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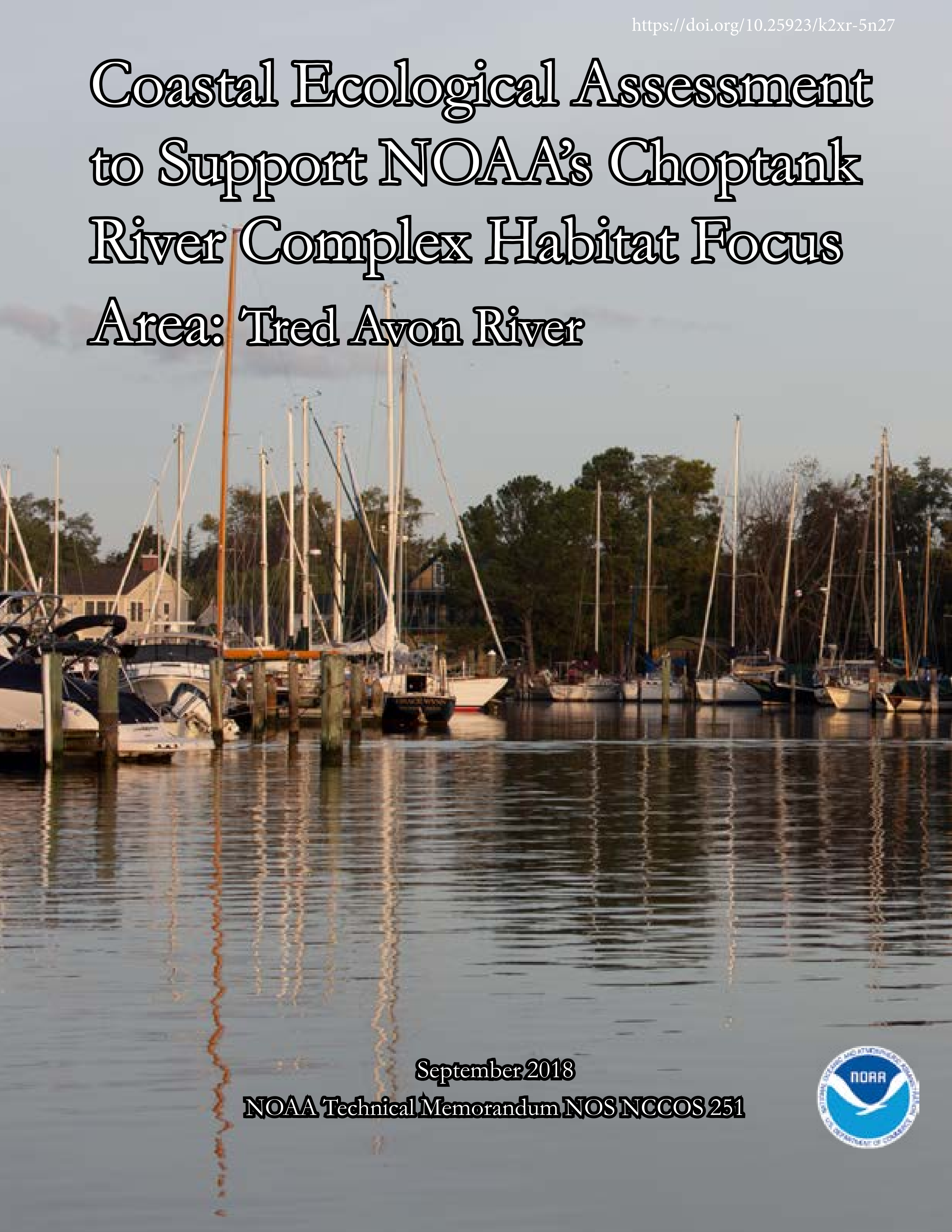
Coastal Ecological Assessment to Support NOAA's Choptank River Complex Habitat Focus Area: Tred Avon River



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NOAA Technical Memorandum NOS NCCOS 251

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Coastal Ecological Assessment to Support NOAA's Choptank River Complex Habitat Focus Area: Tred Avon River

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United States Department of Commerce	National Oceanic and Atmospheric Administration	National Ocean Service
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FOREWARD

The Chesapeake Bay and its watershed are national treasures with ecologic, economic, social, recreational, cultural, and historical value. Changes in land and resource use, such as shifts in marine resource harvest and the conversion of land from forest to agriculture or from agriculture to urban, in the Bay watershed, and other coastal ecosystems, can affect their ability to function properly and to provide valuable ecosystem services.

In 2014, NOAA designated the Choptank River Complex, an economically and ecologically important component of the Chesapeake Bay ecosystem, as one of its Habitat Focus Areas (HFA). Thus, NOAA has focused resources on this watershed around these objectives: habitat restoration and protection; integrating science to inform ecosystem–based management; and, community engagement.

In support of these objectives, NOAA's National Centers for Coastal Ocean Science (NCCOS) and its Federal, State, and local partners conducted an ecological assessment in the Tred Avon River, a main tributary of the Choptank River. The NCCOS Cooperative Oxford Lab is located in Oxford, MD and led the overall assessment. Coastal ecological assessments can provide insights into the trade-offs between land development and aquatic ecosystem condition by analyzing indicators of ecosystem condition and their relationships to human activities within the surrounding waters.

In the analysis of information collected during the study, similarities between the conditions found and potential influencing factors such as land-use were explored. Results show the Tred Avon River ecosystem is in good condition relative to the larger Choptank River and the Chesapeake Bay. Nevertheless, there are clear signs of ecosystem degradation especially in areas affected by rapid growth and development. Several Chesapeake Bay–wide issues were detected in the Tred Avon tributary, such as excess nutrients, high chlorophyll a concentrations, seasonally decreased oxygen levels in bottom waters, and poor water clarity. These signs of degradation were particularly evident at sampling stations near the most urban areas. Encouragingly, model simulations revealed that oyster aquaculture and reef restoration are promising and valuable nutrient removal mechanisms, which may help to ameliorate some of the detected negative impacts to support sustainable use of natural resources.

NCCOS previously developed companion products to the Choptank River Complex HFA: 1) a digital atlas to make accessible a variety of datasets collected over decades in the Choptank watershed, 2) a baseline status report to provide an introduction to the available datasets, and 3) an ArcGIS (ESRI™) geodatabase (https://coastalscience.noaa.gov/project/ecological-assessment-choptank-complex-habitat-focus-area/).

Restoring and sustaining good coastal ecosystem conditions are essential to both the national economy and our quality of life. In order to accomplish these goals, it is important to understand and anticipate changes in the function of coastal ecosystems and in the delivery of their goods and services. By using NCCOS scientific information and tools, we anticipate that managers will be better equipped to balance the impacts of ecosystem stressors with social and economic goals.

Sincerely,

Mark Monaco, Ph.D.
Chief, Marine Spatial Ecology Division
National Centers for Coastal Ocean Science
https://coastalscience.noaa.gov/

EXECUTIVE SUMMARY

Image D1 (Disclaimer page): Great blue heron perched on an osprey nest in the Tred Avon River.
Image TC1 (Table of Contents page): Animal tracks on the shore of the Tred Avon River.
Image ES1 (above): The Chesapeake Bay William Preston Lane, Jr. Memorial Bridge. Image courtesy of Ben Longstaff. Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/).

The Chesapeake Bay is the largest estuary in the United States with a total of 18,804 kilometers (11,684 miles) of shoreline along the main stem and its tributaries (CBP 2018a). The ecology of the Chesapeake Bay and its watershed are national treasures and provide environmental, economic, social, cultural, recreational, and historical value. The condition of the Chesapeake Bay, however, has degraded over time due to ever increasing pressures of population growth and land development. The conversion of forests and wetlands into agricultural and urban lands and the loss of underwater vegetation has contributed to increased sediment loading and nutrient pollution and to shifts in marine resource harvests and other important ecosystem services. Degradation of the structure and function of the Chesapeake Bay aquatic ecosystem from human actions reduces the Bay's resiliency. The watershed's citizens, county planners, and state managers face major challenges in their efforts to balance land use planning decisions and conservation priorities.

In 2014, the Choptank River complex was designated a NOAA Habitat Focus Area (HFA) to serve as a catalyst for the integration of conservation activities related to habitat restoration, science and monitoring, and community engagement in this key watershed of the Chesapeake Bay. The Choptank River complex provides food and critical habitat such as wetlands, oyster reefs, and freshwater streams for many Chesapeake Bay species including commercially important striped bass, blue crabs, and oysters. It supplies valuable seafood and supports agriculture as well as recreational fishing, boating, hunting, and other activities. Continued human population growth and land development has put pressure on the watershed and threatens key habitats for fish and aquatic resources. The location of historic oyster beds in the Choptank watershed led to their designation as protected oyster sanctuaries and the target of reef restoration activities by state and federal partners.

In this assessment, we analyzed the impacts of land use on the condition of the aquatic ecosystem in the Tred Avon River, an important tributary of the Choptank River, over the period 2015–2017. The Tred Avon River is a good example of a watershed where multiple types of land use are competing for space and where urbanization is slowly replacing farm fields and forests. This watershed is representative of different land uses, with relatively high development at the headwaters near Easton and at the mouth near the Town of Oxford, as well as agriculture and undeveloped land along the shorelines extending between.

Results from our earlier ecological assessments, in which comparisons were made among river systems dominated by a particular land use (agriculture, urban, mixed forest), indicate the signals from land use impacts are stronger upstream than downstream (Leight et al. 2014, 2015). Thus, our approach to the Tred Avon River ecological assessment was targeted to tidal waters in eight selected sub-watersheds representing different dominant land uses.

The condition of each of the eight selected sub-watersheds in the Tred Avon River was assessed using a suite of indicators including water quality, benthic habitat condition, benthic community condition, fish community composition, contaminants, and fish health. In our analysis of information collected, we looked for similarities between the conditions found and potential influencing factors such as land use.

Overall, our study shows that the Tred Avon River is a tributary in relatively good condition compared to other areas of the Choptank River and the larger Chesapeake Bay. Similarly, the 2017 ShoreRivers Chesapeake Bay report card for the Tred Avon River, based primarily on samples collected in the main stem of the river, is also positive (ShoreRivers 2018). Nevertheless, there are signs of ecosystem degradation in areas affected by rapid growth and development in the region and thus efforts to protect and conserve critical fish habitat and spawning areas must remain a priority.

Results show that each of the eight selected sub-watersheds of the Tred Avon River showed some signs of stress and indeed several Chesapeake Bay-wide issues were clearly detected, including excess nutrients, high chlorophyll *a* concentrations, seasonally decreased oxygen levels in bottom waters, and poor water clarity.

Signs of degradation were particularly evident in the sub-watershed nearest Easton (TA1), the most highly developed location in the assessment, which was impacted by multiple stressors – low dissolved oxygen in bottom waters, the presence of chemical contaminants above low-level NOAA thresholds, high levels of nutrients, high chlorophyll *a* concentrations, high fecal bacterial counts, and poor water clarity.

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.

The fish health assessment index and benthic index of biotic integrity indicators detected significant differences among tributaries within the Tred Avon River, underscoring the utility of these indices and the importance of within–river sampling resolution.

In a separate but related study included in this report, we conducted modelling studies to quantify oyster ecosystem services of nutrient removal through filtration by oysters at restored reefs and aquaculture sites in the Tred Avon River and other locations in the Choptank watershed. Encouragingly, we discovered that oyster related nutrient removal ecosystem services can contribute in a positive way to nutrient management in the Tred Avon and Choptank Rivers as oyster tissue has recently been approved as a nutrient Best Management Practice (BMP) in the Chesapeake Bay.

Analysis of the indicators of ecosystem condition in the Tred Avon River and their relationship to human activities provides insights into the trade-offs between development on land and the condition of the aquatic ecosystem. This information is critical to striking a balance between supporting the needs of increasing population growth and protecting vital ecosystem services that have benefited generations of communities residing locally or in the larger Chesapeake Bay watershed.

Image ES3. A skipjack under sail on the Choptank River. The skipjack is a traditional fishing boat used on the Chesapeake Bay for oyster dredging.

INTRODUCTION

Figure IN1. The Choptank River watershed (yellow border) is located within the Chesapeake Bay watershed (black border) on the mid-Atlantic coast of the United States. (Source: Esri, Digital Globe, GeoEye Earthstar Graphics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN and the GIS User Community.)

The Chesapeake Bay and its watershed have historically supported vibrant industries including fishing, shipping, agriculture, recreation, tourism, and real estate. Over 570 million pounds (258,547,651 kilos) of seafood are produced annually in the estuary including economically and ecologically important species such as oysters, blue crab, scallops, striped bass, and menhaden (NRCS 2018). Nearly 30 percent of the watershed is agricultural land with corn, soybeans, wheat, hay, pasture, fruits, vegetables, dairy products, and poultry as important products (NRCS 2018). In 2013, the estimated value of the Chesapeake Bay watershed for selected ecosystem services (food production, climate stability, air pollution treatment, water supply, water regulation, waste treatment, aesthetics, and recreation) was $107 billion per year (Phillips & McGee 2016; CRS 2018).

Like many of the nation's coastal estuaries, the negative impacts associated with deforestation, urbanization, shoreline hardening, and agriculture have been significant agents of change in the Chesapeake Bay. The 18 million people that live and work in the Chesapeake Bay watershed affect the health of the nation's largest estuary through their daily activities. Land use changes, increased sediment loads and nutrient pollution, overfishing and overharvesting, and increased contaminants entering the Bay watershed have degraded water quality, critical fisheries habitat, and valuable ecosystem services. Human land use activities can be expected to increase in the Chesapeake Bay watershed with a projected population of 21 million people by 2040 (CBP 2018).

Human land use activities can have wide-ranging impacts on coastal water quality. Agriculture, development, and industry can negatively impact aquatic ecosystems by releasing four broad classes of pollutants including nutrients, sediments, chemical contaminants, and pathogenic bacteria. Deforestation, agriculture, and impervious surfaces increase runoff from land and erosion, transporting sediment into the water as well as nutrients along the way. High nutrient amounts result in excessive algae and low oxygen levels (hypoxia) which harm aquatic organisms. Pesticides and other chemical contaminants entering the water are toxic to aquatic life and degrade critical habitats. In addition, physical stressors such as the armoring of shorelines to protect waterfront properties from erosion and storm surge reduce the abundance and diversity of aquatic life (Currin et al. 2015; Kornis et al. 2017; Crum et al. 2018; Prosser et al. 2018).

In 2014, the Chesapeake Bay watershed-wide agreement strengthened decades of conservation efforts by implementing key restoration programs to reduce nutrient and sediment loads since many parts of the Chesapeake Bay contain excess nitrogen, phosphorous and sediment, and are listed as impaired under the Clean Water Act. The Chesapeake Bay Total Maximum Daily Load (TMDL), or "pollution diet" underpins Watershed Implementation Plans (WIPs) developed to reduce nutrient and sediment loads in each of the watershed states and District of Columbia. These plans set pollution reduction targets for sources like agricultural runoff, storm water runoff, and wastewater by the year 2025 so that water quality goals can be met. Recent improvements in water clarity and submerged aquatic vegetation (e.g. Lefcheck et al. 2018) show that progress is being made, however, the ecological condition of the Chesapeake Bay and its watershed remains impaired (CBF 2016; CRC, UMCES 2018).

In order to continue to improve the condition of the Chesapeake Bay watershed in spite of the ever-increasing pressures of population growth, precise information on the effects of land use change in the watershed will be critical for quantifying and predicting the impacts on water quality, aquatic life, and ecosystem condition. Residents, planners, and managers can make informed decisions when equipped with the knowledge needed to balance land use planning decisions and conservation priorities.

In this study, we assessed the ecological condition of the Tred Avon River in the Choptank River Complex watershed, a NOAA Habitat Focus Area. We assessed the relative impacts of land use on the condition of the aquatic ecosystem in the Tred Avon River in a three–year field study (2015–2017) using a suite of observations focused on water quality, benthic condition, and the health of aquatic organisms. By analyzing these indicators of ecosystem condition and their relationship to human activities within the surrounding watershed, this assessment provides insights into the impact of land development on aquatic ecosystems.

In our previous ecological assessments of river systems in Chesapeake Bay with varying land uses (Leight et al. 2014, 2015), we detected differences based on the level of urban development, particularly in bottom habitat condition and in fish health for mesohaline rivers. However, differences observed in nutrients, contaminants, and dissolved oxygen levels within the watersheds of the river systems suggested that a finer scale assessment might help to reveal the effects of various stressors on conditions within the sub-watersheds of a river system. Consequently, the focus of this ecological assessment is on sub-watersheds dominated by different land uses within the Tred Avon River.

A better understanding of the impacts of stress on the condition of sub-watersheds of river systems in the Chesapeake Bay will help to shed light on the stressors and impacts effecting a single river system as well as the larger Chesapeake Bay watershed. For example, if the impacts of impervious surfaces effect fisheries and benthic communities at a smaller spatial scale than previously realized, then this new knowledge would aid in the ability to effectively implement management actions.

This document is divided into chapters and subchapters. The chapters address the indicators mentioned previously and the subchapters address variables within each of these categories.

Throughout the document there are pop-out boxes that provide instructive and descriptive detail about environmental subjects or historical background.

Figures, graphs, schematics, or maps are included as illustrations to further understanding. Letters used to identify the figure legends refer to the section in which a legend is located (e.g. IN = Introduction; WS = Watershed; DG = Data Guide; WQ = Water Quality; BH = Benthic Habitat Condition; BC = Benthic Community Condition; CF = Contaminants in Fish Tissue; FC = Fish Community Composition; FH = Fish Health Assessment; SY = Synthesis; PA = Partners). Legends included in pop-out boxes are further labeled with "PB" e.g. INPB. The error bars shown on graphs represent 95 percent confidence limits based on the standard error of the mean.

Photographs are cited only when an image was neither obtained from nor associated with NOAA.
All data collected during this study will be stored in the National Centers for Environmental Information Repository (https://www.ncei.noaa.gov/).

Ecosystem Condition

An ecosystem considered to be in good condition (e.g. unimpacted) is an ecosystem with its various components (biological, physical and chemical) operating effectively to maintain a functioning system within the limits of natural variability to support a diverse and productive system (Fig. INPB1). It allows for multiple uses and should also be resilient to some level of stress (Rapport et al. 1998). Nutrient runoff and aquatic algal growth are relatively low, dissolved oxygen is high, and light penetrates far into the water column. Pathogen and contaminant levels are low and aquatic organisms are abundant, diverse, and healthy.

On the contrary, an estuary regarded to be in poor condition (e.g. impacted) is out of balance and unsustainable. Nutrient runoff is high, leading to algal blooms and low dissolved oxygen in bottom waters. Suspended sediment and algal growth block light from reaching the bottom. Pathogen and contaminant levels are high and aquatic organisms are depleted and unhealthy.

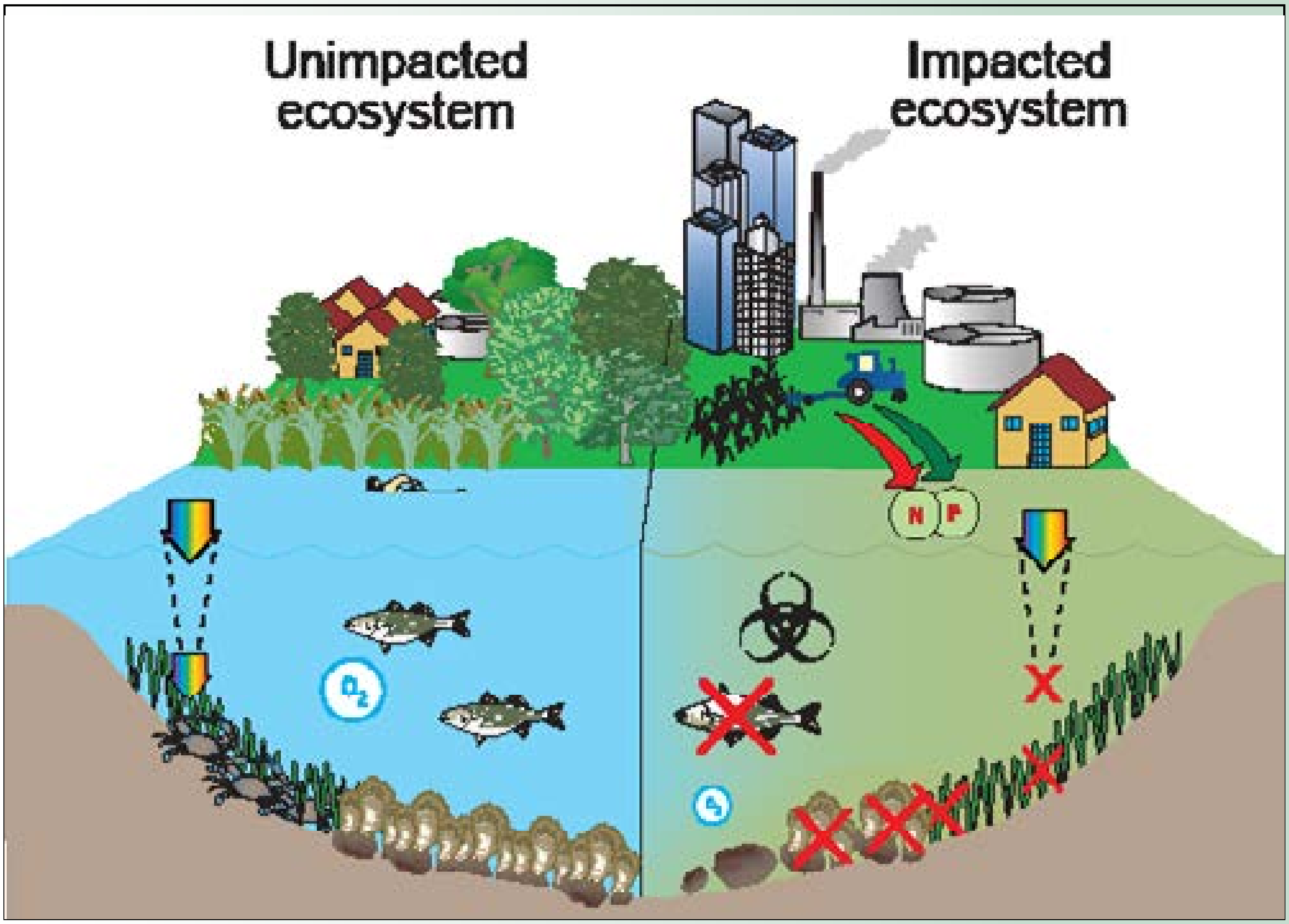


Figure INPB1. Conceptual diagram of land use and ecosystem services.

WATERSHED OVERVIEW

Choptank River Complex

The Choptank River complex, which includes the Choptank and Little Choptank Rivers, is located on the Eastern Shore of Maryland, east of the Chesapeake Bay mainstem (Fig. IN1). The Choptank River, with headwaters in Delaware, is the longest river on the Delmarva Peninsula. The name 'Choptank' is thought to originate from the Nanticoke Indian's word tshapetank meaning "a stream that separates" or "place of big current." This area is a treasured part of the Chesapeake Bay ecosystem, representing critical habitat for spawning striped bass (*Morone saxatilis*) and river herring, as well as historically abundant oyster reefs. Residents of the watershed—including many families who have lived there for multiple generations—have traditionally been employed in agriculture or commercial fishing. Today agriculture continues to be the predominant land use (58 percent) with the remainder being forested (29 percent) and developed (5 percent) (Dorfman et al. 2016).

The Choptank watershed serves as a microcosm of the larger Chesapeake Bay, and as such, was selected as a NOAA Habitat Focus Area (HFA) in 2014 to serve as a catalyst for the integration of conservation activities related to habitat restoration, science and monitoring, and community engagement. Choptank HFA presents an opportunity to focus habitat protection and restoration efforts on a representative piece of the larger landscape. The Choptank River provides food and critical habitat such as wetlands, oyster reefs, and freshwater streams for many Bay species including commercially important striped bass (*M. saxatilis*), blue crabs (*Callinectes sapidus*), and oysters (*Crassostrea virginica*). It supplies valuable seafood and supports agriculture as well as recreational fishing, boating, hunting, and other activities.

Similar to the wider Chesapeake Bay, human population growth and land development has put pressure on the Choptank River watershed, threatening key habitats for fish and aquatic resources. For example, nearly 50,000 acres of wetlands have been lost from the watershed. Large–scale restoration efforts in the watershed are focused on historic oyster beds located in protected oyster sanctuaries where they are the target of reef restoration activities by State and Federal partners.

Choptank River Complex Habitat Focus Area

In 2014, the Choptank River complex was designated by NOAA as one of ten habitat focus areas (HFA) in the United States. The HFA's provide an opportunity to concentrate meaningful investments in places of national significance and at spatial scales that increase the ability to achieve ecosystem objectives and translating services provided by healthy ecosystems for the benefit of local communities. Objectives for Choptank HFA are habitat restoration and protection, integrating science to inform management, and community engagement. The Chesapeake Bay Watershed Agreement, signed by Chesapeake Bay Program partners in 2014, set restoring oysters (*Crassostrea virginica*) in 10 Bay tributaries by 2025 as a major goal. Work in the Choptank HFA is accomplishing restoration of three tributaries toward this goal: Tred Avon and Little Choptank rivers and Harris Creek.

