fish disease than the two agricultural rivers. Nutrient loads in these rivers were expected to be low because forested land is effective at trapping runoff in the dense network of tree roots that permeate the soil. Furthermore, more undisturbed land was expected to correlate to healthier individual fish, because forested lands leach much less pollutants into the water body than urban or agricultural lands.

Although the relatively high incidence of fish disease seen in the agricultural systems may be related to high densities of individuals living in close proximity and the associated stress, the Nanjemoy had the highest fish densities of all rivers, but also the lowest disease incidence. The Rhode was also the most balanced river in terms of fish diversity and the Nanjemoy averaged more than five times the number of fish captured per trawl than the Magothy. However, the Rhode and Nanjemoy both had conditions that indicated some stress. For example, both rivers suffered from poor water clarity, with the Nanjemoy having the worst water clarity of all rivers. The prevalence of crab parasites was also higher in the Rhode and Nanjemoy, when compared to the urban and agricultural rivers of similar salinity. While the presence of fish parasites was high in the Nanjemoy, fish from the Rhode had much lower incidence of parasites.

An interesting interplay between water clarity and nutrient concentrations emerged that helped to contrast conditions in the two relatively undeveloped rivers, the Rhode and Nanjemoy. These two rivers had poor water clarity, but perhaps for slightly different reasons. Indicator bacteria and phosphorus concentrations were very high in the Nanjemoy, while chlorophyll *a* concentrations were relatively low. Because phosphorus and indicator bacteria tend to bind to sediments, suspended sediments likely played a significant role in the poor water clarity there. While sediments also likely played a role in Rhode River water clarity, and the influx of large amounts of sediment from the heavily forested headwater area of the watershed has been noted [81], the high level of chlorophyll *a* in the Rhode suggests a more important role for phytoplankton in water clarity conditions there. The unexpected presence of elevated suspended sediment concentrations in the two forested watersheds may be related to resuspension of sediments from subtidal mud flats [81].

In addition to land use, a major factor separating the six rivers was salinity. In anticipation of this, two sets of three rivers were selected during the study design to represent mesohaline rivers (Corsica, Rhode, and Magothy; sampled 2007-2011) and oligohaline rivers (Nanjemoy, Middle, and Sassafras; sampled 2010-2012). For chlorophyll *a*, Secchi depth, and submerged aquatic vegetation (SAV), the index criteria used to assess condition depended on salinity. This was most apparent for SAV, where the goals for restoring SAV beds are greater in moderately saline areas than in low salinity regions. Additionally, the three low salinity rivers had higher fish abundances in both the nearshore (seine) and mid-river (trawl) habitats, likely due to the predominance of white perch and their recruitment from nearby freshwater spawning grounds.

**Image S3:** NOAA scientists from the Cooperative Oxford Laboratory photographed this small boat while conducting a sampling mission.

Although a number of the variables showed interannual variability, only a few varied the same way across all six rivers. Chlorophyll *a* scores tended to degrade from 2007 to 2012 for all rivers. In contrast, index scores for crab host response and fish macrophage aggregates had notable interannual variability for all rivers that did not follow a sustained chronologic trend. Macrophage aggregate scores were particularly variable in the last three years of the study, making it the only factor that had considerably more variation between years than between rivers. For macrophage aggregates, most systems had elevated levels in 2010, and very low levels in 2011. However, systems with greater white perch abundance tended to have lower index scores than those with smaller perch populations. In addition to abundance, elevated macrophage aggregates also correlated with elevated indicator bacteria and higher turbidity in the water, and higher air temperature.

Several management implications can be drawn from this study. Primary among them is the need for managers to persist in current efforts to reduce non-point introduction of nitrogen, phosphorus and sediments to Chesapeake Bay tributaries. This particularly applies to the urbanized Magothy River and the heavily forested Nanjemoy where suspended sediments contribute to water quality issues. Another management implication is the need to preserve habitat to support diverse and healthy fish populations, particularly in spawning areas of the Bay. Our findings suggest that abundances and health of fish may involve trade-offs, with highly eutrophied systems supporting moderate to large numbers of fish, but in poorer health. A third implication is that there remains a need to better assess the impact of crab health on population sizes for setting appropriate harvest limits.

## Study Conclusions

- All rivers showed some signs of stress with the Rhode River being least impacted overall.
- The strongest signals in this study were detected for excessive nutrients and phytoplankton in watersheds with predominant agricultural uses.
- The strongest organismal indicator was for lower fish disease prevalence in the heavily forested Nanjemoy watershed
- Urban rivers had good water clarity and healthy fish, but excess nutrients and low dissolved oxygen were observed in bottom waters in the relatively deep Magothy River.
- No strong chronological trends were detected but there were some weak correlations between air temperatures and both fish abundance and the intensity of macrophage aggregates in fish tissues.
- Fish health was inversely related to nutrients, phytoplankton, and fish abundance.
- Crab health results were mixed with heaviest parasite incidence in low development areas and lowest host response incidence in high development areas.
- Rivers in different salinity zones seem to behave differently for a number of variables, especially for submerged aquatic vegetation and fish abundance.

# Thank You to Our Partners

**Organizations**

The Cooperative Oxford Laboratory is indebted to:

NOAA Chesapeake Bay Office
Maryland Department of Natural Resources
Maryland Department of Agriculture
University of Maryland

**Individuals**

The following individuals provided integral support for this endeavor:

Ana Baya, Bob Bingaman, Sarah Bornhoeft, Juli Brush, Rebecca Burton, Captian Skip Collier, Jimmy Councilman, Blair DeLean, Steve Early, AJ Fry, Dorothy Howard, Lois Lane, Jay Lewis, Rudy Lukacovic, Meg Maddox, Laura Marson, Margaret McGinty, Maggie Miller, Jen O'Keefe, Chris Ottinger, Matt Rhodes, Laura Robertson, Kristi Shaw, Suzanne Skelley, Cindy Stine, Crystal Thomas, Sue Tyler, Jim Uphoff, Bob Wood.

The following individuals also lent an invaluable helping hand:

Pam Baker, David Bruce, Ron Cheezum, Tracy Gill, Steve Giordano, Mejs Hasan, LeeAnn Hutchison, Hannah Martin, Ed Martino, Mark Matsche, Bart Merrick, Kevin Rosemary, Howard Townsend, and Butch Webb.

**Image P1:** Rain did not deter field sampling.

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