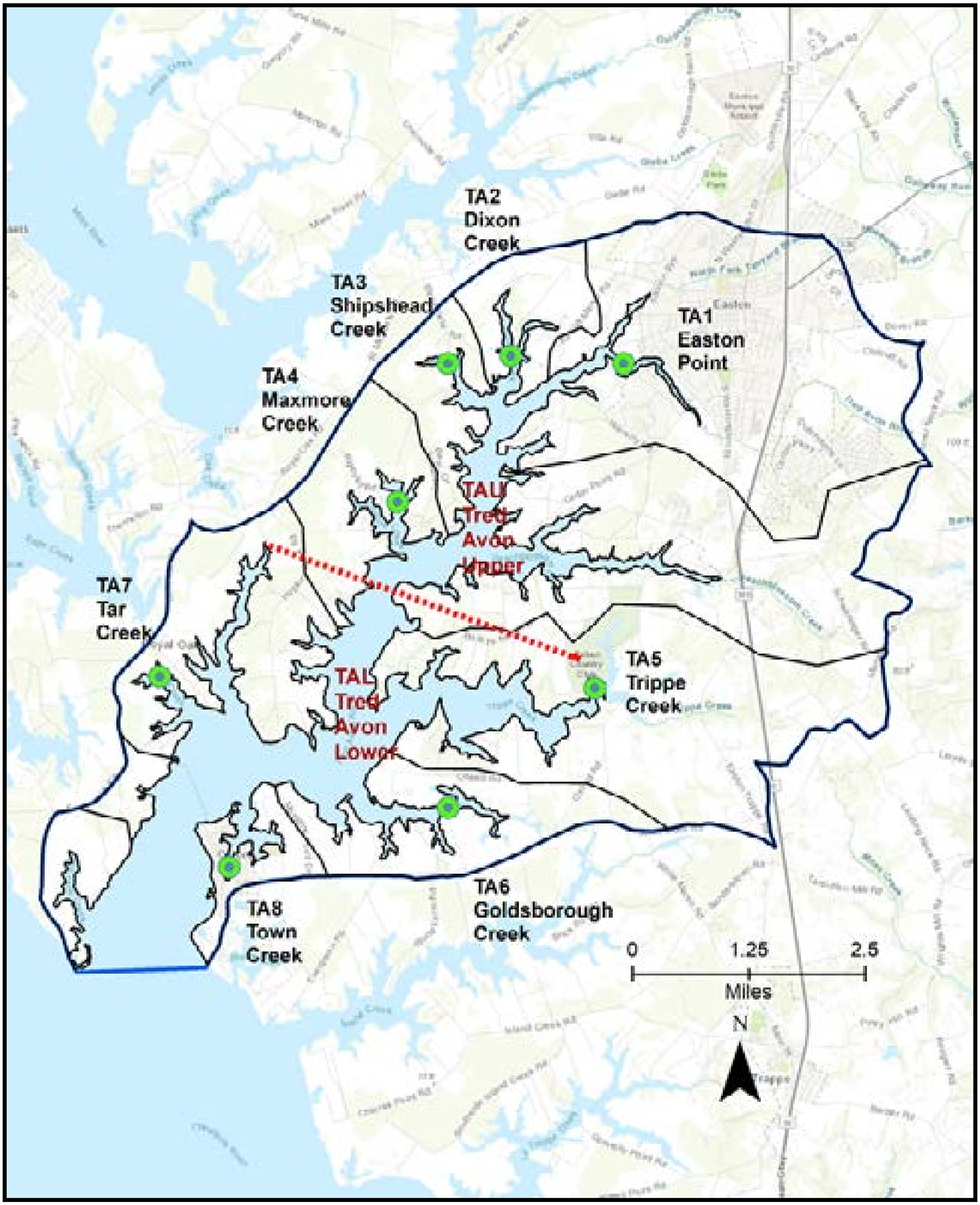


Figure WS1. Map of the Tred Avon River and its watershed showing the locations of eight sub-watershed sampling stations (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). The red dotted line separates the lower Tred Avon River (TAL) from the upper Tred Avon River (TAU). Sources: Esr, HERE, Garmin Intermap, increment P Corp GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey Ersi Japan, METI, Esri China (Hong Kong), swiss topo, ©OpenStreetMap contributors, and the GIS User Community.

Image WS1. View of Tred Avon River opposite the Town of Oxford, Maryland.

TRED AVON RIVER

We conducted our ecological assessment of the Tred Avon River, an important tributary of the Choptank River, over the period 2015–2017. This watershed is representative of different land uses, with relatively high development at the headwaters near Easton and at the mouth near the Town of Oxford, as well as agriculture and undeveloped land along the shorelines extending inbetween. The Tred Avon River is a good example of a watershed where multiple types of land use are competing for space and where urbanization is slowly replacing farm fields and forests. The Tred Avon River is also the target of oyster reef restoration programs.

The Tred Avon River is a large tributary of the Choptank River located in Talbot County on the Eastern Shore of Maryland (Fig. WS1). Two streams, one to the north, the other to the south form the headwaters of the Tred Avon. Headwaters flow west through or around Easton for roughly 10 kilometers (5.0 miles) and converge at Easton Point where the river widens and flows southwest about 19.3 kilometers (12 miles) to the mouth just south of the town of Oxford at Benoni Point.

The Tred Avon River watershed has a land area of 126.91 square kilometers and an open water area of almost 31 square kilometers. The amount of hardened shoreline in the Tred Avon River is estimated to be approximately 34–37 percent which includes riprap, bulkheads, groin fields and marinas (Dorfman et al. 2016). Agriculture is the predominant land cover at nearly 60 square kilometers in the watershed and corn, soybeans, wheat, and poultry are important products in the region. Eighteen percent of the watershed is developed land (Dorfman et al. 2016) with population centers located in the towns of Easton and Oxford. The amount of impervious surface coverage is approximately 9 percent of the land area. The remaining area includes tracts of mixed forest along the Tred Avon watershed.

Eight sub-watersheds of the Tred Avon with differences in the dominant type of land use (urban, agriculture, mixed forest) were selected for our field studies (Fig. WS1). The drainage area associated with these sub-watersheds was determined by using stream and ditch maps presented in the National Hydrography Dataset (NHD; USGS 2018). The sub-watersheds were located in the mesohaline zone of the river where salinity can range from 3 to 15 parts per thousand. The sampling stations for water quality, contaminants, and fish community composition indicators were selected randomly in tidal waters of each of the eight sub-watersheds (Fig. WS1).

COOPERATIVE OXFORD LABORATORY

The Tred Avon ecological assessment provided an opportunity for Cooperative Oxford Laboratory (COL) to continue to provide scientific information to the local community. The Town of Oxford has previously sought technical guidance from COL concerning nuisance flooding and an upgrade to the wastewater treatment plant, and was the site of a previous NOAA-funded climate vulnerability assessment (Fleming et al. 2017).

Image WSPB1. The campus of the Cooperative Oxford Laboratory (COL) is located on the Tred Avon River and houses NOAA National Centers for Coastal Ocean Science, NOAA Chesapeake Bay Office, Maryland Department of Natural Resources, and U.S. Coast Guard Station Oxford in Oxford, Maryland. The large L-shaped dock extends from the COL campus which is located in the center of the image.

Table WS1. Key attributes of watersheds assessed in eight selected sub-watersheds of Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek.)

WATERSHED FACTS						
Location	Area (acres)	Impervious Surface (%)	Septics[a] #	Docks[b] #	Marinas[b] #	Armored Shoreline[c] %
TA1	5889	23	411	52	2	23
TA2	924	4	39	30	0	22
TA3	890	3	56	19	0	27
TA4	1411	3	61	27	0	43
TA5	4728	4	325	82	0	28
TA6	1694	3	60	16	0	13
TA7	2264	4	103	26	0	28
TA8	568	18	8	57	11	62

([a]Maryland Department of Planning 2018; [b]Google Earth (viewed 5/17/2018); dock count does not include docks that are part of a marina; [c]Berman et al. 2005)

Easton Point – Tred Avon Station 1 (TA1)

Image WS2. Aerial view of Easton Point – Tred Avon Station 1 (TA1) showing confluence of two streams forming upper Tred Avon River, Tanyard Branch (left) and Papermill Branch (right).

Easton Point (TA1) is at the head of the Tred Avon River (Image WS1) and is formed by the confluence of two streams, Tanyard Branch and Papermill Branch (Image WS2). Easton Point is surrounded by land consisting of the highest impervious surface (~23 percent) and second highest level of development (35 percent) in the Tred Avon watershed (Table WS1). A working waterfront lines the point, with two marinas, 52 private docks, several businesses, and an industrial complex (Table WS1). A former golf course, which closed in 2016, is also located adjacent to this area, although the property has not been maintained in recent years. Although many of the properties in this sub-watershed are connected to a wastewater treatment plant which does not discharge to the Tred Avon River, there are still more than 400 private septic systems. Today the population of the town of Easton is close to 18,000, more than a four–fold increase since 1912 (~4,000 population) and more than twice the population in 1988 (~8,000).

HISTORIC EASTON POINT[a]

Originally called Talbot Courthouse, the town of Easton was founded in 1778. Easton Point, known variously as Cow Landing, Cowe Landing, Booker Landing and Town Point, was established in the 1790s. Tidal flushing at the point between the two branches of the river carved a deep-water landing. Interior agricultural areas were accessible to small-to-medium vessels via the branches which offloaded to larger ships at the landing, serving as Easton's transportation hub and linking the area with larger cities on Chesapeake Bay. Development of the town and conversion of woodlands to fields caused inevitable filling of the branches on either side of Easton Point. By the late 19th century, continual dredging was required to provide the deep channel and turning basin required by large vessels. Tobacco was the primary trade in the 17th and 18th centuries but was later replaced by corn and wheat. Grain, lumber, fertilizer, and coal became mainstay businesses of the 19th and 20th centuries. Sailing schooners shipped bulk commodities while steamboats transported passengers and perishables. Steamboats plied the waters of Tred Avon River between 1816 and 1932, increasing Easton's export potential. Easton Point eventually became the major steamboat center on the Eastern Shore of Maryland with the last steamboat landing there in 1932. The image (WSPB1) below shows the Potomac and Calvert steamers racing after leaving the Baltimore Harbor (photograh byA. Aubrey Bodine – Copyright © Jennifer B. Bodine – Courtesy of AAubreyBodine.com).The Calvert made landings on the Choptank and Tred Avon Rivers.

Extensive lumber and coal yard operations continued at Easton Point after the Civil War and into the early twentieth century. Canning technology improved to the point of commercial viability and one of the first packing houses on the Eastern Shore was established at Easton Point Landing in 1848. Packing house capability led to commercial peach and oyster operations and many farm acres were converted to peach orchards. In the late 19th century the Baltimore, Chesapeake and Atlantic Railway Company docked streamliners at Easton Point. The last freight train to travel between Oxford and Easton was in 1957. Oysters were always important to local infrastructure and were used for roads, infill, and fertilizer. Petroleum, fertilizers, and imported road materials were the dominant port commodities in the 20th century with 5 oil companies located at the landing in 1955. Today oil companies, marinas, a seafood company, an environmental electronics company, and a stone distributor remain. A revitilization plan is being considered to connect the Town of Easton to the landing, the town's only waterfront property.

[a]Footner 1979; Preston and Harrington 1983; TCHPC 2015

Dixon Creek – Tred Avon Station 2 (TA2)

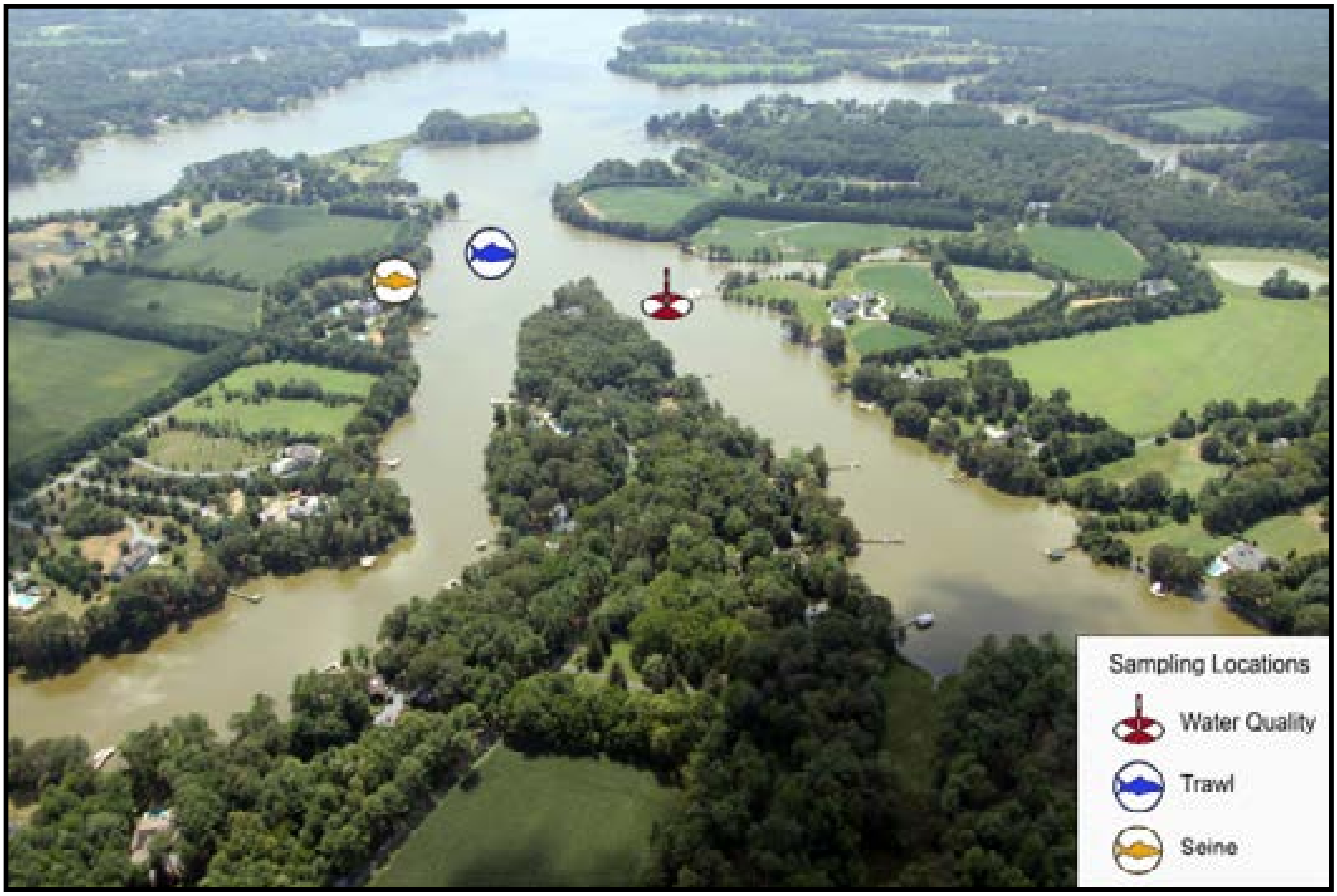


Image WS3. Aerial view of Dixon Creek – Tred Avon Station 2 (TA2).

Land use around Dixon Creek includes the highest percentage of crop land (57 percent) of the eight selected sub-watersheds of the Tred Avon River. There is little impervious surface but there are about 28 houses in the watershed, each with a private dock. There is a small industrial site at the head of Dixon Creek (Table WS1). The shoreline is primarily natural, although there are areas of riprap and a few bulkheads that make up less than 25 percent of the shoreline (Table WS1). Dixon Creek also has the highest percentage of wetlands (6 percent) of the eight selected sub-watersheds of the Tred Avon River.

Shipshead Creek – Tred Avon Station 3 (TA3)

Image WS4. Aerial view of Shipshead Creek – Tred Avon Station 3 (TA3).

Shipshead Creek is surrounded by a mixture of forested and crop land. It shares a mouth with Dixon Creek, but has about twice as much forested land (32 percent; Fig. WS2). There are approximately 20 houses spread out across the watershed, with 19 private docks extending over the water (Table WS1). Areas of riprap and bulkhead occur in this watershed, primarily along the northern shoreline.

Maxmore Creek – Tred Avon Station 4 (TA4)

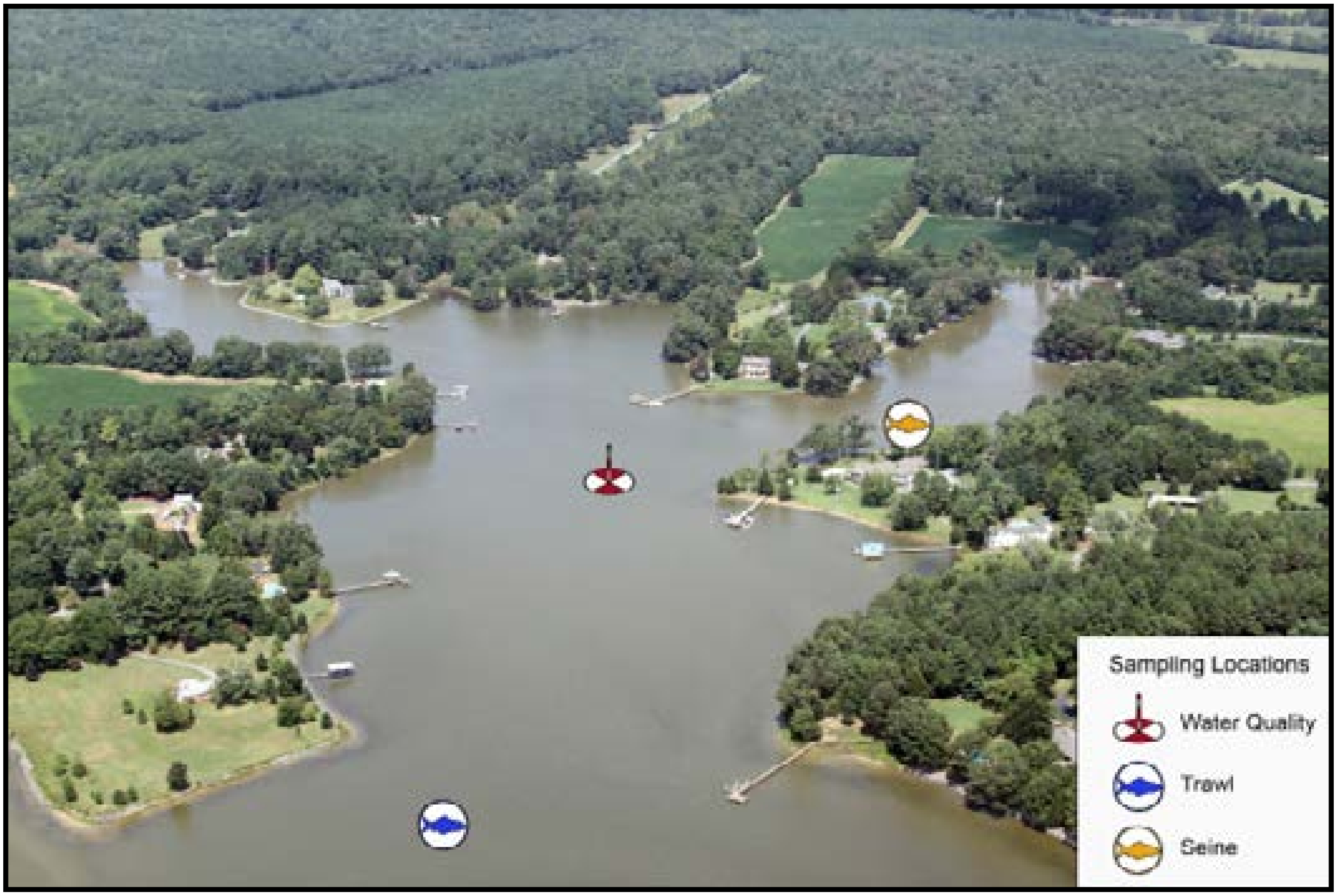


Image WS5. Aerial view of Maxmore Creek – Tred Avon Station 4 (TA4).

The watershed surrounding Maxmore Creek has the highest amount of forested land (48 percent) of the eight sub-watersheds assessed in the Tred Avon River (Fig. WS2). However, the crop land in this watershed is located close to the water, primarily along the southern shore. There is relatively little developed land or impervious surface in this watershed. Maxmore Creek has 27 private homes along its shoreline, each with a private dock (Table WS1).

Trippe Creek – Tred Avon Station 5 (TA5)

Image WS6. Aerial view of Trippe Creek – Tred Avon Station 5 (TA5).

Land use around Trippe Creek is a mixture of crop pasture and forest (Fig. WS2). A golf course also sits along the headwaters of this creek. The shoreline north of the sampling locations is primarily natural and drains crop land and residential areas. However, the shoreline towards the mouth of the Trippe Creek is heavily armored. There are 82 private docks along Trippe Creek (Table WS1).

Goldsborough Creek – Tred Avon Station 6 (TA6)

Image WS7. Aerial view of Goldsborough Creek – Tred Avon Station 6 (TA6).

The first principal sub-watershed upstream of the mouth of the Tred Avon River on the east side is Goldsborough Creek (Fig. WS1), a deep, narrow inlet lined with indentations and sub-creeks. Goldsborough Creek is approximately 2.7 kilometers (1.7 miles) long and has five branches. The second highest percentage (56) of crop land for the eight selected sub-watersheds in Tred Avon River surrounds Goldsborough Creek, and much of the land adjacent to the water is agricultural (Fig. WS2). There are approximately 28 houses spread throughout the watershed with 16 private docks extending into the creek (Table WS1). Almost all of the shoreline along the northern shore is natural. A few sections of hardened shoreline are present on the southern shore and in the two feeder streams.

Tar Creek – Tred Avon Station 7 (TA7)

Image WS8. Aerial view of Tar Creek (TA7).

Tar Creek is close to the mouth of the Tred Avon River (Fig. WS1) and the composition of land use around Tar Creek most closely resembles that of Shipshead Creek (TA3). Tar Creek is composed of a mixture of crop and forest land and there is very little developed land or impervious surface (Fig. WS2). There are 26 private docks extending into the waters of Tar Creek (Table WS1). Tar Creek demonstrated the highest surface water salinities for the eight stations (Fig. WQPB1); however, it should be noted that average salinities for all stations ranged only from 10.7–12.5 parts per thousand based on seasonal water quality sampling over the period 2015–2017.

Town Creek – Tred Avon Station 8 (TA8)

Image WS9. Aerial view of the Town of Oxford with Town Creek in center of image where Tred Avon Station 8 (TA8) is located.

Town Creek is surrounded by the Town of Oxford to the west and agricultural fields to the east. The watershed contains the highest percentage of developed land (36 percent) in the Tred Avon River watershed, although the percent impervious surface (~18 percent) trails that of Easton Point (TA1) (Table WS1). Fifty-seven docks and 11 marinas (piers with greater than 10 slips) line most of the shoreline, which is hardened by riprap or bulkheading throughout the majority of the creek (Table WS1). The Town of Oxford manages a secondary wastewater treatment facility that releases approximately 125,000 gal/day of effluent (Scott Delude, Public Works Director, personal communication) into the headwaters of Town Creek. A new, more efficient wastewater treatement facility is expected to be completed in 2019. The town's population is nearly 700 today.

HISTORIC OXFORD

Oxford was Talbot County's earliest town, developed in 1694 as a port–of–entry for English merchant ships trading manufactured goods for tobacco from nearby plantations. Oxford was named a port in 1683 likely due to its good harbor surrounded by fertile fields, a protected ship repair area, and access to Chesapeake Bay and beyond. As the first and only port–of–entry on the Eastern Shore of Maryland, the town gained significant prominence in colonial days and flourished for over 75 years. The economy began to wane in the 1700s but revived in the mid-1800s. Boat building prospered in the late 1800's and two steamboat wharves serviced the rail and boat services. The oyster industry also boomed in the late 1800's along with skipjacks and packing houses. In the early 1900s, World War II slowed commerce across the nation and boat building endured as the main successful business operation.

The decline of the oyster industry over the years has diminished the number of watermen, skipjacks, and packing houses throughout Chesapeake Bay although Oxford's harbor continues to support a handful of commercial watermen and hosts seven boatyards. Ongoing oyster restoration efforts in the Tred Avon River and other Bay areas, as well as aquaculture development, are expected to increase oyster populations in the future. Today Oxford maintains its charm and community spirit and serves as a popular destination for tourists and retirees.

Image WSPB1. Aerial view of the Town of Oxford on the Tred Avon River, a tributary of the Choptank River, shows a steamboat near the town dock in 1930 (left; H. Robins Hollyday Photography Collection, courtesy of the Talbot Historical Society, Easton, MD). Town Creek is visible in the center of the image. Much of the farmland and forest in the background remains relatively undeveloped today. In 1947, oysters (*Crassostrea virginica*) harvested from the Choptank River were unloaded at Long Dock in Baltimore Harbor, selling for $3.00 a bushel (right; photograph by A. Aubrey Bodine – Copyright © Jennifer B. Bodine – Courtesy of AAubreyBodine.com). The price of a bushel of oysters today ranges from $45 (wholesale) to $65 (retail) (Judd Vreeland, Chesapeake Bay Waterman, personnel communication).

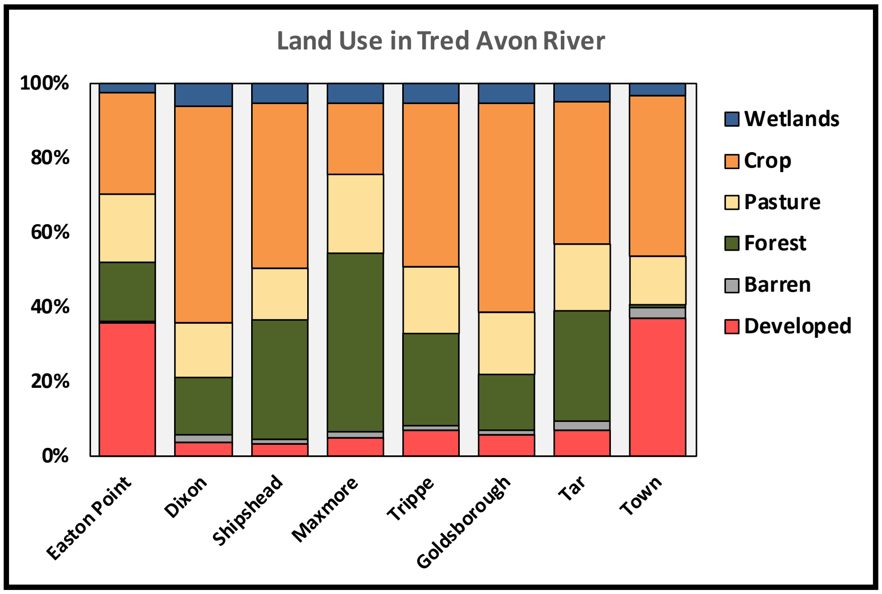


Figure WS2. Percent land use types within sub-watersheds in the Tred Avon River study area. Pasture refers to grasslands, most likely associated with agriculture (Anderson et al. 1975).

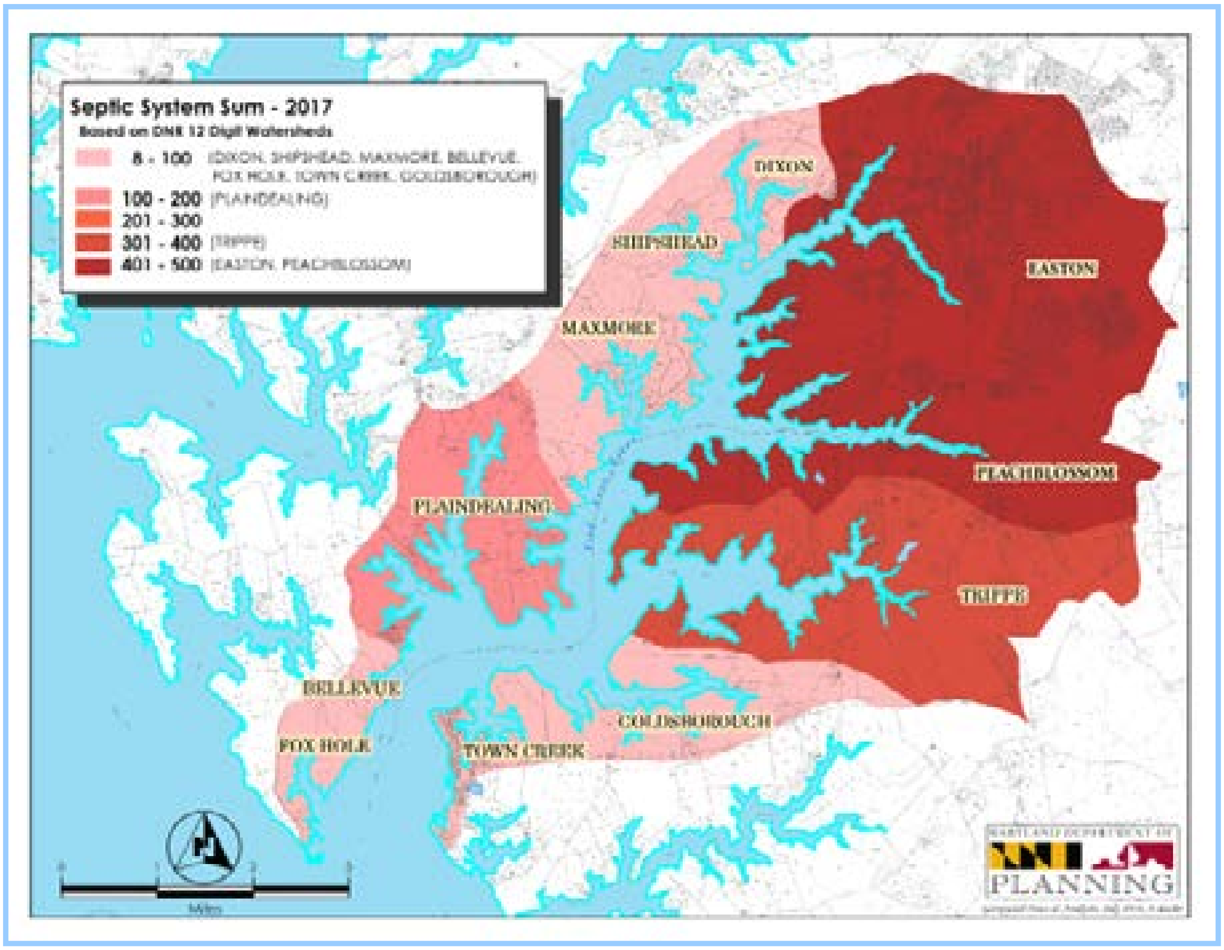


Figure WS3. Number of septic systems located in sub-watersheds of the Tred Avon River area. Map courtesy of Maryland Department of Planning, Geospatial & Data Analysis Division (Data Source: MD Property View, featuring parcel point data records for 2017).

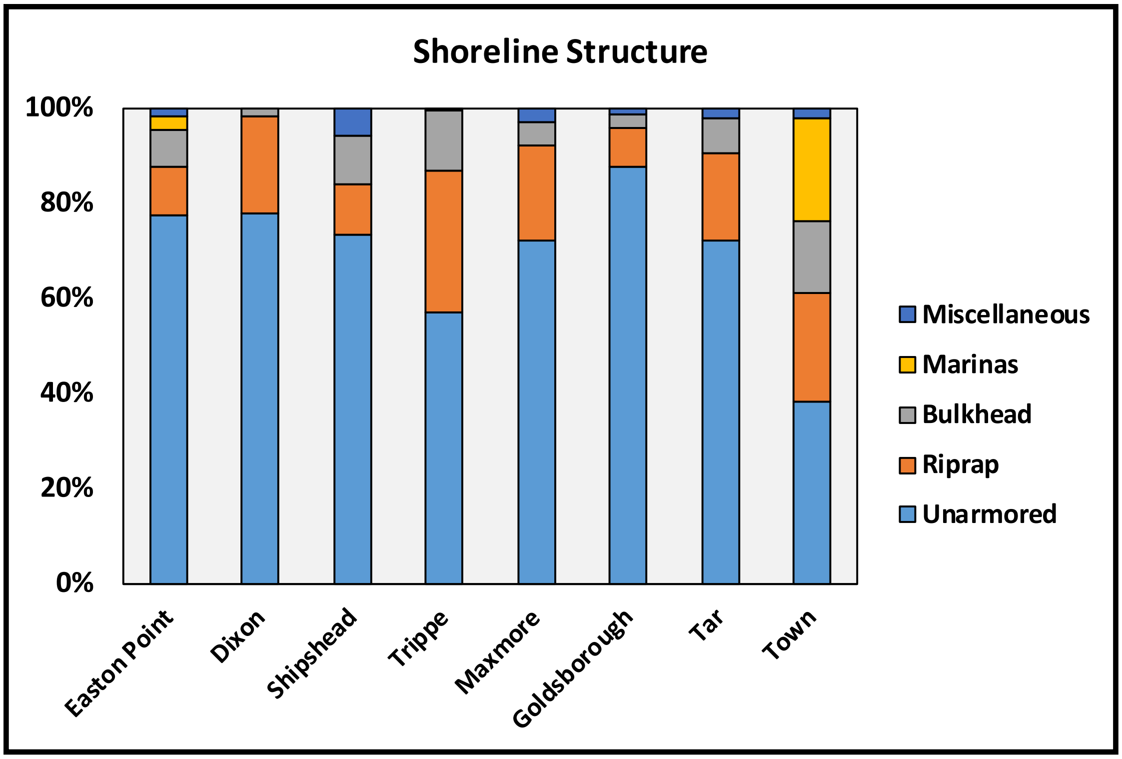


Figure WS4. Composition of shorelines in eight sub-watersheds of the Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). Bulkhead includes dilapidated/failing bulkhead. (Data source: VIMS 2005.)

Image WS10. Natural shorelines (top left) are decreasing in Chesapeake Bay as land development increases. Shorelines are being armored with bulkheads (top right) and rip rap (botton left) to protect waterfront properties from erosion and storm surge; however, armoring reduces the abundance and diversity of aquatic life. In contrast, living shorelines (bottom right) maintain continuity of the natural land–water interface and reduce erosion while providing habitat value and enhancing coastal resilience.

A Climatological Note

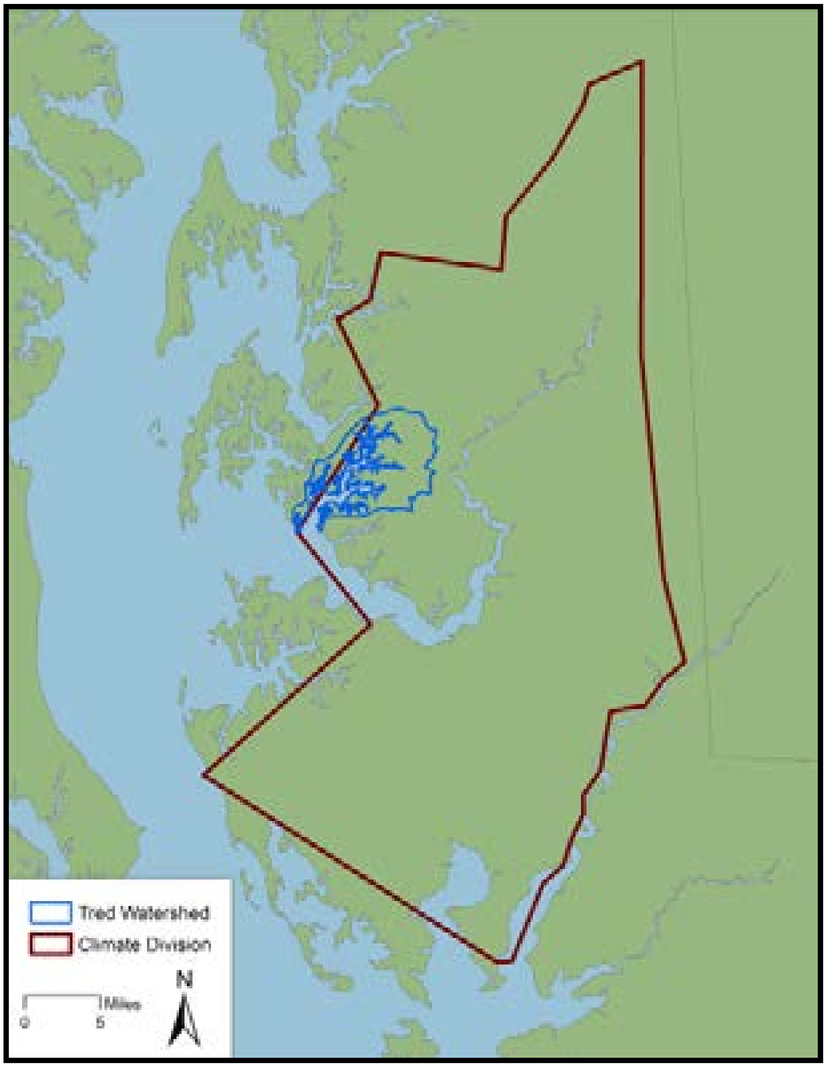


Figure WS5. The map on the left shows the climate division used for climate data in this study in the mid-eastern shore near the Tred Avon River watershed.

Air temperature and precipitation values in the Chesapeake Bay are presented here to provide contextual climate information for the Tred Avon River.

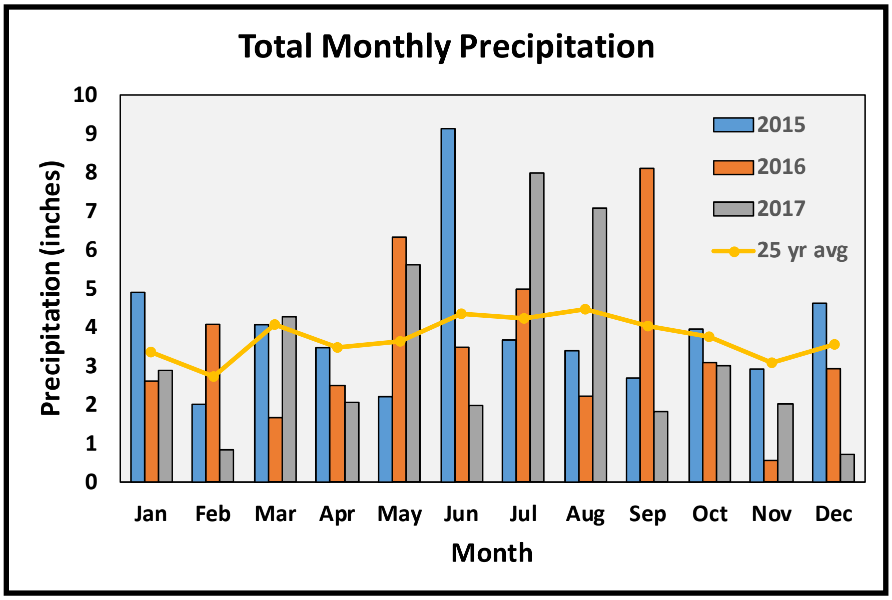
Climate data was collected from the National Climatic Data Center (NCDC 2018) using the climate division information from the mid-eastern shore. This data is quality assured and presented by geographic area (a.k.a climate division) as monthly averages (air temperature) or totals (precipitation).

Although the ecological assessment presented in this document was not designed to address changes in condition due to climate or weather patterns, coastal water conditions are clearly influenced by climate. For example, long-term (e.g. decadal and multi-decadal) changes in air temperature and precipitation have been linked to changes in nutrient levels, dissolved oxygen levels in bottom waters, zooplankton populations, fish populations, and fecal bacteria in surface waters (Leight et al. 2015). Annual climate variability and within-year timing of precipitation and air temperature changes also impacts other components of the estuarine ecosystem such as nutrient loads and water clarity. For example, increased precipitation leads to increased nutrients and sediments washing into the Chesapeake Bay (Najjar et al. 2010).

The amount of precipitation that the Chesapeake region receives each year is increasing. Since 1900, the Chesapeake has received 5.2 to 16.8 millimeters (0.2 – 0.7 inches) more precipitation each decade. This equates to nearly a 12 percent increase over the time period (Changing Chesapeake 2018). Air temperature also appears to be rising with fewer frost days and more summer nights per year and a longer growing season (Changing Chesapeake 2018).

During 2015–2017, precipitation was generally about average in January through April and October through December (Figure WS6). However, all three years were marked by above average precipitation totals in summer. For example, rainfall in June of 2015 was extremely high, topping 22.86 cm (9 inches), but dropped off in July and August. Precipitation in 2016 was highest in May and September with lower amounts in June and July. Rainfall totals in both July and August of 2017 were above average.

Average annual temperatures were generally similar to temperatures over the last 25 years (Fig. WS6). However, average monthly temperatures in February and March of 2015 were notably below average before rising to above average temperatures in May and June. In 2016, average monthly temperatures were higher than the 25–year average in July through October, indicating a hotter than usual summer.



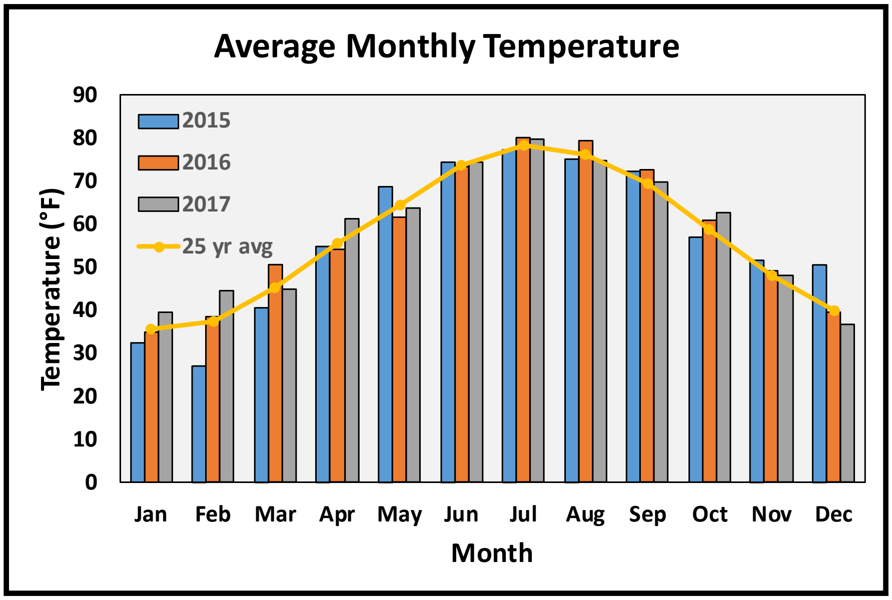


Figure WS6. Total monthly rainfall (top) for the years 2015–2017 and average monthly temperatures (bottom) as compared to normal conditions (average data for last 25 years collected in 1993–2017; yellow lines) from climate division data for the mid-eastern shore of the Maryland portion of Chesapeake Bay (NCDC 2018).

GUIDE TO THE PRESENTATION AND GRADING OF DATA

In the sections for each indicator, background information about the indicator is included and the methodology summarized. Method protocols may be found in Messick et al. (2013) unless other references are cited. Historical information is included occasionally to help the reader understand human activities in the surrounding watersheds. Results of the study are displayed graphically as described below.

Charts of the Data We Measured

Bar charts with blue bars (Fig. DG1) compare assessment variables among eight sampling stations in the Tred Avon River, in their original units. The error bars display 95 percent confidence limits (based on the standard error of the mean), which provide a relative estimate of differences between average conditions for the eight selected sub-watershed sampling stations, but not an absolute measure of significance.

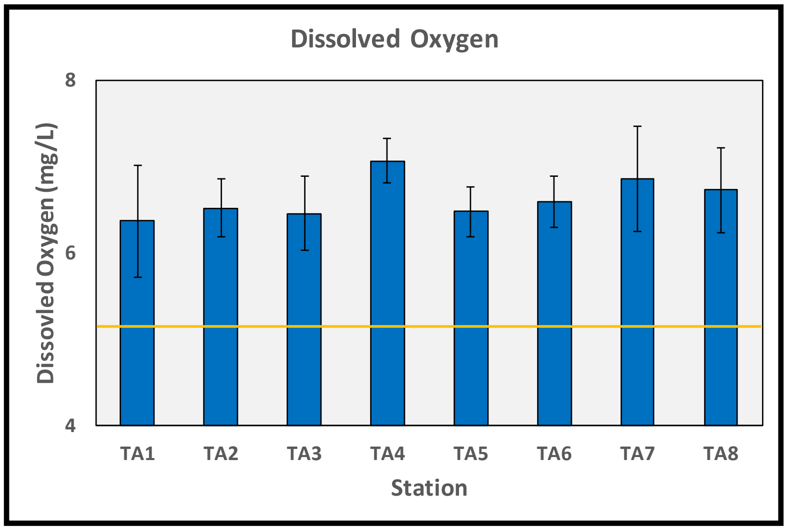


Figure DG1. An example of a blue bar chart used to compare assessment variables among the eight selected sub-watershed sampling stations in the Tred Avon River, in their original units (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). The error bars display 95 percent confidence limits, which provide a relative estimate of differences among average conditions for the eight stations, but not an absolute measure of significance. The yellow line represents criteria data, when available.

How We Scored Measurements

Criteria boxes explain how measured values were translated into scores for the variables assessed. Wherever possible, variables were assessed using the same evaluation methods as those used to calculate Chesapeake Bay report cards (EcoCheck 2011). For water quality variables, each observation was scored on a scale of 0–5 based on established criteria, as recommended by EcoCheck (2011). For some variables (such as dissolved oxygen and indicator bacteria densities), scoring was pass/fail (0 or 5), while most other variables were scored as any integer in the range of 0 to 5. In contrast, the benthic community condition was scored on a 1 to 5 scale in order to be consistent with the existing scoring methods of the Chesapeake Bay Index of Biotic Integrity (Llanso and Dauer 2002). The scoring methodology and relevant publications are included in the text for each variable.

Table DG1. Tables like the one below explain how measured values are translated into scores for the variable assessed.

Dissolved Oxygen Criteria Open Water Designated Use	
Dissolved Oxygen (mg/L)	Score
< 5.0	0
≥ 5.0	5

How We Graded Variables

Water Quality

As is done for Chesapeake Bay report cards (EcoCheck 2011), scores for variables with existing criteria were then averaged, divided by 5, and multiplied by 100 to give a grade of 0 to 100. Heat maps are included to present the grades for each station by year. The colors range from red, orange, yellow, light green, and dark green and correspond to scores of <20, 20–<40, 40–<60, 60–<80 and >80, respectively (Table DG2).

Table DG2. Tables like the one below explain the grading scale applied to any variables where scoring criteria exist e.g. water quality.

Average Score	Grade	Color Code	Condition
4 - 5	≥ 80	Dark Green	Very Good
3 - 4	60 - < 80	Light Green	Good
2 - 3	40 - < 60	Yellow	Marginal
1 - 2	20 - < 40	Orange	Degraded
0 - 1	< 20	Red	Severely Degraded

Other Variables

Grading for variables lacking scoring criteria are explained in the methods description for those variables.

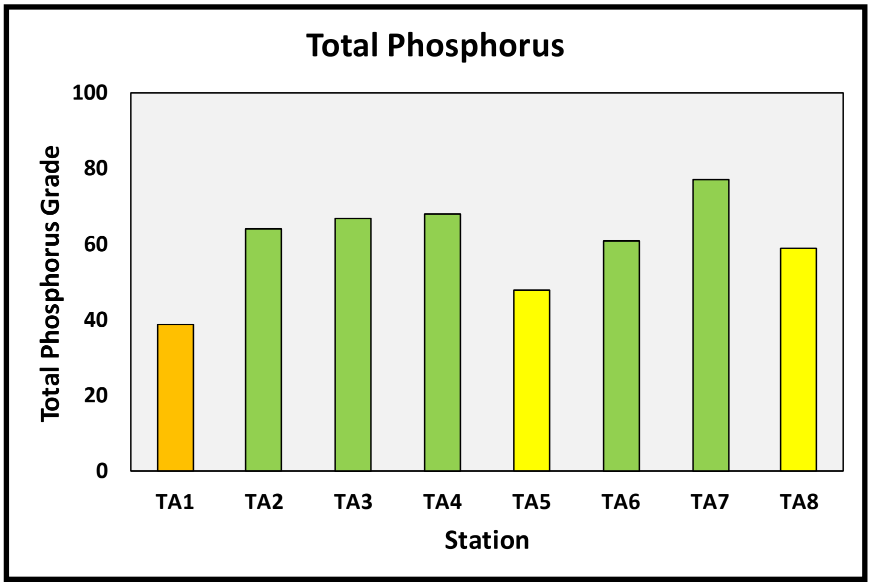
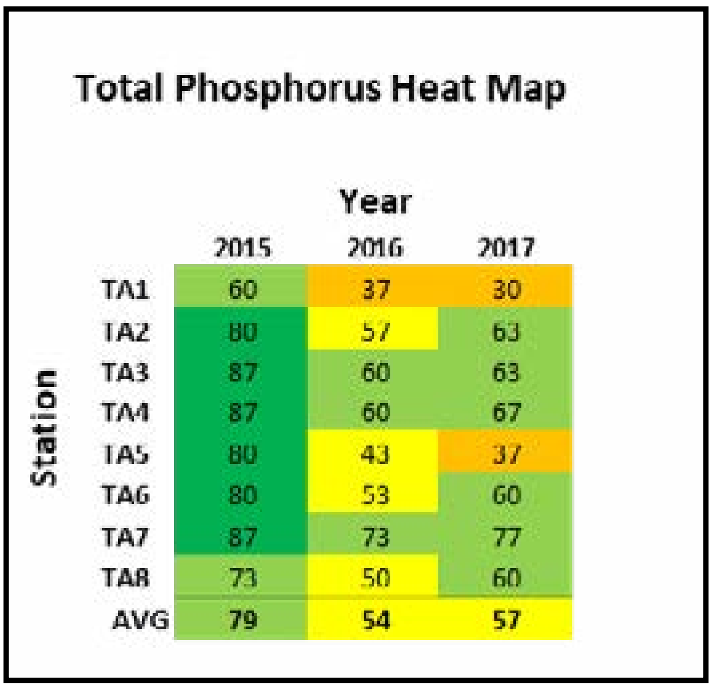


Figure DG2. Bar charts like the above illustrate the grades for each variable at the eight sampling stations in the Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek).



Total Phosphorus Heat Map

Station	2015	2016	2017
TA1	60	37	30
TA2	80	57	63
TA3	87	60	63
TA4	87	60	67
TA5	80	43	37
TA6	80	53	60
TA7	87	73	77
TA8	73	50	60
AVG	79	54	57

Figure DG3. Heat maps like the one above show the grades for each variable by the selected sub-watershed sampling station in the Tred Avon River and by year (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek).

Findings

- At the end of the results section for each variable, findings are bulleted in a box to summarize the results illustrated in the bar charts and heat map.

WATER QUALITY

Image WQ1. View of Goldsborough Creek (TA6), Tred Avon River.

Introduction

Water is essential to sustenance of human life and the environment. In addition to protecting public health, water quality is critical for sustaining the ecological processes that support native fish and shellfish populations, vegetation, wetlands and birdlife. Farming, fishing, recreation, and tourism thrive when good water quality is maintained.

Water quality is commonly defined by the following characteristics:

- Physical (e.g. temperature, turbidity and clarity, color, salinity, suspended solids, and dissolved solids)
- Chemical (e.g. pH, dissolved oxygen, nutrients, organic and inorganic compounds including toxicants)
- Biological (e.g. bacteria, algae)

Water quality is closely linked to the surrounding environment and supports a diverse community of organisms in an environment in good condition. For example, aquatic organisms rely on adequate levels of dissolved oxygen for metabolism, water clarity for primary production, and relatively low nutrients for balanced trophic conditions. Water quality often declines as rivers flow through regions impacted by agriculture, development, or recreational activities.

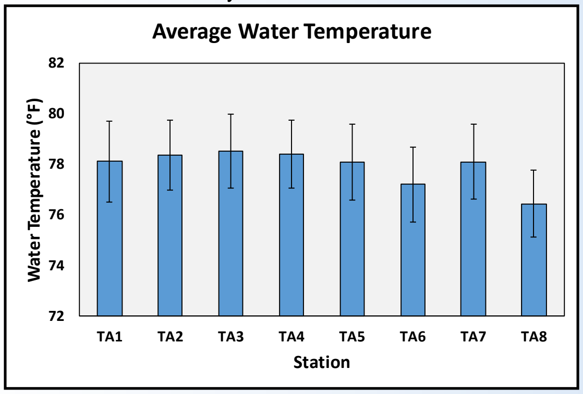
In this study, we examined a suite of water quality indicators to assess the condition of the water at the eight selected sub-watershed sampling stations in the Tred Avon River relative to established criteria and goals that represent conditions necessary to support balanced communities of organisms. Dissolved oxygen, nitrogen, phosphorous, chlorophyll *a*, fecal indicator bacteria, water clarity, temperature, and salinity were the indicators measured at each sampling station. We measured these indicators once during each spring, summer and fall over the period 2015–2017 at all eight sampling stations in the Tred Avon River (three sampling events per year at 8 sampling stations). For each sampling event, water quality measurements were collected at the same relative time of day, during three different days per year, and in the same tidal state. Sampling during large rain events was avoided.

Dissolved oxygen, water temperature and salinity were measured every half meter in depth at each of the eight sub-watershed sampling stations. For dissolved oxygen, measurements were collected at multiple depths because aquatic organisms rely directly on the presence of oxygen and it is common for changes in oxygen levels to occur over various depths. Water temperature and salinity were measured over multiple depths because these two variables are needed to assess several of the indicators, such as dissolved oxygen conditions, and provide background for comparison of the eight selected sub-watersheds in the Tred Avon River (Fig. WQPB1).

Method protocols for each of the following water quality indicators are described in Messick et al. 2013 unless cited otherwise. All variability within data groups are presented as standard error in tables and as 95 percent confidence limits using the standard error (SE*1.96) for plots.

Temperature and Salinity

Water temperature and salinity can be important factors for determining the distribution of species and the relative condition of a waterbody. In the Chesapeake Bay, water temperature and salinity are largely regulated by the mixing of freshwater and ocean waters in a complex but predictable movement of waters inside the Bay. These variables are presented here to provide context to the water conditions in the tributaries studied and because they are important in determining which scoring criteria are used for many of the variables used to assess condition.



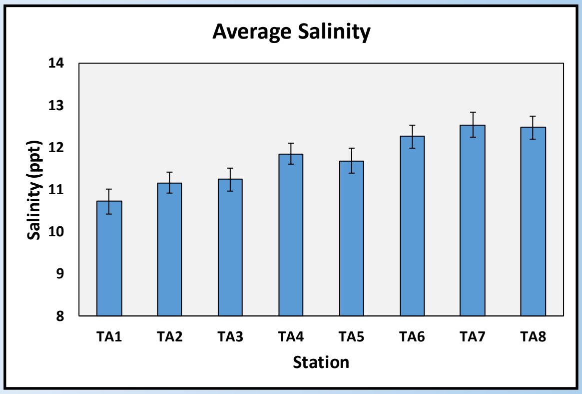


Figure WQPB1. Average water temperature (left) and salinity (right) measured during water quality sampling each spring, summer and fall of 2015–2017 at eight selected sub-watershed sampling stations in the Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). Error bars represent 95 percent confidence intervals.

DISSOLVED OXYGEN

Background

Dissolved oxygen is the amount of free oxygen that is present in water. Nearly all aquatic animals need dissolved oxygen to breathe and survive. The amount of dissolved oxygen in an estuary's water is a primary factor that determines the type and abundance of organisms that can live there.

Oxygen enters the waters of Chesapeake Bay by diffusion from the atmosphere and photosynthesis by aquatic plants. The mixing of surface waters by wind and waves increases the rate at which oxygen from the air can be dissolved or absorbed into the water. The solubility of oxygen, or its ability to dissolve in water, decreases as the water's temperature and salinity increase. Dissolved oxygen levels in Chesapeake Bay can vary seasonally, with the lowest levels occurring during the late summer months when temperatures are highest.

Low levels of oxygen (hypoxia) or no oxygen levels (anoxia) can occur in bottom waters when excess nutrients (eutrophication) fuel large algal blooms that are subsequently decomposed by microorganisms through consumption of dissolved oxygen. In Chesapeake Bay, stratification of the water column occurs in the main stem and lower portions of some tributaries as water temperatures increase and storm frequencies decrease (Leight et al. 2014). During the summer, when microorganisms are most active, stratification can inhibit mixing of oxygen-deprived bottom waters with oxygen-rich surface waters. In this study, the amount of free oxygen dissolved in water was measured at the eight selected sub-watershed sampling stations in the Tred Avon River to determine the quality of water and its ability to support life.

Methods

We measured levels of dissolved oxygen in the spring, summer and fall over the period 2015–2017 at the eight water quality sub-watershed sampling stations in the Tred Avon River. Dissolved oxygen concentrations (milligrams/liter) were recorded at the surface, bottom and at 0.5 meter depth increments using an YSI® datasonde (YSI, Inc., Yellow Springs, OH) equipped with an optical dissolved oxygen membrane probe.

All eight selected sub-watershed sampling stations were located in areas considered by the Chesapeake Bay Program to be open, non-stratified waters. Therefore, dissolved oxygen measurements from all depths were compared to the U.S. Environmental Protection Agency (EPA) criteria of 5.0 milligrams/liter (EcoCheck 2011). If a measurement exceeded the criteria it was scored as a 5; if it did not it was scored as a 0. Scores at each sub-watershed sampling station were averaged for each year and averaged for all years sampled.

Table WQ1. Threshold criteria for dissolved oxygen for open, non-stratified waters (EcoCheck 2011) (mg/L=milligrams per liter).

Dissolved Oxygen Criteria Open Water Designated Use	
Dissolved Oxygen (mg/L)	Score
< 5.0	0
≥ 5.0	5

Results

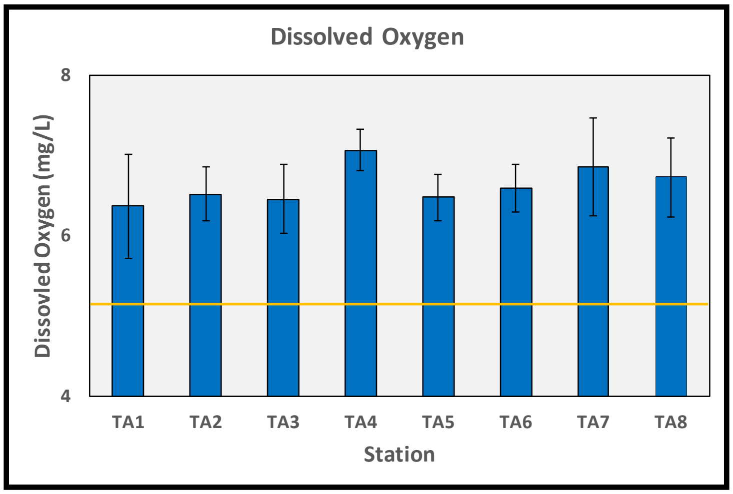


Figure WQ1. Average dissolved oxygen concentrations measured in top, bottom, and increments of 0.5 meters of water at eight sub-watershed sampling stations in the Tred Avon River, 2015–2017 (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). The yellow line represents EPA criteria of 5.0 milligrams per liter (mg/L). Error bars represent 95 percent confidence intervals.

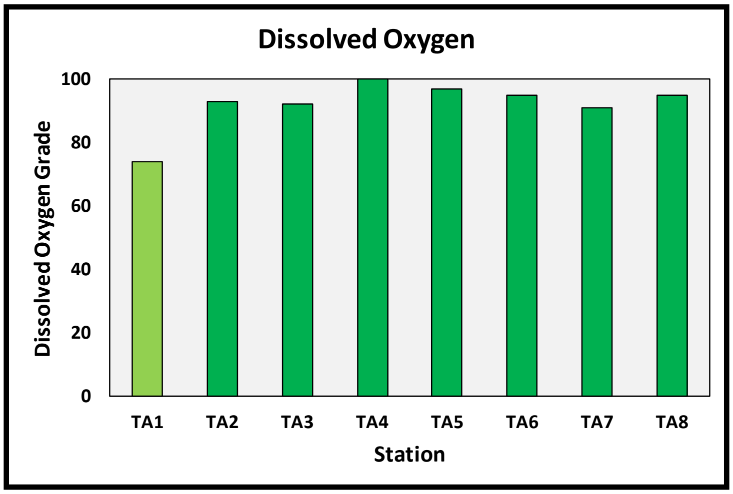


Figure WQ2. Dissolved oxygen grade for average dissolved oxygen concentrations measured in top, bottom, and 0.5 m increments of water at eight sub-watershed sampling stations in the Tred Avon River, 2015–2017 (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek).

Dissolved Oxygen Heat Map

Station	2015	2016	2017
TA1	92	80	44
TA2	94	100	85
TA3	93	100	80
TA4	100	100	100
TA5	94	100	100
TA6	100	93	92
TA7	100	100	67
TA8	88	100	100
AVG	95	97	84

Figure WQ3. Heat map of dissolved oxygen grades measured in 2015, 2016, and 2017 at the eight sub-watershed sampling stations in the Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). Averaging across rows will provide the same value as presented in Figure WQ2.

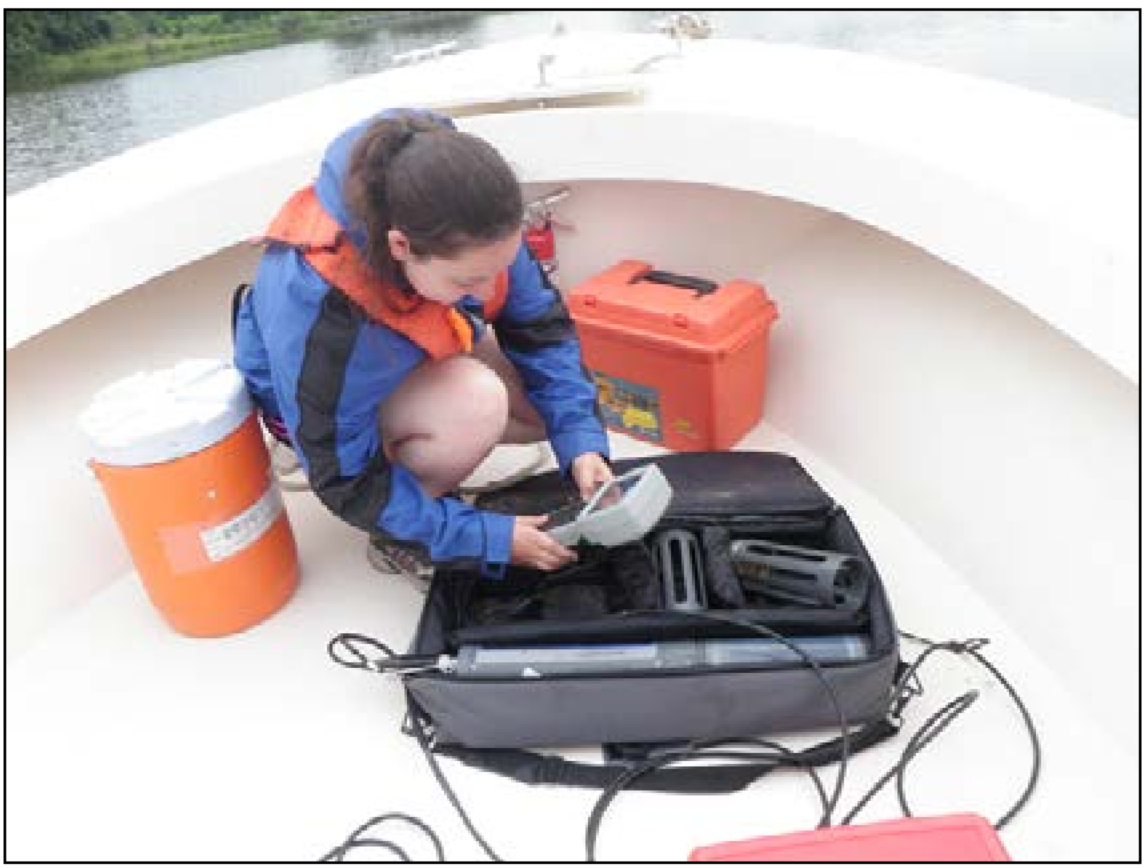


Image WQ2. A YSI data sonde® (YSI, Inc., Yellow Springs, OH) is being assembled prior to measuring water quality parameters such as dissolved oxygen, temperature, salinity, and turbidity in the Tred Avon River ecological assessment.

BOTTOM DISSOLVED OXYGEN

Aquatic organisms including benthos (organisms living in, or, or near the bottom), fish, and crabs respire as water flows across their gills and oxygen is passed into their blood or hemolymph. Hypoxic (low oxygen) conditions in water inhibits the ability of organisms to get the oxygen they need to survive. Excess nutrients in the water, or eutrophication, can fuel the growth of algae blooms which sink and are decomposed by oxygen-consuming bacteria. Algae-consuming bacteria are most active at high summer temperatures and can create hypoxic areas by using up oxygen in the water and making it harder for aquatic organisms to get the oxygen they need to survive.

Fish, crabs, and other mobile organisms may escape hypoxic or anoxic (no oxygen) conditions by relocating, thereby reducing the abundance and diversity of aquatic species in a community. Similarly, larger predators may relocate when benthos and other non-mobile prey die from exposure to anoxic or hypoxic conditions and/or other stressors such as sediment contaminants.

In the Tred Avon ecological assessment, bottom dissolved oxygen levels at Easton Point (TA1) were observed below the criteria of 5.0 milligrams per liter (Table WQ1). We observed a decline in abundance and diversity of most fish species during our fish community composition sampling at Easton Point (TA1) when low dissolved oxygen events were recorded at the station (see Fish Community Composition chapter).

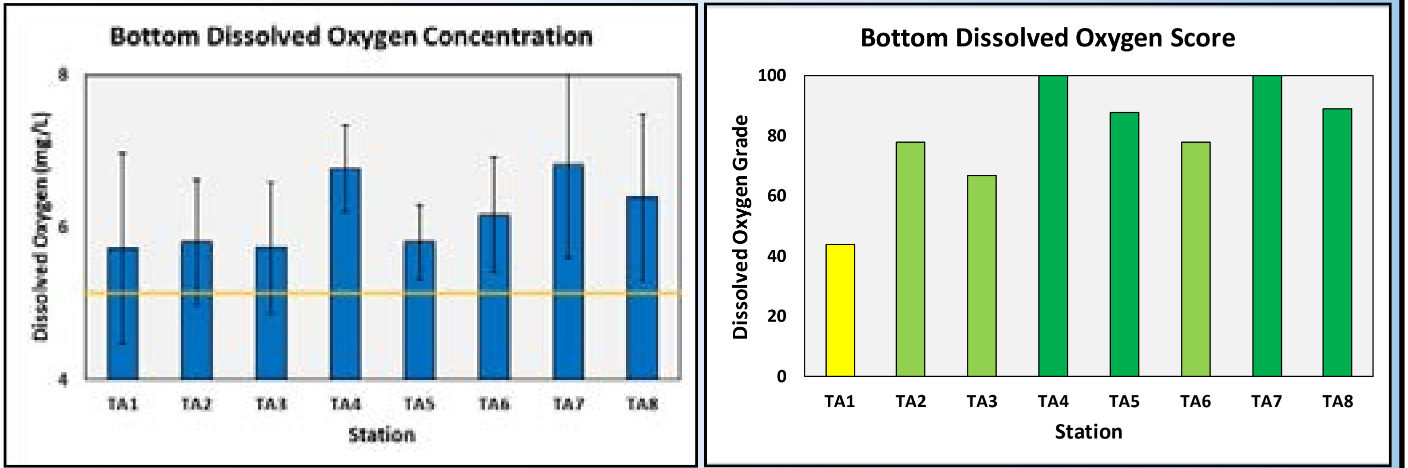


Figure WQPB2. Bottom dissolved oxygen concentrations (left) and scores (right) at eight sub-watershed sampling stations in the Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). The yellow line represents EPA criteria of 5.0 milligrams per liter (mg/L). Error bars represent 95 percent confidence intervals.

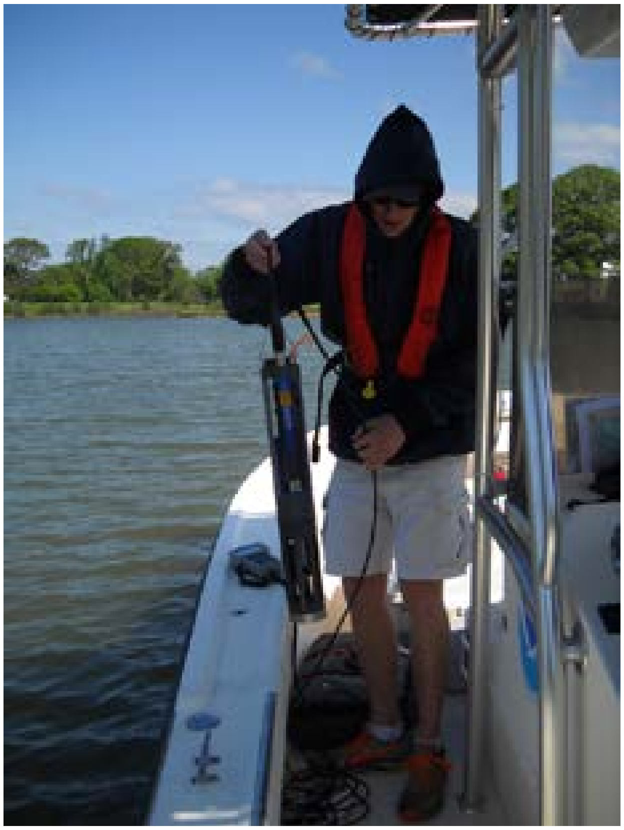


Image WQ3. A YSI data sonde® (YSI, Inc., Yellow Springs, OH) is used to measure water quality parameters in the Tred Avon ecological assessment.

Dissolved Oxygen Findings

- In general, dissolved oxygen levels in the eight selected sub-watersheds of the Tred Avon River are sufficient to support active aquatic communities. Average dissolved oxygen grades were greater than 90 percent at the eight selected sub-watershed sampling stations except Easton Point (TA1) which was 74 percent.

- Bottom dissolved oxygen grades (see WQPB2) averaged 44 percent at Easton Point (TA1) and 67 percent at Tar Creek (TA7) with the remaining sub-watersheds at 78–100 percent. The dissolved oxygen levels at Easton Point (TA1) were more similar to those found in the Magothy River, a relatively deep river with limited flushing located on the western shore of the Chesapeake Bay than to levels found in other tributaries of the Bay on the eastern shore, such as the Corsica and Sassafras Rivers (Leight et al. 2015).

- Dissolved oxygen grades were lower in 2017 than in 2015 or 2016, with the lowest grades given for Easton Point (TA1) and Tar Creek (TA7) in 2017.

NITROGEN

Background

Nitrogen is an essential building block for amino acids, proteins and deoxyribonucleic acid (DNA) and is a necessary nutrient for all organisms. Although nitrogen is abundant naturally in the environment, it is also introduced into coastal waters from atmospheric deposition, wastewater treatment facilities, groundwater flow, and runoff from land in urban areas (e.g. impervious surfaces) and agricultural fields and facilities. Excess nitrogen in estuaries causes problems by fueling the rapid and excessive growth of plants and bacteria. When overproduction occurs, algae sink to the bottom and are decomposed by oxygen-consuming bacteria. Aquatic organisms may swim away or die when bottom waters have little or no dissolved oxygen.

As human population growth continues to increase along the coast, impacts from pollution due to nutrients such as nitrogen also increases. For this reason, the concentration of nitrogen in the water provides an important indicator of water quality and habitat condition. Nitrogen levels might be expected to increase through the winter and spring due to runoff and greater groundwater discharge from frequent rain showers and lower evaporation. We collected water samples for nitrogen analysis from the eight selected sub-watershed sampling stations in the Tred Avon River during each spring, summer and fall over the period 2015-2017.

Methods

Image WQ4. A water sample collected for nutrient analyses.

In this study, we submerged acid-washed 500 milliliter plastic bottles just below the surface of the water to collect water samples for nitrogen (Image WQ4) analysis (Messick et al. 2013). A subsample of the water was filtered using a 0.7 micrometer glass-fiber filter to collect the particulates. Dissolved nitrogen was measured directly from the water samples while particulate nitrogen was measured from the material retained on the filters. In order to compare nitrogen concentration in the samples with established water quality criteria, inorganic and organic nitrogen compounds, in both dissolved and particulate forms, were combined to establish a total nitrogen concentration.

Nitrogen concentrations were converted to a score ranging from 0 to 5, based on previous reports for mesohaline waters found in the Tred Avon River (Table WQ2; EcoCheck 2011).

Table WQ2. Total nitrogen (mg/L = milligrams per liter) threshold table for determining scores in mesohaline waters found in Tred Avon River (EcoCheck 2011).

Total Nitrogen Criteria Mesohaline Waters	
Total Nitrogen (mg/L)	Score
> 1.5	0
> 1.0 – ≤ 1.5	1
> 0.8 – ≤ 1.0	2
> 0.6 – ≤ 0.8	3
> 0.5 – ≤ 0.6	4
≤ 0.5	5

Results

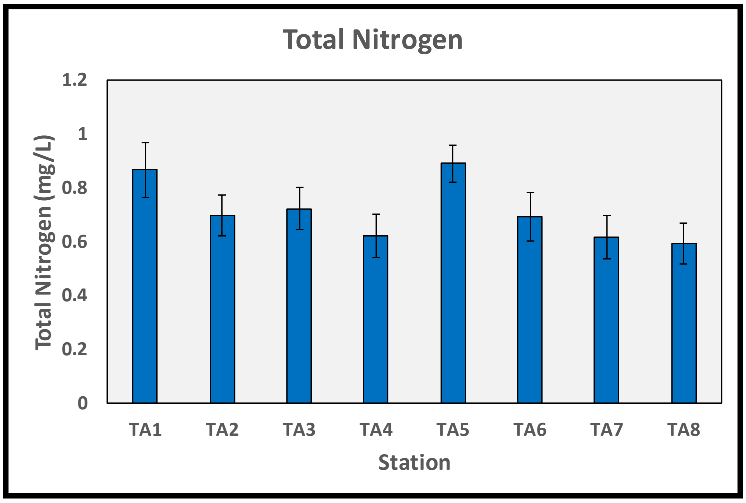


Figure WQ4. Average total nitrogen concentrations (mg/L = milligrams per liter) over the period 2015–2017 in eight sub-watershed sampling stations in the Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). Error bars represent 95 percent confidence intervals.

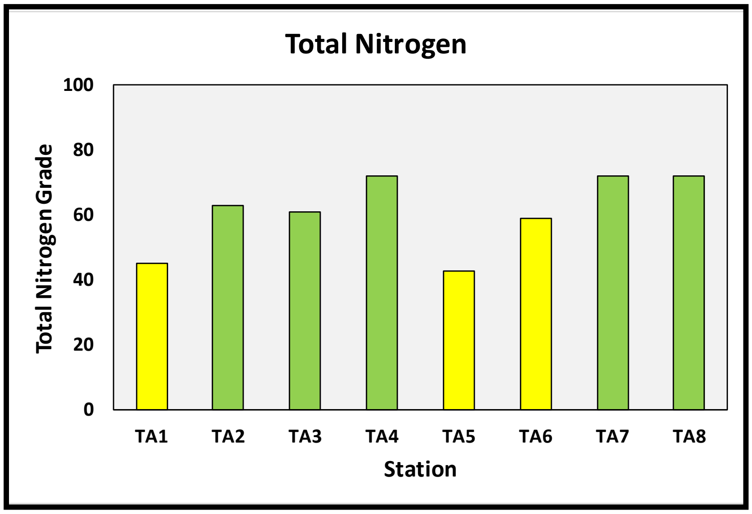
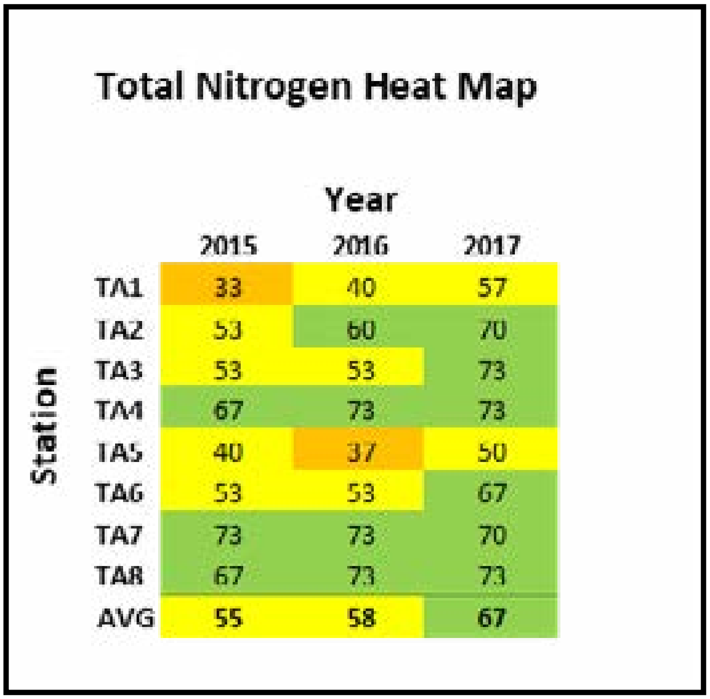


Figure WQ5. Average total nitrogen grades (2015–2017) in eight sub-watershed sampling stations in the Tred Avon (TA1 Easton Point; TA2 Dixon; TA3 Shipshead; TA4 Maxmore; TA5 Trippe; TA6 Goldsborough; TA7 Tar; TA8 Town Creek).



Total Nitrogen Heat Map

Station	2015	2016	2017
TA1	33	40	57
TA2	53	60	70
TA3	53	53	73
TA4	67	73	73
TA5	40	37	50
TA6	53	53	67
TA7	73	73	70
TA8	67	73	73
AVG	55	58	67

Figure WQ6. Heat map of total nitrogen scores by year and station in the Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). Averaging across rows will provide the same values as presented in Fig. WQ5.

Nitrogen Findings

- On average, total nitrogen concentrations were highest at Easton Point (TA1) and Trippe Creek (TA5).
- Total nitrogen grades were marginal for Easton Point (TA1), Trippe Creek (TA5), and Goldsborough Creek (TA6). The remainder of the eight sub-watersheds were graded as 'good.'
- In most cases, nitrogen grades improved from 2015 to 2017, perhaps showing positive results from conservation efforts on land to reduce nitrogen inputs to the Chesapeake Bay. These improvements have been noted Bay–wide (Lefcheck et al. 2018).

PHOSPHORUS

Background

Phosphorus is an essential nutrient for all cellular organisms and occurs naturally in most aquatic systems. Natural sources of phosphorus include sediment derived from natural geologic formations, atmospheric deposition (especially of dust, organic matter, and biological waste (e.g. from waterfowl). Additional anthropogenic sources of phosphorus include fertilizer, agricultural and urban runoff, industrial and domestic sewage as well as faulty or overloaded septic systems. Phosphorus tends to attach to soil particles and can be transported into surface-water in runoff from pastures, crops, sewage wastewater, and atmospheric deposition or sediment erosion. Excess available phosphorous in aquatic systems, similar to problems caused by excess nitrogen, can lead to algal blooms that clog waterways and deplete dissolved oxygen in bottom waters. These poor conditions may be lethal to fish and shellfish. As land use patterns change and the watershed's population grows, the amount of phosphorus, as well as nitrogen and sediment, entering Chesapeake Bay waters continues to increase.

We measured levels of phosphorus once during each spring, summer, and fall over the period 2015–2017 at the eight selected sub-watershed sampling stations in the Tred Avon River.

Methods

Image WQ5. NOAA Cooperative Oxford Laboratory scientists process water samples collected for nutrient analyses.

We submerged acid-washed 500 millilter bottles just below the surface to collect water samples for phosphorus analysis. A subsample of the water was filtered using 0.7 micrometer glass-fiber filters to collect the particulates. Dissolved phosphorus was measured directly from filtered water and particulate phosphorus was measured from the material retained on the filters (Messick et al. 2013). In order to compare phosphorus concentrations in the samples with established water quality criteria, inorganic and organic phosphorus compounds, in both dissolved and particulate forms, were combined to establish a total phosphorus concentration.

Phosphorus concentrations were scored based on a scale ranging from 0 to 5 as shown below (Table WQ3).

Table WQ3. Score criteria for total phosphorus in mesohaline water of Tred Avon River (mg/L = milligrams per liter) (EcoCheck 2011).

Total Phosphorus Criteria Mesohaline Waters	
Total Phosphorus (mg/L)	Score
> 0.15	0
> 0.08 – ≤ 0.15	1
> 0.06 – ≤ 0.08	2
> 0.04 – ≤ 0.06	3
> 0.02 – ≤ 0.04	4
≤ 0.02	5

Results

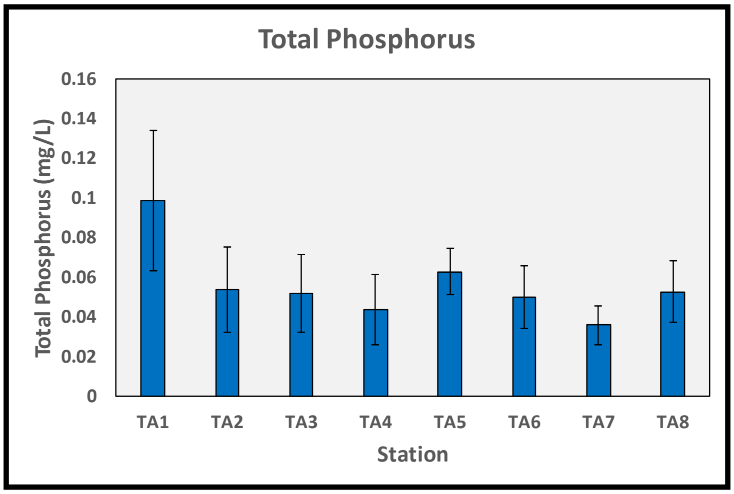


Figure WQ7. Average total phosphorus concentrations in milligrams per liter (mg/L) for the eight sub-watershed sampling stations in the Tred Avon River over the period 2015–2017 (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). Error bars represent 95 percent confidence intervals.

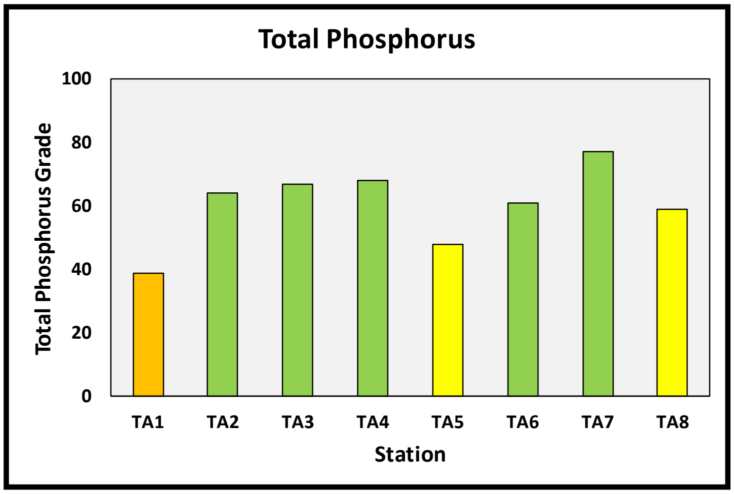


Figure WQ8. Average total phosphorus grades (2015–2017) for the eight sub-watershed sampling stations in the Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek).

Total Phosphorus Heat Map

Station	2015	2016	2017
TA1	60	37	30
TA2	80	57	63
TA3	87	60	63
TA4	87	60	67
TA5	80	43	37
TA6	80	53	60
TA7	87	73	77
TA8	73	50	60
AVG	**79**	**54**	**57**

Figure WQ9. Heat map of total phosphorous grades by year and station in Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). Averaging across rows will provide the same value as presented in Figure WQ11.

Phosphorous Findings

- Similar to the observations for total nitrogen, total phosphorus concentrations (Fig. WQ7) were highest at Easton Point (TA1) followed by Trippe Creek (TA5).
- The lowest total phosphorous concentrations occurred at Tar Creek (TA7).
- Easton Point (TA1) was the only sub-watershed of the Tred Avon River that was assessed to be degraded for total phosphorous. Trippe Creek (TA5) and Town Creek (TA8) were graded as marginal.
- Unlike grades for nitrogen, grades for phosphorus were best in 2015, which had below average rainfall in all months between April and September except June. The worst grades occurred in 2016.

WATER CLARITY

Background

Water clarity is an important indicator of water quality and overall condition of an aquatic ecosystem. In many coastal estuaries, sediments and nutrients from both point (a single source of discharge such as a sewage treat plant) and non-point sources (multiple non-discharge sources such as runoff from agriculture or residential areas) are washed into the water and decrease water clarity directly, in the case of suspended sediments, or indirectly, in the case of nutrient-driven algal blooms. Water clarity can vary naturally due to tides, storm events, wind patterns and changes in sunlight. In addition, colored dissolved organic matter, such as tannins, are natural byproducts of forested wetlands and can alter water clarity, particularly in brackish parts of the estuary. Mud and silt washed from land can also be resuspended by boating and dredging activities, decreasing water clarity. Clear waters are characterized by low concentrations of suspended soil particles, algae, and dissolved or particulate organic matter.

Secchi depth provides a measure of light penetration into water and is a function of the absorption and scattering of light in the water. The amount of sediment, plankton, and colored dissolved organic matter in water affect the depth to which light will penetrate. Because water clarity is closely related to light penetration, it has important implications for the diversity and productivity of aquatic life that a system can support. For example, clearer water allows more sunlight to reach and sustain submerged aquatic vegetation. The vegetation, in turn, produces oxygen, provides habitat for fish and shellfish and provides food for waterfowl, fish and mammals.

Methods

We used a Secchi disk to measure water clarity at the eight selected sub-watershed sampling stations in the Tred Avon River in each spring, summer and fall over the period 2015–2017. The disk is a small flat disk, 20 centimeter (~8 inches) in diameter, with alternating black and white painted quadrants. The disk is lowered into the water until the black–and– white pattern on the disk is no longer visible, which is the point called Secchi depth. This is a widely-used technique (Preisendorfer 1986), but as readings are affected by sun angle, cloud cover, and other lighting factors, it provides only an approximate assessment of water clarity. We compared our Secchi depth against established criteria (EcoCheck 2011) for mesohaline waters (Table WQ4).

Grades for Secchi depth for the Chesapeake Bay report cards (UMCES 2018) are often the lowest grades of all indicators, suggesting that the criteria for this indicator may be harder to achieve than some of the other variables used for assessing ecosystem condition.

Table WQ4. Secchi depth score criteria in mesohaline waters (left; EcoCheck 2011) and example of a Secchi disk (right).

Water Clarity Criteria Mesohaline Waters	
Secchi Depth (meters)	Score
< 0.3	0
≥ 0.3 – < 0.6	1
≥ 0.6 – < 1.0	2
≥ 1.0 – < 1.6	3
≥ 1.6 – < 1.8	4
≥ 1.8	5

Results

Average Secchi depths at the eight selected sub-watershed sampling stations in the Tred Avon River are shown below. Higher values represent better water clarity.

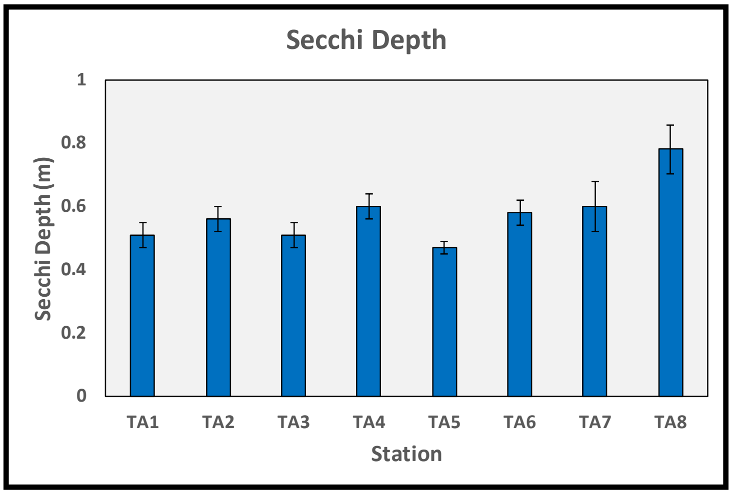


Figure WQ10. Average Secchi depth measurements 2015–2017 in meters (m) at eight sub-watershed sampling stations in the Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). Error bars represent 95 percent confidence intervals.

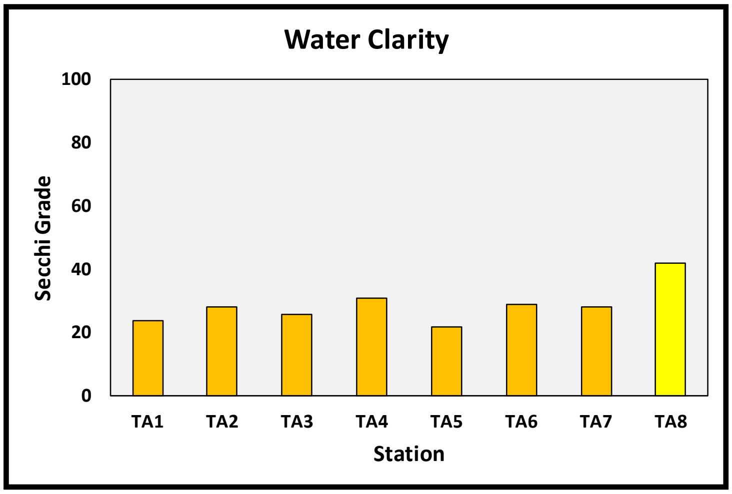


Figure WQ11. Average Secchi depth grades for the eight sub-watershed sampling stations in the Tred Avon River over the period 2015–2017 (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek).

Secchi Depth Heat Map

Station	2015	2016	2017
TA1	20	20	33
TA2	25	26	34
TA3	24	20	34
TA4	25	34	34
TA5	20	20	26
TA6	28	27	33
TA7	25	40	20
TA8	40	41	45
AVG	26	29	32

Figure WQ12. Heat map of Secchi depth grades by year and sub-watershed sampling station in the Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). Averaging across rows will provide the same values presented in WQ11.

Water Clarity Findings

- Water clarity was low in each of the eight sub-watersheds assessed in the Tred Avon River but was slightly better at Town Creek (TA8).
- A slight improvement in water clarity in the Tred Avon River from 2015 to 2017 corresponded to an increase in submerged aquatic vegetation (SAV) as reported by Virginia Institute of Marine Science (VIMS 2017) though improvements in summertime water clarity could certainly still be made.
- Town Creek (TA8) had the highest grade for water clarity despite having a relatively high amount of developed land.
- The criteria for the water clarity variable may be more conservative than the criteria for other water quality variables.

CHLOROPHYLL *A*

Background

At the base of the marine food web are single-celled algae and other plant-like organisms known as phytoplankton. Like plants on land, phytoplankton use chlorophyll and other light-harvesting pigments to carry out photosynthesis. Since the majority of photosynthetic organisms contain chlorophyll *a*, measurements of this pigment serve as an indicator of phytoplankton abundance and biomass in coastal and estuarine waters.

Phytoplankton growth depends on available sunlight, water temperature, and nutrient levels. Waters with very high levels of nutrients from fertilizers, septic systems, sewage treatment plants, and urban runoff may have high concentrations of chlorophyll *a* and excess densities of algae. When these algae populations bloom, sink, and undergo decomposition by bacteria, dissolved oxygen levels in the water are depleted and threaten the survival of fish and shellfish.

We measured the chlorophyll *a* concentrations at the eight selected sub-watershed sampling stations in the Tred Avon River in each spring, summer, and fall seasons over the period 2015–2017 to estimate phytoplankton abundance and biomass.

Methods

We submerged plastic bottles (500 milliliters) just below the surface of the water to collect water samples for chlorophyll *a* analysis. Chlorophyll *a* was measured by filtering 50–100 milliliters of water through a pre-rinsed 0.7 micrometer filter. The filters were stored on dry ice in the field and transferred to a -80° C (-112° F) freezer in the lab. Chlorophyll *a* concentrations were measured (in micrograms of chlorophyll *a* per liter of water) from the filters using high performance liquid chromatography.

Image WQ6. NOAA scientist from Cooperative Oxford Laboratory filters a water sample collected from Town Creek (TA8) for chlorophyll *a* analysis.

Table WQ5. Score criteria for chlorophyll *a* concentrations measured in surface waters in Tred Avon River (EcoCheck 2011) (µg/L = micrograms per liter).

Chlorophyll *a* Criteria Mesohaline Waters		
Chlorophyll *a* Spring Mar–May (µg/L)	Chlorophyll *a* Summer Jul–Sep (µg/L)	Score
> 49.8	> 35.8	0
> 19.1 – ≤ 49.8	> 15.8 – ≤ 35.8	1
> 11.1 – ≤ 19.1	> 11.0 – ≤ 19.1	2
> 6.2 – ≤ 11.1	> 7.7 – ≤ 11.0	3
> 2.09 – ≤ 6.2	> 1.7 – ≤ 7.7	4
≤ 2.09	≤ 1.7	5

Results

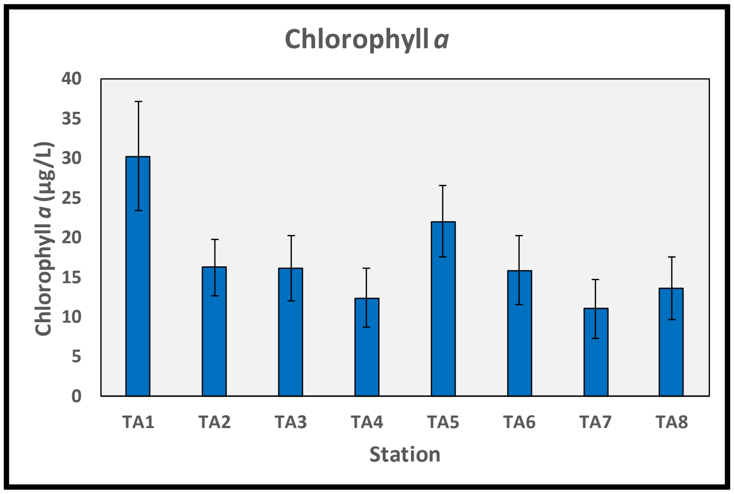


Figure WQ13. Average concentrations of chlorophyll *a* in micrograms per liter (µg/L) collected each spring, summer, and fall from the eight sub-watershed sampling stations in the Tred Avon River over the period 2015 to 2017 (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). Error bars represent 95 percent confidence intervals.

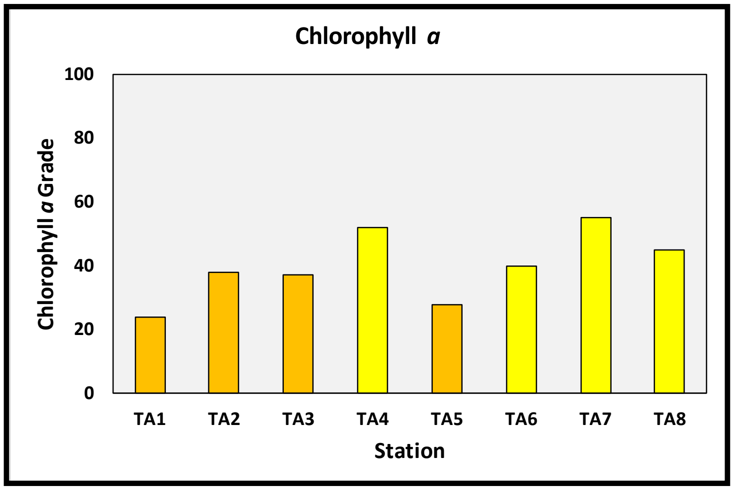


Figure WQ14. Average chlorophyll *a* grades in surface waters collected at the eight sub-watershed sampling stations in the Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek).

Chlorophyll *a* Heat Map

Station	Year 2015	2016	2017
TA1	15	12	40
TA2	27	31	50
TA3	27	27	53
TA4	27	47	70
TA5	20	20	40
TA6	27	40	47
TA7	53	53	57
TA8	33	50	47
AVG	29	35	51

Figure WQ15. Heat map of chlorophyll *a* grades by year and sub-watershed sampling station in Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). Averaging across rows will result in the same values presented in Figure WQ14.

Chlorophyll *a* Findings

- Chlorophyll *a* levels at the eight sub-watershed sampling stations in the Tred Avon River indicated marginal to degraded conditions, as might be expected from the relatively high nitrogen and phosphorus concentrations in these locations.
- Easton Point (TA1) and Trippe Creek (TA5) had the highest concentrations and poorest grades for chlorophyll *a*.
- There was notable improvement in chlorophyll *a* concentrations from 2015 to 2017, coinciding with an improvement in nitrogen concentrations.

INDICATOR BACTERIA

Background

Fecal indicator bacteria levels (e.g. *Enterococcus* spp.) are used to measure the sanitary quality of water for recreational, industrial, agricultural and water supply purposes. Indicator bacteria are normal inhabitants of the gastrointestinal tract of humans and other warm-blooded animals and are generally non-disease causing, but indicate the likelihood of fecal contamination and the potential presence of pathogens associated with fecal matter. Due to the large number of bacteria, viruses and other disease-causing microorganisms found in the environment, it is impractical to monitor water quality for every pathogen on a routine basis.

Sources of fecal indicator bacteria include wastewater treatment plant effluent, leaking septic systems, storm water runoff, sewage discharge from recreational boats, animal waste, improper land application of manure or sewage, and runoff from manure storage areas, pastures, rangelands, and feedlots. Natural, non-fecal reservoirs of environmental indicator bacteria include plants, sand, soil, and sediments that contribute to a certain background level in ambient waters (USEPA 2018a).

The indicator bacteria *Enterococcus* spp. is the most commonly used indicator to assess recreational waters. The detection of enterococci bacteria in the environment indicates the presence of viruses, bacteria, and other pathogens that can result in human illness by direct contact (e.g. swimming) and consumption of fish or shellfish harvested from contaminanted waters. Significant amounts of enterococci in a water body can negatively affect recreational and economic values of aquatic resources.

For this study, we used the indicator *Enterococcus* spp. bacteria to assess potential sewage pollution at the eight selected sub-watershed sampling stations in the Tred Avon River. Because our study focused on environmental conditions rather than seafood consumption by humans, we chose to use this indicator for recreational water. However, routine monitoring of waters over shellfish harvest areas by the Maryland Department of the Environment (MDE) is conducted in the Tred Avon River for shellfish sanitation using fecal coliforms (not *Enterococcus* spp.). Because shellfish can concentrate both indicator bacteria as well as the pathogens for which they act as a proxy, the criteria for assessing risk from consuming shellfish has lower thresholds than the criteria for recreational uses. In 2018, the upper reaches of the Tred Avon River, including Easton Point (TA1), Dixon Creek (TA2), and Shipshead Creek (TA3) were closed to shellfish harvesting due to exceedances of the more conservative shellfish-waters criteria.

Methods

Bacteria were isolated using standard methods (APHA 1992) which involve filtering sample water, incubating filters on selective culture media, counting bacterial colonies on the media, and comparing the counts, or densities, to threshold criteria determined by USEPA (2004).

The criteria of 104 colony forming units (cfu) per 100 milliliters of sample is the threshold recommended by USEPA (2004) and used by the MDE to classify "designated beach areas." Although samples for this study were not collected at beaches, these criteria represent reasonable indicators of risk from recreational activities in estuarine waters (Wade et al. 2003; APHA 1998; USEPA 2004).

Table WQ6. Criteria for indicator bacteria (*Enterococcus* spp.) concentrations in recreational waters (cfu = colony forming units) (USEPA 2004).

Indicator Bacteria Criteria Recreational Waters	
Enterococcus spp. concentration (cfu)	Score
> 104	0
≤ 104	5

Results

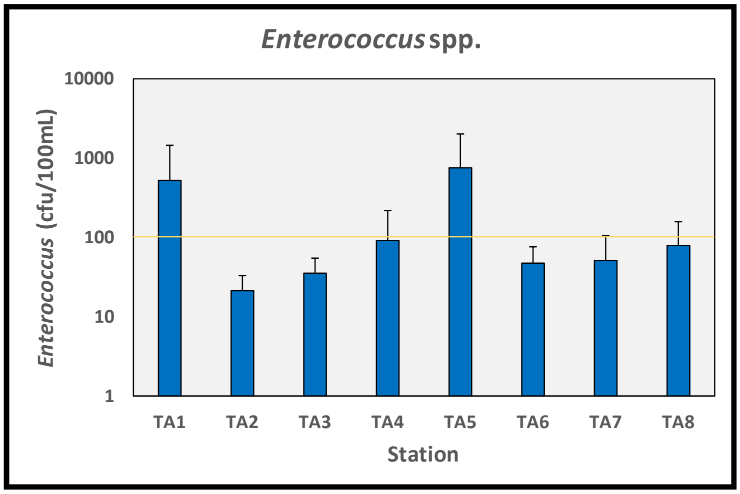


Figure WQ16. Average concentrations of *Enterococcus* spp. measured each spring, summer, and fall at the eight sub-watershed sampling stations in the Tred Avon River over the period 2015–2017 (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). Yellow line represents established criteria of 104 colony forming units per 100 milliters (mL) of sample (USEPA 2004). Note that the y-axis is a log scale and only positive error bars are shown. Error bars represent 95 percent confidence intervals.

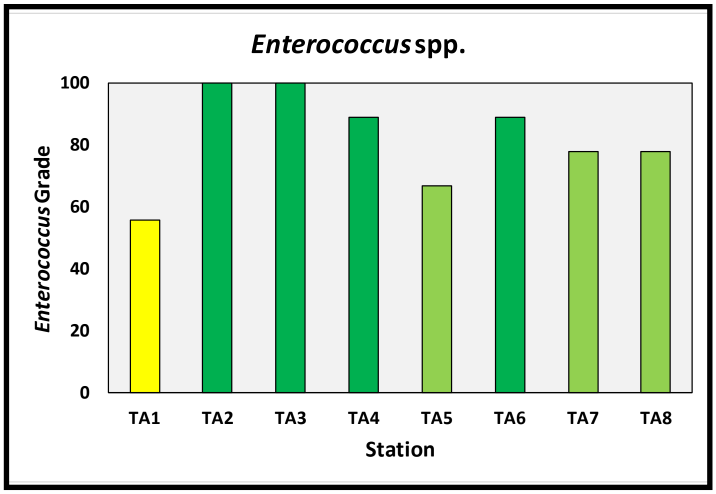


Figure WQ17. Average *Enterococcus* spp. grades in the eight sub-watershed sampling stations in the Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek).

Enterococcus spp. Heat Map

Station	2015	2016	2017
TA1	33	67	67
TA2	100	100	100
TA3	100	100	100
TA4	67	100	100
TA5	100	33	67
TA6	67	100	100
TA7	67	67	100
TA8	100	67	67
AVG	**79**	**79**	**88**

Figure WQ18. Heat map of *Enterococcus* spp. grades by year and sub-watershed sampling station in the Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). Averaging across rows will provide the same values shown in Figure WQ17.

Indicator Bacteria Findings

- The majority of samples contained *Enterococcus* spp. concentrations below the recreational criterion.
- However, the concentrations of indicator bacteria in surface waters suggest some periodic risks to humans from recreational activities, especially at Easton Point (TA1).
- The lowest grades occurred at Easton Point (TA1) in 2015 and Trippe Creek (TA5) in 2016.

BENTHIC HABITAT CONDITION

Image BH1. A Young-modified Van Veen grab is used to collect sediments for laboratory analyses.

Introduction

The sediments at the bottom of the Chesapeake Bay form a critical habitat that supports economically and ecologically important species. A diverse community of small organisms lives within these sediments. These organisms help to process organic matter and serve as prey for larger organisms. This community includes microscopic plants and invertebrates like clams, oysters, crustaceans and worms. Benthic community condition is influenced by many factors, including dissolved oxygen concentrations, sedimentation, and chemical contamination (Dauer et al. 2000; Leight et al. 2014). Many pollutants are attracted to solid particles and therefore can accumulate in the sediments and negatively impact those organisms living on or in the sediments. Aquatic organisms living in the water column may also be exposed to pollutants when sediments are resuspended into the water column after storm events, dredging or other activities, or when they consume organisms living in bottom sediments.

The composition and abundance of benthic communities provide a snapshot of existing environmental conditions because benthic organisms are relatively stationary and unable to escape direct impacts from toxic chemicals, pathogens, low dissolved oxygen, or other stressors. The condition of the benthic habitat was assessed at the eight selected sub-watershed sampling stations (Fig. WS1) representing varying dominant land uses in the Tred Avon River (Fig. WS2) by measuring the diversity and abundance of the benthic community, the concentrations of chemical contaminants, and levels of sediment toxicity.

In the Tred Avon River, we measured concentrations of chemical contaminants in the sediment, toxicity of the sediment, and the condition of the benthic community of organisms. Sampling occurred once in August 2015 at each of the eight sub-watershed water quality sampling stations over the period 2015–2017. Interannual variability for these contaminants was not assessed.

SEDIMENT PARTICLE SIZE

Sediment particle size affects the available surface area and binding capacity of contaminates to the particles, affects the pore size, the likelihood of resuspension, and the amount and types of organic matter that collect in the benthic habitat. In turn, these characteristics affect the toxicity of benthic contaminants and the benthic community structure. Therefore, in the Tred Avon ecological assessment, we measured the particle sizes of sediment collected from each of the eight sub-watershed sampling stations using the Wentworth scale for describing grain sizes (Wentworth 1922).

Each of the eight sub-watershed sampling stations (TA1–TA8) was dominated by fine particles (silt and clay), with slightly more sand particles occurring at Easton Point (TA1).

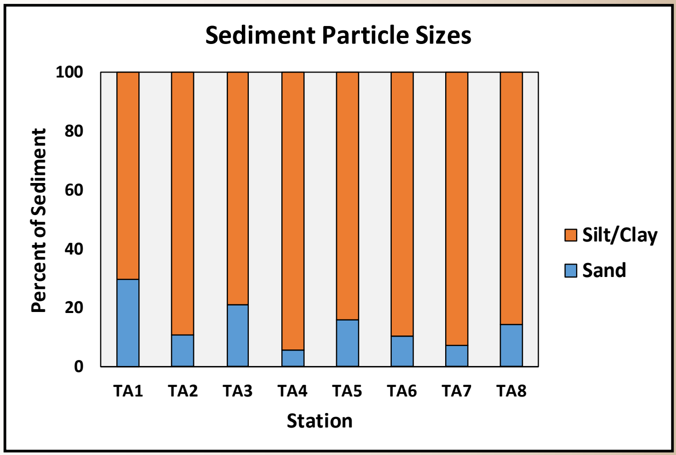


Figure BHPB1. Particle sizes of sediment samples from the eight sub-watershed sampling stations in the Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek).

Chemical Contaminants in Sediments

Background

Chemicals discharged from urban, industrial and agricultural sources can enter waterways and settle in sediments. These contaminants include a wide variety of toxic chemicals such as metals, polychlorinated biphenyls (PCBs; man-made chemicals primarily used as electrical coolants), polycyclic aromatic hydrocarbons (PAHs; chemicals made from petroleum products or resulting from the incomplete combustion of fossil fuels), polybrominated diphenyl ethers (PBDEs; a type of flame retardant), and other persistent pesticides (e.g. chlordane and dichlorodiphenyltrichloroethane (DDT). These chemical contaminants and their breakdown products can persist for long periods in sediments where they can be toxic to bottom-dwelling animals and can accumulate in their tissues and be transferred throughout the food web.

The concentrations of chemical contaminants and levels of sediment toxicity were assessed in sediments collected from the eight sampling stations in the Tred Avon River (Fig. WS1). Established criteria were used to classify degraded versus non-degraded conditions based on levels of sediment contaminants and toxicity (Table BH1).

Methods

We collected two replicate sediment samples from each of the eight selected sub-watershed sampling stations in the Tred Avon River in August 2015 using a Young-modified Van Veen sampler (Image BH1). The surficial 2–3 centimeters of sediment was removed from 2–3 grabs, homogenized, and divided into separate jars for metal, organic, and toxicity analyses. Containers were stored either in the freezer or refrigerator, as appropriate, and shipped while being kept cool to NCCOS Hollings Marine Laboratory, Charleston, SC for analyses.

Sediments were analyzed for the concentrations of 20 metals, 28 PAHs, 14 PBDEs, 86 PCBs, and 25 pesticides using analytical chemistry methods (Fulton et al. 2007; Leight et al. 2011). Concentrations of 24 chemicals (Appendix) were compared to sediment quality guidelines established by NOAA/NCCOS (Long et al. 1998; Hyland et al. 2003). For each of these chemicals there is an Effects Range Low (ERL) value which is the concentration where toxic impacts were measured in 10 percent of previous studies, and an Effects Range Median (ERM) value, which is the concentration at which toxic impacts were detected in 50 percent of previous studies. The ratio of the concentrations of each chemical in our samples to its ERM value is called the ERM Quotient (ERMq). The average ERMq for all 24 chemicals at a sample location is called the mean ERMq. This mean ERMq value is a measure of the overall toxicity of a sediment sample, based on the 24 chemicals considered (Hyland et al. 2003).

The U.S. Environmental Protection Agency (USEPA 2018b) credits the ERL and ERM as valuable benchmarks that assist in providing a uniform context for evaluating contaminant levels within estuaries. ERL and ERM are considered guidelines to help categorize the range of concentrations in sediment below which effects are scarcely observed or predicted (below the ERL) and the range above which effects are generally or always observed (above the ERM).

All values below the median detection limit (MDL) were treated as having a zero concentration. All PCB congeners (similarly structured molecules) were added together to compare against the "Total PCB" criterion.

Table BH1. Sediment contaminant criteria (mg/L = milligrams per liter; ERL = Effects Range Low; ERM = Effects Range Median; ERMq = Effects Range Median quotient).

Criteria (mg/L)	Score
No ERL exceedances	5
1 + ERL exceedance(s) & Mean ERMq < 0.098	2.5
Mean ERMq $\geq$ 0.098	0

Results

Table BH2. Sediment contaminant scores based on number of exceedances of Effects Range Low (ERL) and Effects Range Median (ERM) at eight sub-watershed sampling stations in the Tred Avon River in August 2015 (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek).

Station	Number of ERL Exceedances	Number of ERM Exceedances	Mean ERM Quotient	Score
TA1	8	0	0.138	0
TA2	2	0	0.05	2.5
TA3	2	0	0.051	2.5
TA4	0	0	0.045	5
TA5	0	0	0.04	5
TA6	0	0	0.032	5
TA7	0	0	0.038	5
TA8	4	0	0.116	0

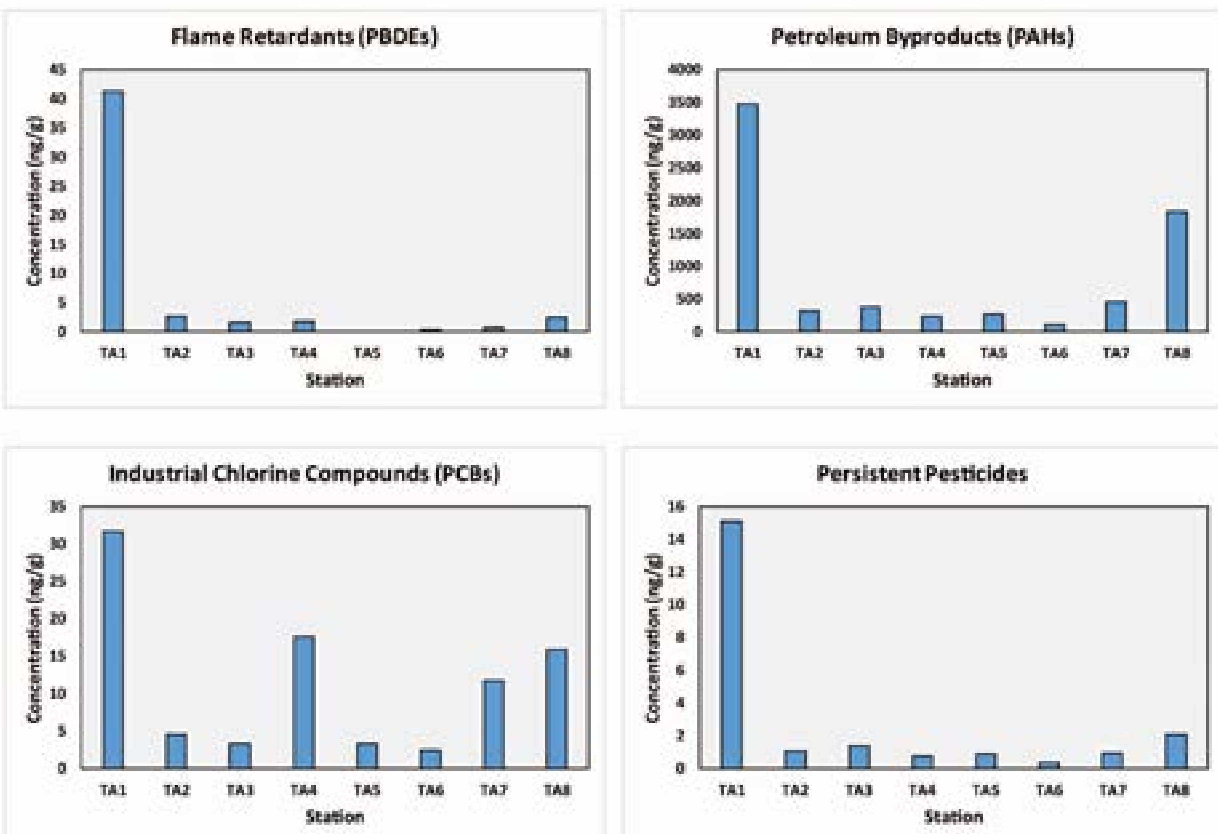


Figure BH1. Total concentrations of contaminants in nanograms per gram (ng/g) in sediments collected from the eight sub-watershed sampling stations in the Tred Avon River in August 2015 (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). The concentrations of all chemicals measured for each chemical class and sampling station were summed.

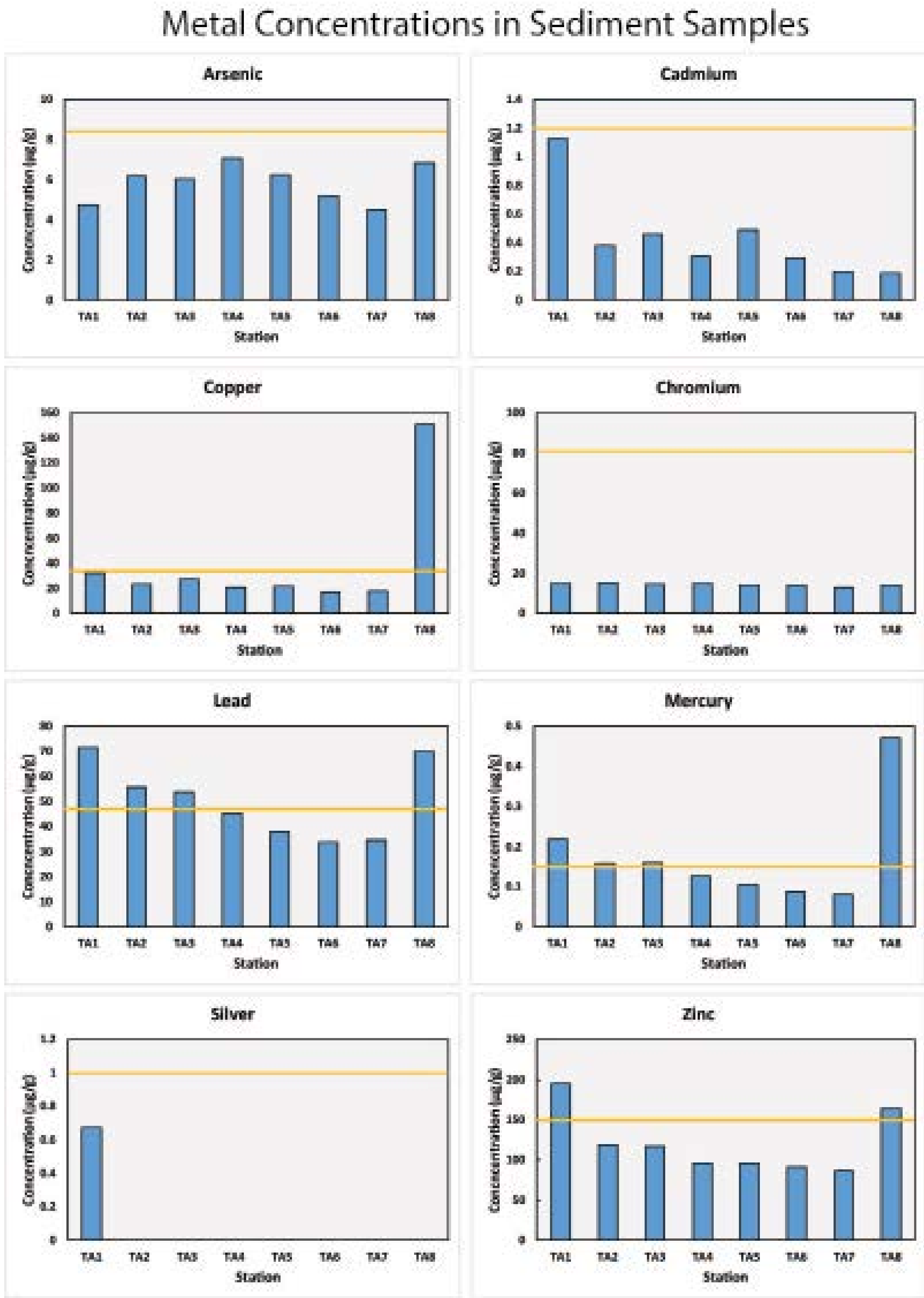


Figure BH2. Concentrations of selected metals in micrograms per gram in sediment samples from the eight sub-watershed sampling stations in the Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). Yellow lines show the Effects Range Low (ERL) value for each metal shown (Hyland et al. 2003).

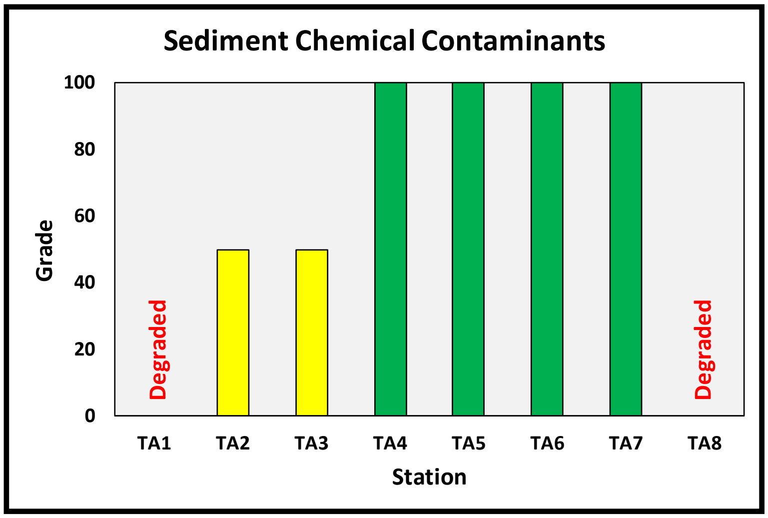


Figure BH3. Grading for the eight sub-watershed sampling stations in the Tred Avon River based on concentrations of the chemical contaminants that have existing sediment quality criteria (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek).

Sediment Contaminant Findings

- Easton Point (TA1) and Town Creek (TA8) were both degraded based on the presence of multiple contaminants above the ERL value and a high mERMq.
- The distribution of chemical contaminants in the benthic sediments suggests a connection with developed land in the surrounding drainage area, but with different mixtures of chemicals found at the two relatively developed areas, Easton Point (TA1) and Town Creek (TA8).
- Sixteen contaminants, primarily metals, were found at concentrations above their ERL value. Sources of metals to the Chesapeake Bay include atmospheric deposition, runoff from both urban and agricultural lands, and wastewater treatment plants (USEPA et al. 2012). The presence of all these sources in Town Creek (TA8) may have contributed to the high levels of some metals in that tributary.
- Easton Point (TA1) had the highest contaminant concentrations for PAHs, PCBs, and persistent pesticides.
- Town Creek (TA8) had the highest total metals concentrations.

Sediment Toxicity

Background & Methods

Whole sediment toxicity testing is a useful tool for predicting whether contaminated sediments will have adverse effects on benthic dwelling organisms. The Microtox® assay (Modern Water, Inc., UK) is an *in vitro* testing system which uses bioluminescent bacteria to detect toxic substances in sediment and other substrates. When exposed to a toxic substance, the respiratory process of the bacteria is disrupted and their luminescence is reduced. The percent of sediment in solution that causes a 50 percent drop in light from the bioluminescent bacteria, relative to the controls, is called the EC50. This term refers to the half maximal effective concentration or the amount of toxicant which induces a response halfway between the baseline and maximum after a specified exposure time. Since all the sediment samples examined in this study contained greater than 20 percent silt-clay content (Fig. BHPB1) as determined by the Benthic Index of Biotic Integrity, the relevant criteria is an EC50 of 0.2 percent (Ringwood et al. 1997).

Table BH3. Percent sediment in solution causing toxicity using Microtox® assay.

Criteria (%)	Condition
< 0.2	Toxic
≥ 0.2 – ≤ 0.3	Marginal
≥ 0.3	Non-toxic

Results

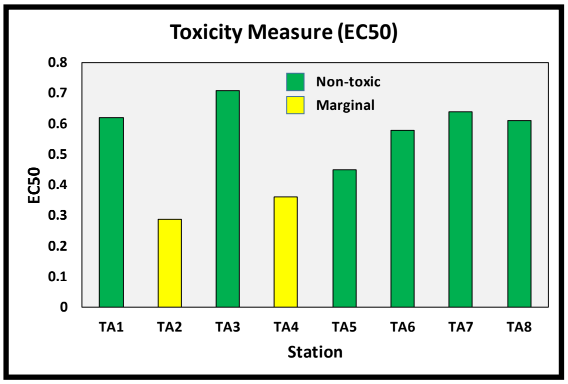


Figure BH4. Toxicity measure (EC50) based on Microtox® analysis of sediment samples from the eight sub-watershed sampling stations in the Tred Avon River in August 2015 (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek).

Sediment Toxicity Findings

- None of the sediment samples from any of the eight sub-watershed sampling stations in the Tred Avon River (TA1–TA8) were classified as toxic.
- Dixon Creek (TA2) and Maxmore Creek (TA4) had sediments with marginal toxicity, despite the relatively low concentrations of chemical contaminants at Maxmore Creek (TA4).
- The lack of toxicity for Easton Point (TA1) and Town Creek (TA8) indicates that the notable levels of chemical contaminants found in sediments from these sub-watersheds is not sufficient to cause toxicity in the Microtox® assay. The reason for this mismatch in results is unclear. Perhaps the levels of contaminants fall near to but below the level that would cause toxicity to the particular microorganism used in this toxicity test.

Benthic Index of Biotic Integrity

Background

The Benthic Index of Biotic Integrity (B-IBI) is a scientific tool used to identify and classify water and benthic habitat impairment by associating anthropogenic influences with biological activity for a body of water. B-IBI measures the condition of the benthic community living in or on soft bottom areas of a waterbody. The Chesapeake B-IBI (Llanso and Dauer 2002) was used to determine the quality of the eight sub-watersheds (TA1–TA8) in the Tred Avon River in terms of the benthic dwelling community.

Methods

We collected two replicate benthic samples and one sediment sample from unvegetated soft substrates (sand or mud) in August 2015 from the eight sub-watershed sampling stations in the Tred Avon River using a Young-modified Van Veen grab (Image BHX) with a sampling area of 0.0440 square meters to a depth of 10 centimeters. Benthic samples were gently sieved through a 0.5 millimeter mesh screen using ambient seawater. The material captured on the seive was transferred to 1 liter labeled plastic jars, preserved in seawater with 10 percent buffered formalin and Rose Bengal stain, and transported to the contracting laboratory for analysis.

In the lab, all benthic macroinvertebrates were removed, sorted by major taxonomic groups (i.e. Annelida, Mollusca, Crustacea) and identified to the lowest practical taxonomic level. Taxon specific, ash-free dry weight (AFDW) biomass was calculated using methods provided in USEPA, 1995. The eight sediment samples were each analyzed for percent silt/clay content distribution and percent water content per USEPA (1995) (Fig. BH1).

Results

All of the eight selected sub-watersheds in the Tred Avon River (Fig. WS1) fell within the mesohaline salinity class for applying the B-IBI metric scoring. Scoring of the mesohaline habitat is independent of sediment type (unlike several other habitats).

Benthic abundance and biomass data collected from the two replicate samples for each of the eight selected sub-watershed sampling stations were averaged and compared with established criteria. A score of 1 to 5 was assigned with lower scores representing higher degradation.

It should be noted that the B-IBI scale of values is 1 to 5 instead of the 0 to 5 scale applied in other variables reported in this document and is based on standard methods used to calculate the Chesapeake B-IBI (Llanso and Dauer 2002). Since the criteria are not evenly distributed between 1 and 5, the B-IBI is shown in the original scale and color code based on the criteria. These criteria were developed based on a set of restoration goals that describe the conditions of benthic communities expected in benthic habitats with little or no environmental stress or disturbance (Ranasinghe et al. 1994).

Table BC1. Criteria score for Benthic-Index of Biotic Integrity (#/m² = number per square meter; g/m² = gram per square meter).

	Criteria Score		
	5	3	1
Shannon-Wiener Diversity	≥ 2.5	≥ 1.7 – < 2.5	< 1.7
Abundance (#/m²)	≥ 1500 – < 2500	≥ 500 – < 1500 or 2500 – < 6000	≥ 500 – < 6000
Biomass (g/ m²)	≥ 5 – < 10	≥ 1 – < 5 or ≥ 10– < 30	< 1 or ≥ 30
Abundance of Pollution-Indicative Species (percent)	≤ 10	> 10 – ≤ 20	> 20
Biomass of Pollution-Sensitive Species (percent)	≥ 80	≥ 40 – < 80	< 40

Table BC2. Benthic-Index of Biotic Integrity (B-IBI) grades in the eight sub-watersheds of the Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek).

Grading of Average Variable Score	
B-IBI Score	Condition
≥ 3.0	Meets Restoration Goals
2.7 – 2.9	Marginal
2.1 – 2.6	Degraded
≤ 2.0	Severely Degraded

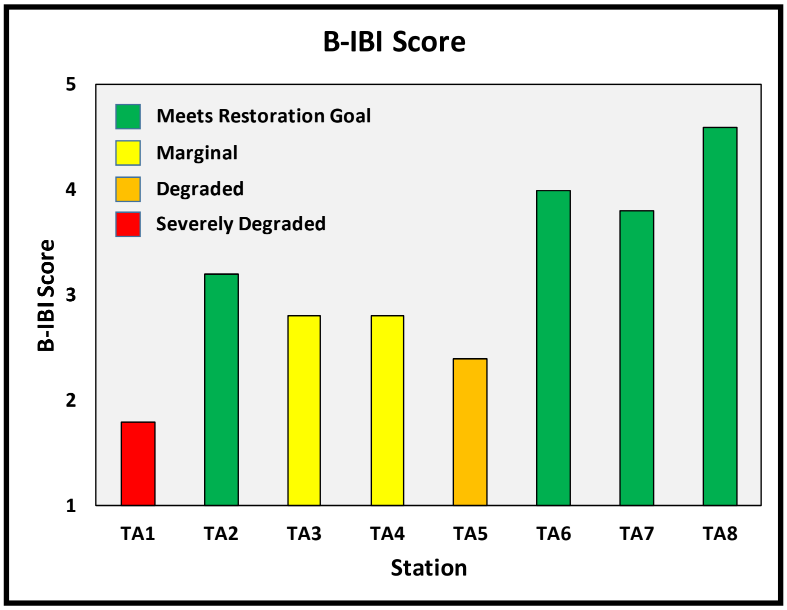


Figure BC1. Benthic-Index of Biotic Integrity (B-IBI) scores for the eight sub-watersheds in the Tred Avon River in August 2015 (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek).

Benthic Index of Biotic Integrity Findings

- The benthic community was severely degraded at Easton Point (TA1) and degraded at Trippe Creek (TA5).
- Despite being located in a relatively developed watershed, the benthic community at Town Creek (TA8) had the best B-IBI score.

Table BH4. Summary of benthic triad analysis for sediment samples collected from Tred Avon River stations in August 2015 (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek).

	TA1	TA2	TA3	TA4	TA5	TA6	TA7	TA8
Chemical Contaminants	Degraded	Marginal	Marginal	Good	Good	Good	Good	Degraded
Toxicity	Good	Marginal	Good	Marginal	Good	Good	Good	Good
Benthic Community	Severely Degraded	Good	Marginal	Marginal	Degraded	Good	Good	Good

Benthic Habitat Findings

- Each of the eight sub-watershed sampling stations (TA1–TA8) was dominated by fine particles (silt and clay), with slightly more sand particles occurring at Easton Point (TA1).
- The benthic community was severely degraded at Easton Point (TA1), the uppermost and most urban sub-watershed of the Tred Avon River in this study. Eight chemical contaminants at Easton Point (TA1) exceeded their ERL values. There is also seasonal hypoxia in bottom waters here.
- In contrast, the benthic community at Town Creek (TA8), also associated with relatively high developed land and impervious surface, met criteria for un-degraded conditions, despite the presence of four metals exceeding their ERL values. Dissolved oxygen in bottom waters was a much higher concentration at Town Creek (TA8) than at Easton Point (TA1).
- Compared to sediment contaminant levels measured in 210 samples from the mainstem and the lower sections of most rivers of the Chesapeake Bay (Hartwell and Hameedi 2007), the contaminant levels in the Tred Avon River were most similar to sites on the eastern shore of Maryland and middle reaches of the main-stem Bay, with relatively low inputs for land based sources and relatively low concentrations of persistent chemical contaminants in benthic sediments. However, contaminant levels at Easton Point (TA1) and Town Creek (TA8) are more typical of some western shore locations where increased inputs from urban land use results in greater inputs, but well below that of stations in highly-industrialized Patapsco (MD) and Elizabeth (VA) Rivers.

CHEMICAL CONTAMINANTS IN FISH TISSUE


Image CF1. Fish species collected for whole body contaminant analyses include *Morone americana* (white perch), a source of seafood in Chesapeake Bay (left), and *Fundulus heteroclitus* (mummichog), (right).

Background

Environmental contaminants can have negative impacts on ecosystem condition as well as fish health by reducing growth, development, reproduction, and survivability of individuals and populations. In addition, the condition of animals that consume contaminated fish such as birds, mammals and humans may also be at risk. Therefore, it is important to examine fish tissue as well as biological, physical and chemical indicators of water quality to capture a complete picture of aquatic ecosystem condition.

Metals and organic compounds are two kinds of chemical contaminants found in the Chesapeake Bay. The most common metal contaminant found in the watershed is mercury according to a U.S. EPA study (USEPA et al. 2012). Although mercury is a naturally occurring element, more than two-thirds of the mercury in the atmosphere comes from human-made products and energy production activities. Mercury is released into the atmosphere through a variety of means such as evaporation from water and land, but primarily through coal-fired utility and incinerator emissions. It enters the watershed through runoff, atmospheric deposition, and when mercury products are poured down household and industrial drains. Once in the water cycle, mercury can convert to methyl mercury which can accumulate in the tissues of fish and other organisms and may be carried up the food chain. Humans are exposed to mercury through fish consumption, contact absorption, or through the inhalation of toxic elemental mercury fumes. Acute exposure to mercury most commonly affects the central nervous system and kidneys in fish, birds and mammals (USEPA 2011).

Common organic chemical contaminants found in the Chesapeake Bay include polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs) and pesticides. PCBs act as flame retardants in electrical equipment and have also been used in the production of inks, adhesives, sealants and caulk. Although PCBs have not been produced in the United States since a 1977 ban, the chemicals continue to enter the environment through accidental leaks, improper disposal, and "legacy deposits." They are widely distributed in aquatic ecosystems, remain sufficiently high in many water bodies to contaminant the food web, and result in consumption advisories for valuable fish and shellfish species (USEPA 2011).

A study by King et al. (2004) showed that levels of PCB concentrations in white perch (*Morone americana*) are strongly linked to the percent of development in a watershed in the Chesapeake Bay, with dangerous PCB levels attained at a relatively low percent of development. PCB levels in fish begin to exceed U.S. EPA recommended levels for restricting food consumption before development reaches 20 percent of the watershed area (King et al. 2004). Levels of PCBs in white perch are more highly influenced by the percent of commercial development closer to the shoreline than by commercial development farther away. This relationship exists for watersheds with less-intensive residential/suburban development as well as watersheds with much urban/commercial development. The type of land use, particularly development, and its proximity to the estuary's tributaries have important impacts on the PCB levels in white perch. In addition to PCBs, the metals mercury and copper are known to bioaccumulate in fish and can cause toxicity to both the fish and its prey, including humans.

The mummichog (*Fundulus heteroclitus*) is an abundant estuarine fish that can tolerate widely varying environmental conditions. Mummichogs are found along muddy marshes, tidal creeks and the sheltered shores of the Chesapeake Bay and serve as an extremely important food source for many larger fish, and shore and sea birds. Mummichogs have a relatively small home range and have been a popular model in toxicological studies. Populations have been reported to develop resistance to methylmercury, kepone, dioxins, polychlorinated biphenyls, and polyaromatic hydrocarbons (Weis 2010).

In this study, the entire bodies of the white perch and mummichogs sampled were analyzed for chemical contaminants as described below.

Methods

Whole white perch from six composite samples were collected in October 2016 and analyzed for chemical contaminant levels. Three pools of 4 adult white perch were collected by hook and line from both the upper (near Easton Point) and the lower Tred Avon River (Fig. WS1). Because initial sampling efforts were unsuccessful in collecting sufficient numbers of white perch within each of the eight selected sub-watershed sampling stations in the Tred Avon River, white perch collections were split between the upper Tred Avon (TAU) and lower Tred Avon (TAL). These regions are demarcated by a line running east to west at Double Mills Point (Figure WS1). Fish were cut ventrally to determine gender and otoliths were removed and examined under a microscope to determine age. White perch of five to seven years of age and equal proportions of males and females formed each pool. Each fish was wrapped separately in acetone-washed aluminum foil, labelled, and placed in plastic storage bags.

Mummichogs were also collected in October 2016 from each of the eight sampling stations in the Tred Avon River using seine nets and minnow traps. Three pools of approximately 10 fish were collected from each of the eight sub-watersheds (TA1–TA8) (Fig. WS1). Mummichogs ranged in size from 60 to 110 millimeters with a similar range of sizes for each composite sample. Pools of fish were wrapped in acetone-washed aluminum foil, labelled, and placed in plastic storage bags.

All white perch and mummichog samples were held on ice in the field and then stored in a –20°C freezer until shipped to NOAA/NCCOS Hollings Marine Lab, SC for further processing. Each pool of whole fish was homogenized and examined for 152 chemical contaminants following standard methods (Balthis et al. 2012).

Results

Contaminant Concentrations in Fish Tissue

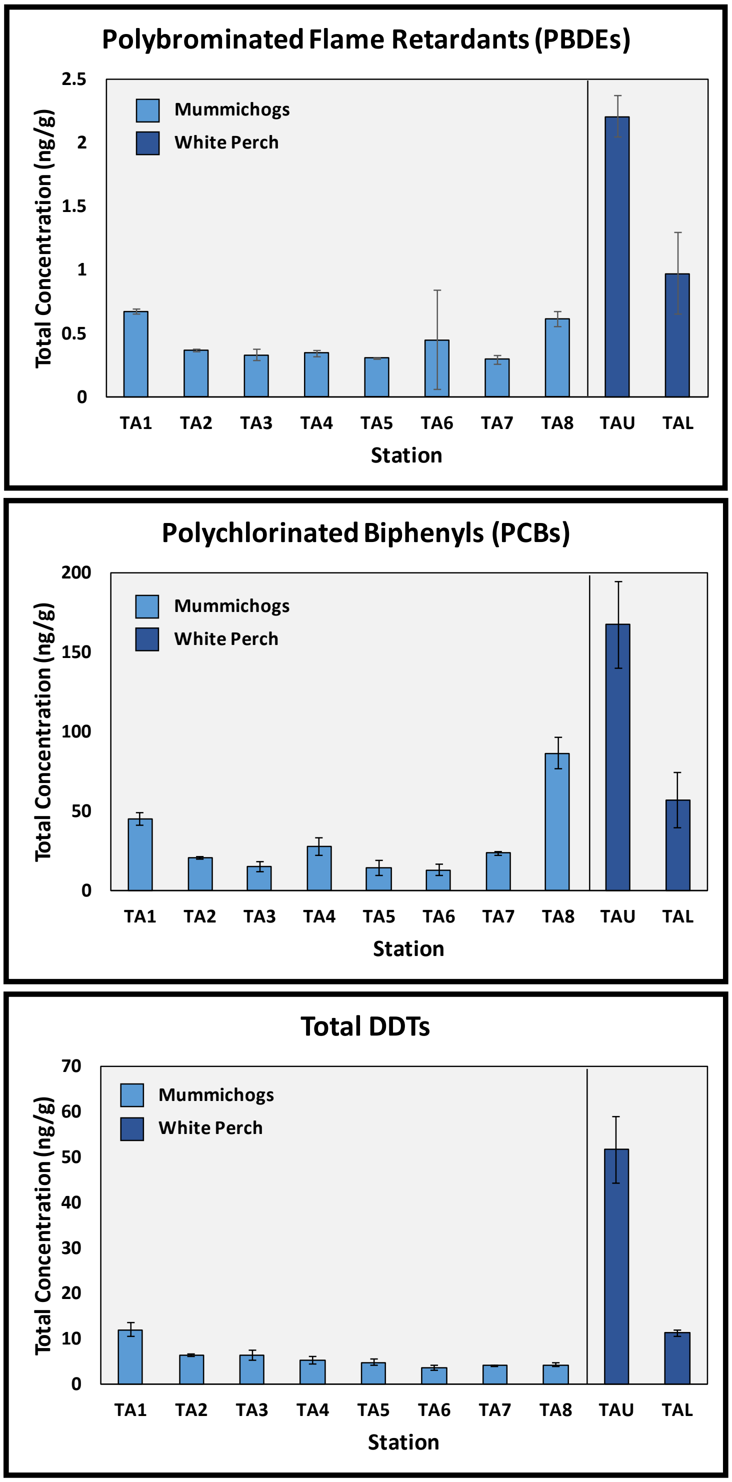


Figure CF1. Total concentrations of classes of contaminants in nanograms per gram (ng/g) in whole bodies of mummichogs (*Fundulus heteroclitus*) and white perch (*Morone americana*) collected from ten Tred Avon River locations in October 2016 (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek; TAL–Lower Tred Avon River; TAU–Upper Tred Avon River). The concentrations of all chemicals measured for each chemical class and sub-watershed sampling station were summed for each of three replicate samples. These totals were then averaged across the three replicate samples. Error bars represent 95 percent confidence limits around those averages.

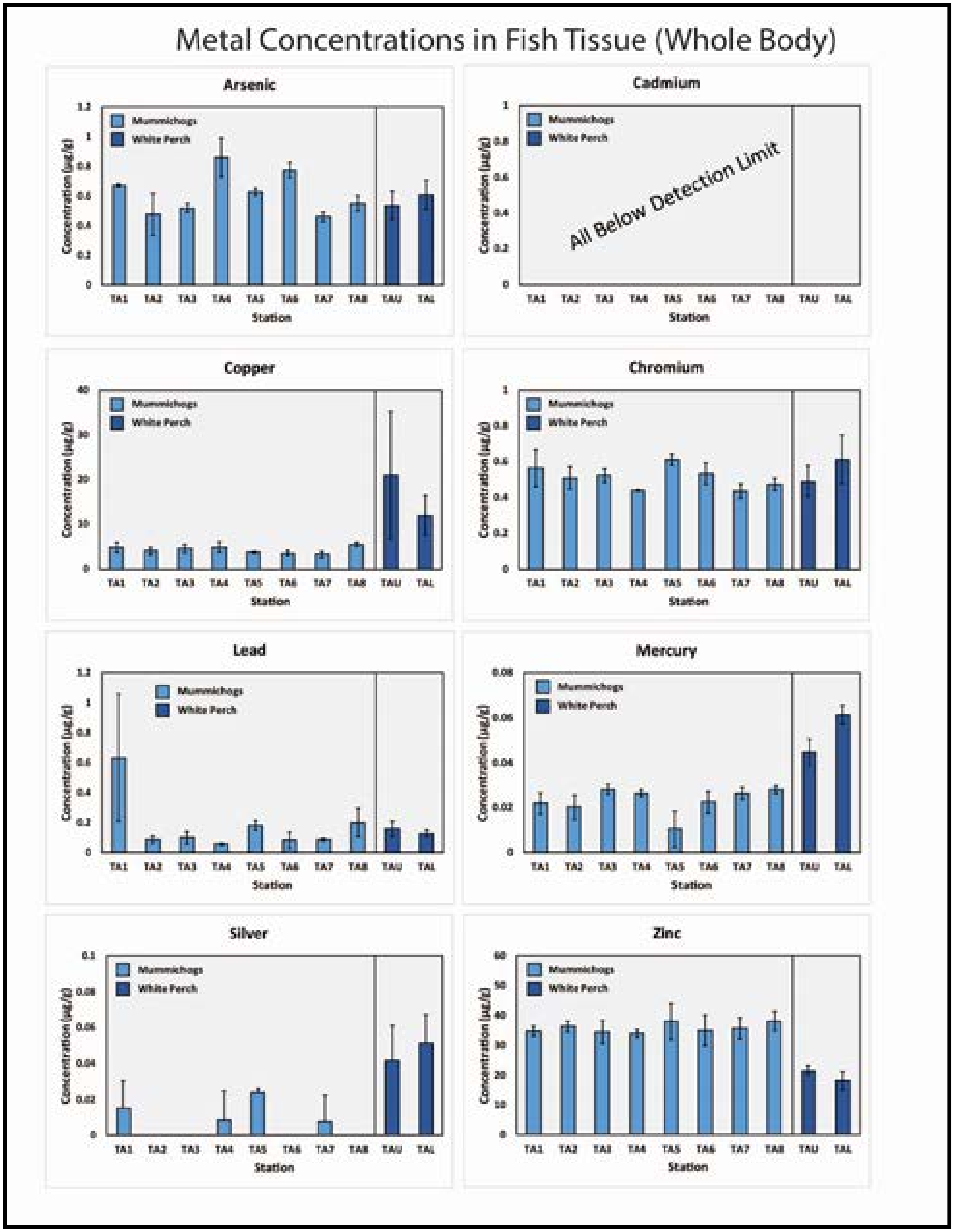


Figure CF2. Total concentrations of selected metals in micrograms per gram (µg/g) in whole bodies of mummichogs (*Fundulus heteroclitus*) and in whole bodies of white perch (*Morone americana*) collected from ten locations in the Tred Avon River in October of 2016 (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek; TAL–Lower; TAU–Upper). Error bars represent 95 percent confidence limits.

Table CF1. Contaminants detected at concentrations above the minimum detection level (MDL) in composite fish samples for white perch and mummichogs.

Metric	Number
Compounds measured	152
Compounds detected above MDL	123
Compounds detected above MDL in all samples	78

Criteria for Assessment

Unlike the established criteria for water quality and benthic habitat variables, the levels of fish tissue contamination that might be expected to have impact on white perch and mummichogs are generally not well understood and no published criteria have been developed. Where criteria exist, they are primarily for human health consumption advisories. However, several studies have provided some useful concentration thresholds for select chemicals and for converting the levels of chemicals in the whole fish body (measured in this study) to those expected in fish muscle (on which human health advisories are based).

Polychlorinated Biphenyls (PCBs)

Based on an extensive literature review (TAMS and MenzieCura 2000), a no-observable-adverse-effects level (NOAEL; the level expected to have observable negative impacts to the fish) of 1900 parts per billion (nanograms per gram) and a lowest observable adverse effect level of 9300 parts per billion for whole body measurements have been calculated for total PCB concentrations. The U.S. EPA has suggested a screening value (the level at which consumption of the fish may have negative impacts on humans) of 12 parts per billion for PCBs in fish fillets (not whole bodies) (USEPA 2014). Using a published conversion ratio of 1.7:1 whole body to fillet for PCB concentrations in fish, the EPA screening value is 20.4 parts per billion.

Metals

Although we did not specifically measure methlymercury, the most toxic form of mercury in tissue, previous studies have determined that most mercury found in fish tissue is in the form of methylmercury (Wagemann et al. 1997). Therefore, we compare mercury levels from our results to those from studies that have found toxic impacts from methylmercury. For example, whole body methylmercury concentrations as low as 0.3 to 0.7 parts per million (microgram per gram) have been found to impact fathead minnow (*Pimephales promelas*) behavior and spawning success (USEPA et al. 2012). The U.S. EPA screening value that is used for formulating fish consumption advisories based on mercury concentration in fish fillets is 0.3 parts per million.

Dichlorodiphenyltrichloroethane (DDT)

Beckvar et al. (2005) suggested that DDT concentrations in whole bodies of fish above 700 parts per billion might have negative, sublethal impacts to the fish. The U.S. EPA has suggested a screening value for fish consumption advisories of 69 parts per billion for fish fillets. In our study, the highest total DDT concentration was 67 parts per billion in whole bodies of white perch from the upper Tred Avon River site (TAU). Although studies have shown that DDT levels tend to be higher in the liver and gills than in the muscle (Pan et al. 2016; Aamir et al. 2016), we did not find a specific published ratio for converting DDT concentrations in the whole bodies of estuarine fish to fillet concentrations.

FISH CONSUMPTION ADVISORIES

Maryland Department of the Environment (MDE) monitors and evaluates contamination levels in fish, shellfish, and crabs throughout Maryland and issues guidelines for recreationally-caught seafood. MDE (2018) has developed an interactive map that provides modernized, user-friendly information on fish consumption advisories for recreationally caught fish.

A consumption advisory is a recommendation to limit or avoid eating certain species of fish caught from specific water bodies due to contaminant levels. Advisories by MDE are based upon PCB levels in fish fillets. Fish from locations across Maryland are tested for two contaminants: methylmercury and polychlorinated biphenyls (PCBs). Both contaminants are thought to pose risks to developing brains, and PCBs are suspected to cause cancer in humans. MDE bases a recommended limit on consumption based on a health risk analysis for a given species from a particular body of water.

For the Tred Avon River, there is a white perch consumption advisory for children due to PCBs (e.g. limit of six meals/month) but not for the general public. In the Choptank River, there are similar advisories for children due to the levels of PCBs in several fish species including white perch.

Chemical Contaminants in Fish Tissue Findings

- Out of 152 compounds measured, 123 were detected at concentrations above the minimum detection level. Seventy-eight of these chemicals were detected above the minimum detection level at all of the 10 sampling areas (eight mummichog and two white perch areas).

- For white perch, fish collected from the upper Tred Avon River (TAU) contained higher concentrations of PCBs, pesticides, and PBDEs than fish from the lower Tred Avon River (TAL), while fish from the lower Tred Avon River (TAL) contained higher levels of several metals.

- Levels of PCBs, pesticides, and PBDEs were lower in mummichogs than in white perch, likely reflecting the lower trophic level of mummichogs and reduced bioaccumulation of these contaminants. PCB concentrations in mummichogs were highest in the two sub-watersheds of the Tred Avon River with the highest amount of developed and impervious land, Easton Point (TA1) and Town Creek (TA8).

- Mercury, PCB, and DDT levels in fish tissues were below levels that indicate impact to the fish, though these reference levels are only considered for each contaminant separately and the combined effect of multiple contaminants to the fish is unknown.

- Using a published ratio to convert PCB levels from whole-body to fillet, the levels of PCBs in white perch from the upper Tred Avon River (TAU) would exceed the EPA screening level for fish consumption.

- Lead and persistent pesticide (e.g. DDT) concentrations were highest at Easton Point (TA1) for both sediment and mummichog tissues. However, most other contaminants did not show similar trends between sediment and mummichog tissues from the same sub-watershed, likely because the mummichog diet is only partially connected to benthic sediments (James-Pirri et al. 2001).

FISH COMMUNITY COMPOSITION

Image FC1. NOAA scientists from Cooperative Oxford Laboratory pull a seine net in fish community composition sampling for the Tred Avon River ecological assessment.

Background

The Chesapeake Bay ecosystem supports a large number of fish species and is a critical nursery and foraging habitat for many migratory fishes (Murdy et al. 1997, Able and Fahay 2010, Buchheister et al. 2013). As with most estuarine and coastal environments, the system is influenced by a variety of stressors including eutrophication, fishing, and climate change. These stressors combine with natural environmental conditions to structure the local fish community in terms of abundance, distribution, and diversity of member species (Buchheister et al. 2013).

The structure of a fish community is determined by the species present and their relative abundances, life stages and size distributions, and its distributions in space and time. Natural variability in fish communities can be related to physical habitat, temperature, salinity, water quality, and other environmental characteristics. High degrees of variability may occur in fish communities due to the geographic distribution of species, alterations in landscape, presence or absence of non-native species, and availability of food and spawning grounds.

In spite of natural variability, fish communities can serve as useful indicators of ecosystem condition by measuring their abundance and diversity (Moyle 1994). Abundance is a measure of the relative proportions of a given group of species in a given environment (Lancia et al. 2005; Leight et al. 2015). In this document, we use abundance to describe the number of fish caught per trawl or seine. Diversity is a measure of the number of species and their abundance in an ecological community. Species richness refers to the number of species in an area. An ecosystem in good condition supports an abundance of fish and a diversity of species. Low abundances and low diversity of fish species may be associated with degraded water quality and habitat due to surrounding land use.

In our fish community composition studies, our primary goals were to assess the relationship between measures of the aquatic ecosystem and watershed land-use effects on fish community composition. We measured the abundance, richness, and diversity of fish in both nearshore shallow waters and mid-river habitats at eight stations in the Tred Avon River every two weeks from July through October over the period 2015–2017.

Methods

We identified, counted, and recorded all species of fish captured in seine and trawl nets at the eight selected sub-watershed sampling stations in the Tred Avon River (Fig. WS1). A 100–foot beach seine and 16–foot otter trawl were deployed in a standardized manner at each station (Messick et al 2013). Sampling occurred annually (2015–2017) with a periodicity of every 2 weeks from July – October. Physiochemical measurements were collected via YSI 6600 data sonde at each sub-watershed sampling station. Water clarity was measured using a Secchi disk.

Differences in abundance of fish caught in open waters using a trawl was compared with abundance of fish caught in near shore shallow waters using a seine. The number of fish species, or species richness, was determined for each catch. To assess ecological community balance, we used the Shannon-Weiner diversity index (Shannon and Weiner 1949) to calculate species evenness, telling us how close in numbers each species in an environment is, and as a relative measure of community condition (Leight et al. 2014).

To align with Chesapeake Bay report cards, scores for abundance were calculated by binning total catch into 5 even quartiles (e.g., 0–20, 21–40, 41–60, 61–80, 81–100) thus converting total catch to a grade of 0 to 100.

Image FC2. Fish caught in nearshore shallow waters using a seine are identified and counted before being returned to the Tred Avon River.

Results

Table FC1. Score criteria for fish abundance.

Score Criteria for Fish Abundance					
Abundance data quartiles	0–20%	21–40%	41–60%	61–80%	81–100%
Score	0–20	21–40	41–60	61–80	81–100

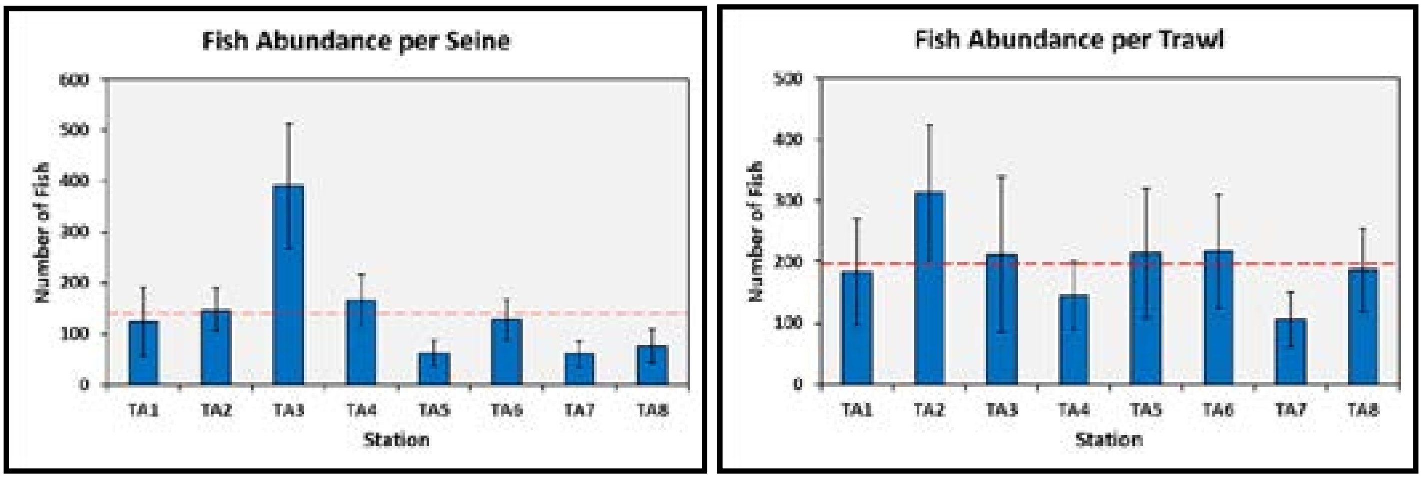


Figure FC1. Comparison of average abundance of fish caught in shallow nearshore waters using a seine (left) and open waters using a trawl (right) in 2015–2017 at the eight sub-watershed samplings stations in the Tred Avon (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). Red line is mean abundance across all sites. Error bars represent 95 percent confidence intervals.

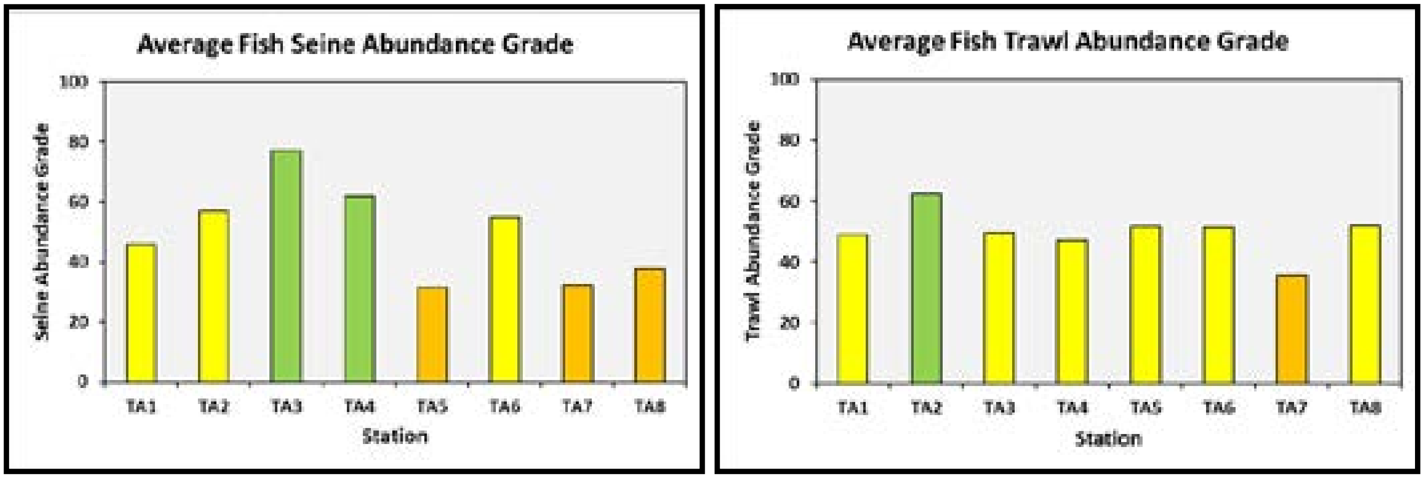


Figure FC2. Average fish seine (left) and trawl (right) abundance grades from 2015–2017 at the eight sub-watershed sampling stations in the Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek).

Seine Abundance

Station	2015	2016	2017
TA1	60	51	23
TA2	76	59	33
TA3	89	72	69
TA4	72	60	52
TA5	59	19	15
TA6	71	45	48
TA7	35	31	30
TA8	41	38	33
AVG	63	47	38

Trawl Abundance

Station	2015	2016	2017
TA1	44	39	59
TA2	64	58	66
TA3	53	46	49
TA4	37	45	54
TA5	50	43	65
TA6	55	38	63
TA7	11	42	56
TA8	52	46	53
AVG	46	45	58

Figure FC3. Heat map of fish abundance grades for seine (left) and trawl (right) hauls for years 2015–2017 at the eight sub-watershed sampling stations in the Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). Averaging across rows will provide the same values shown in Fig. FC2.

Submerged Aquatic Vegetation

We observed increases in submerged aquatic vegetation (SAV) in the Tred Avon River which corresponds with increases seen in the annual, Chesapeake Bay–wide survey by the Virginia Institute of Marine Sciences (VIMS; VIMS 2018). The VIMS survey found that the total size of SAV beds in the Chesapeake Bay surpassed 100,000 acres in recent years (2016–2017), the highest reported since the survey began in 1984 (VIMS 2018). This increase in SAV provides clear evidence of improvements in the Chesapeake Bay and in rivers such as the Tred Avon (Lefcheck et al. 2018), since SAV is sensitive to pollution but quick to respond to water quality improvements (Leslie 2018). In 2014, there were 22 hectares of SAV in the Tred Avon River. About 70 percent of the individual beds had moderate to dense ratings for density (greater than 40 percent coverage of the bed area) (Dorfman et al. 2016).

Similarly, we noted SAV at our seining locations in several sub-watersheds of the Tred Avon including Dixon Creek (TA2), Shipshead Creek (TA3), and Maxmore Creek (TA4). These areas also showed the highest fish abundance and diversity per seine. It is possible that the presence of SAV may be related to the observed increases in fish abundance and diversity.

Twenty-four different species of fish were identified in seine and trawl collections in the eight selected sub-watershed sampling stations in the Tred Avon River over the period 2015–2017. In the trawl collections, bay anchovies (*Anchoa mitchilli)* were the most prevalent fish observed and constituted 72–90 percent of the total fish abundance at each station. Other species caught in the trawls included white perch (*Morone americana*), striped bass (*Morone saxatilis*), hogchoker (*Trinectes maculatus*), weakfish (*Cynoscion regalis*), Atlantic croaker (*Menedia menedia*), spot (*Leiostomus xanthurus*), and flounder (*Paralichthys dentatus*).

The fish species most commonly observed in seine collections throughout the three–year survey included the Atlantic silverside (*Menidia menidia*), mummichog (*Fundulus heteroclitus*), sheepshead minnow (*Cyprinodon variegatus*), white perch (*M. americana*), striped killifish (*Fundulus majalis*), banded killifish (*Fundulus diaphanous*), bay anchovy (*A. mitchilli)*, and menhaden (*Brevoortia tyrannus*).

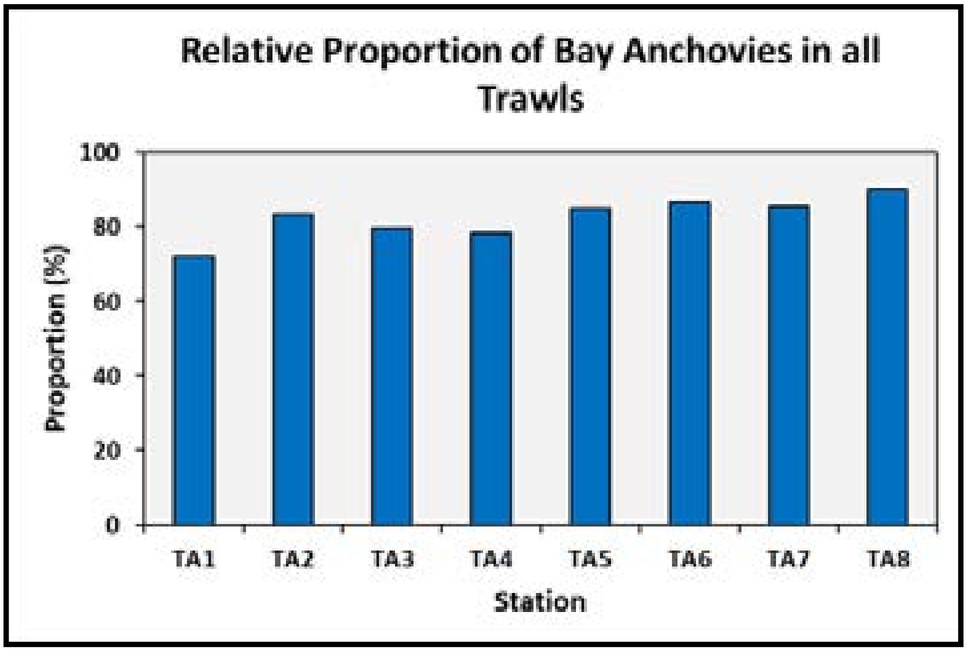


Figure FC4. Relative proportion of bay anchovies (*Anchoa mitchilli*) caught in open water using a trawl in 2015–2017.

The following figures (Fig. FC5–FC9) illustrate the average relative abundance of the top six fish species caught using a seine in shallow near shorewaters at each of the eight selected sub-watershed sampling stations in addition to the average relative abundance of all other species. The relative abundance is the percent composition of a fish species relative to the total number of fish species in the area sampled. The average relative abundance is calculated as the abundance of a species, divided by the total abundance of all species combined. Since bay anchovies were the most prevalent fish observed in trawls, relative abundance charts were not produced for our trawl data.

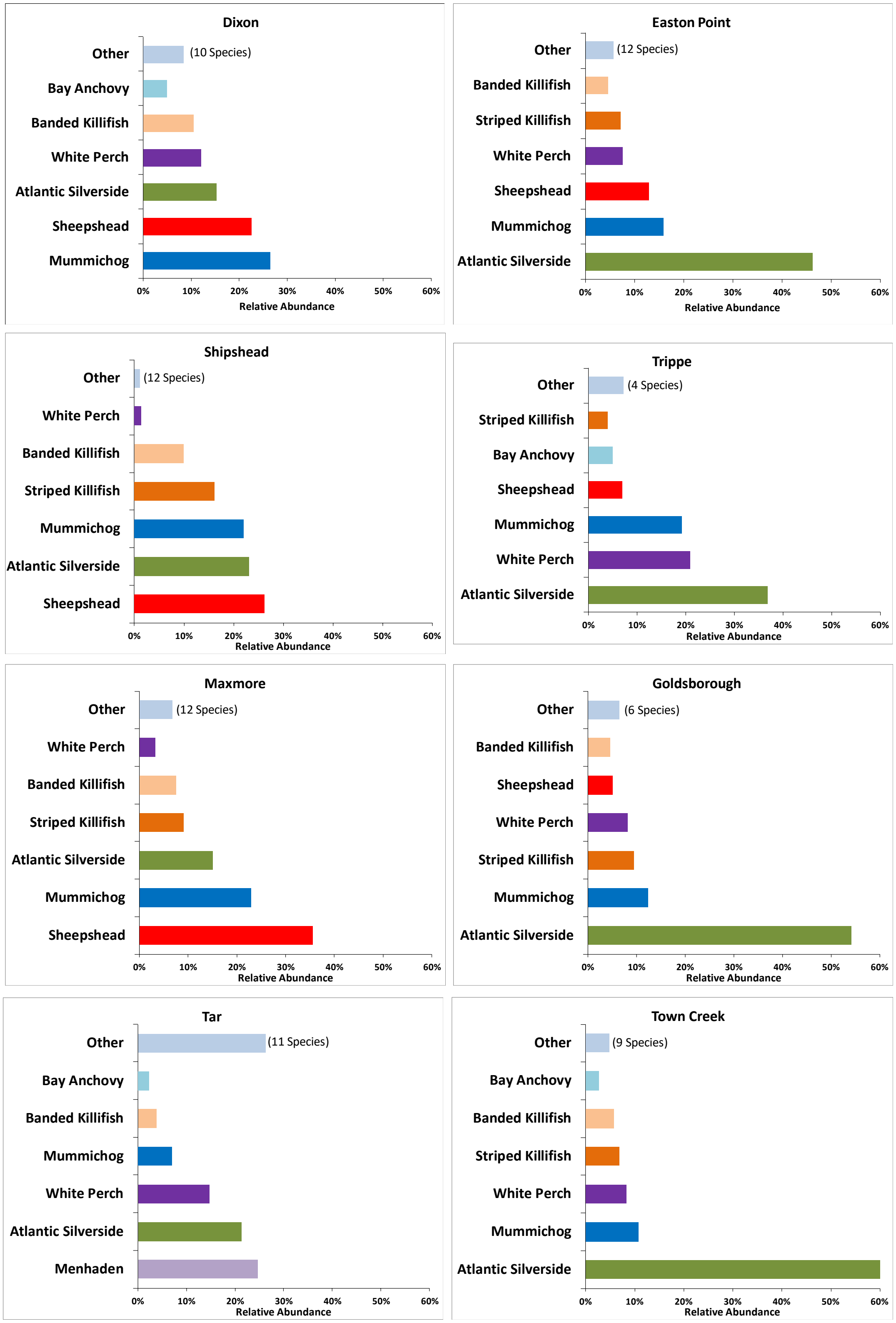


Figure FC5. Average relative abundance of the six most abundant species collected by seine at each of the eight sub-watershed sampling stations in the Tred Avon River in 2015-2017 and the total relative abundance of all other species (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). Relative abundance is the percent composition of a fish species relative to the total number of fish species in the area. 'Sheepshead' refers to sheepshead minnow. Sub-watersheds are arranged in a clockwise fashion starting with the most northwesterly station in the Tred Avon River (TA2 Dixon Creek) (Fig. WS1).

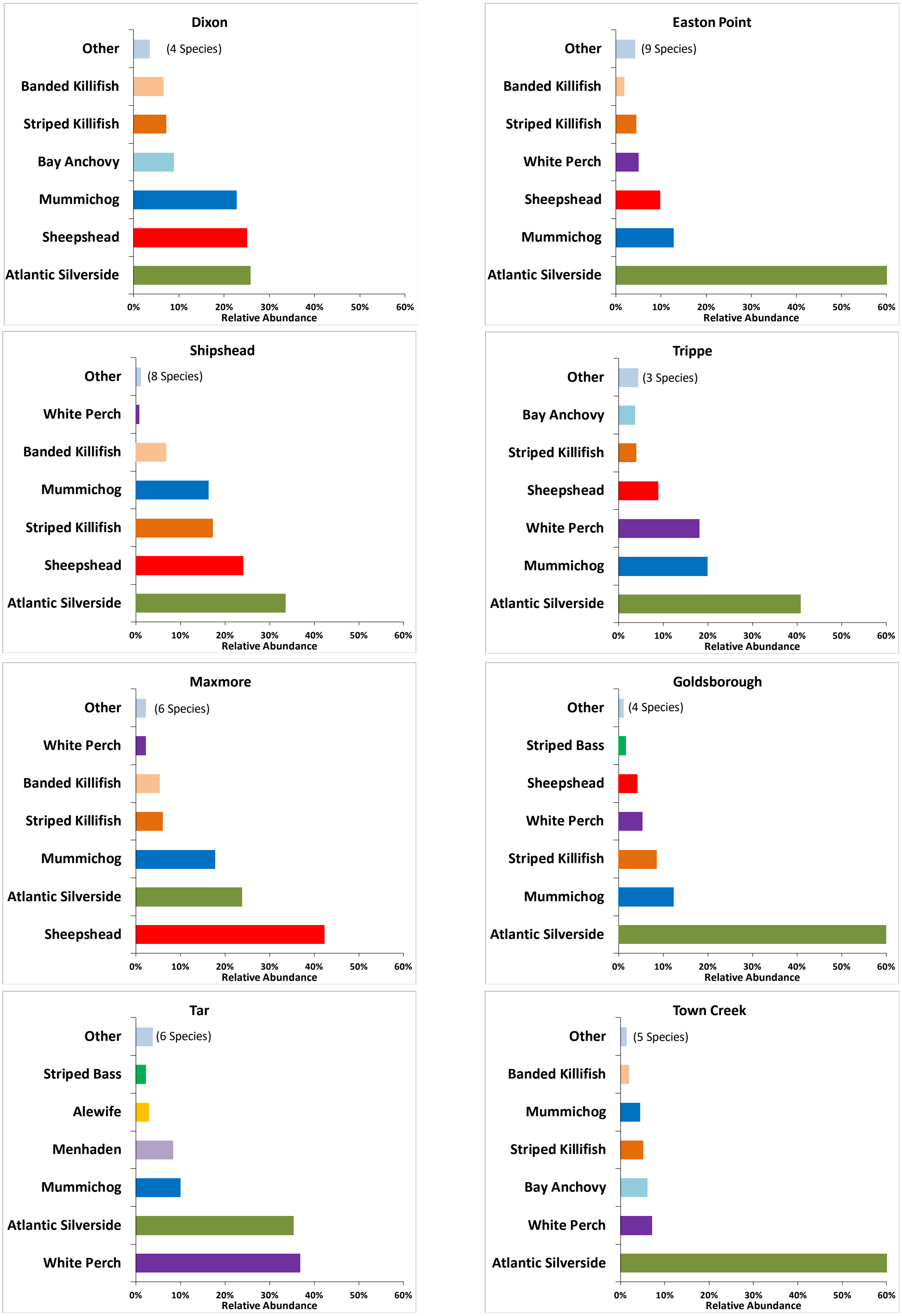


Figure FC6. Average relative abundance of the six most abundant species collected by seine at each station in the Tred Avon River in 2015 and total relative abundance of all other species (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). Relative abundance is the percent composition of a fish species relative to the total number of fish species in the area. 'Sheepshead' refers to sheepshead minnow. Sub-watersheds are arranged in a clockwise fashion starting with the most northwesterly station in the Tred Avon River (TA2 Dixon Creek).

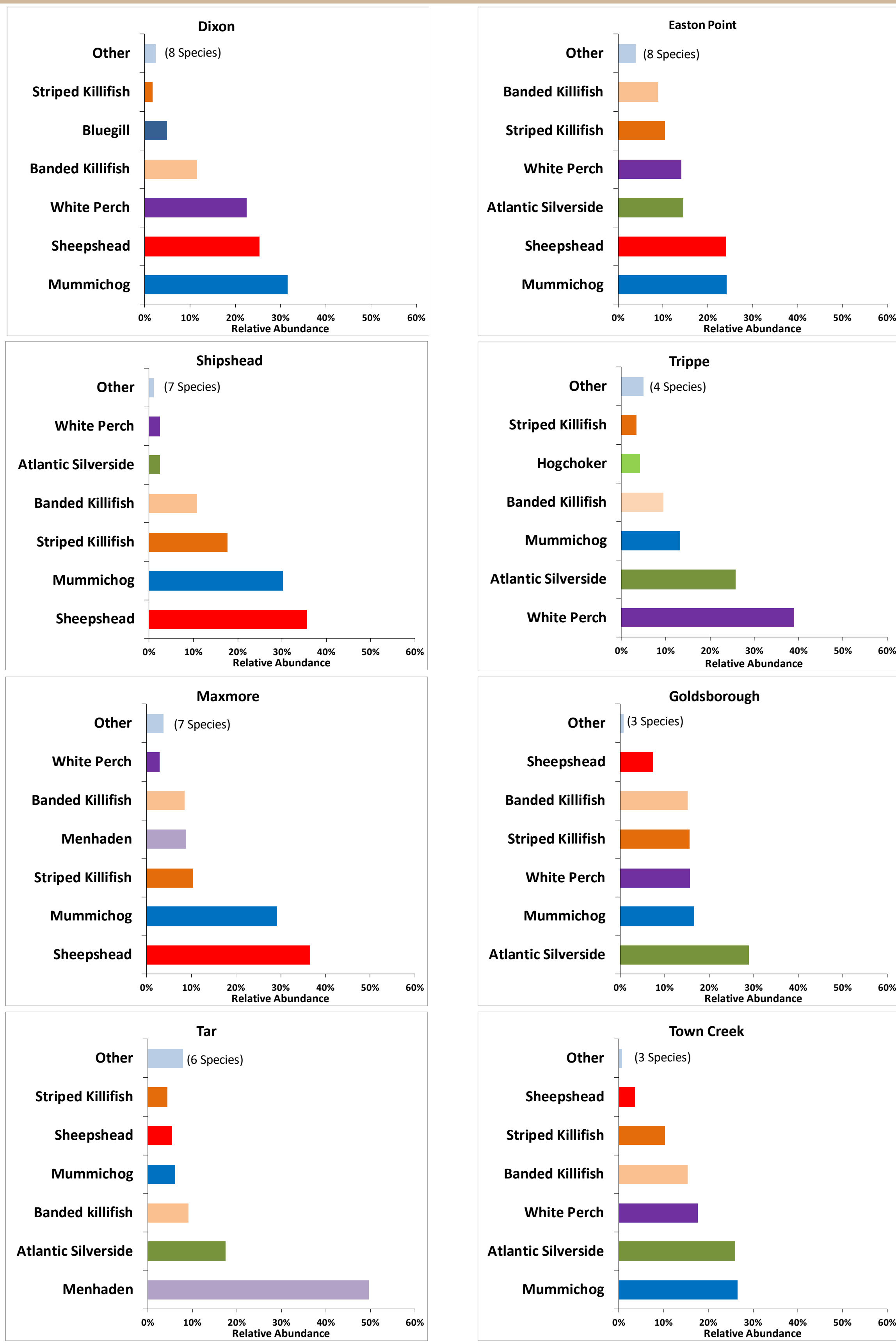


Figure FC7. Average relative abundance of the six most abundant species collected by seine at each of the eight sub-watershed sampling stations in the Tred Avon River in 2016 and total relative abundance of all other species (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). Relative abundance is the percent composition of a fish species relative to the total number of fish species in the area. 'Sheepshead' refers to sheepshead minnow. Sub-watersheds are arranged in a clockwise fashion starting with the most northwesterly station in the Tred Avon River (TA2 Dixon Creek) (Fig. WS1).

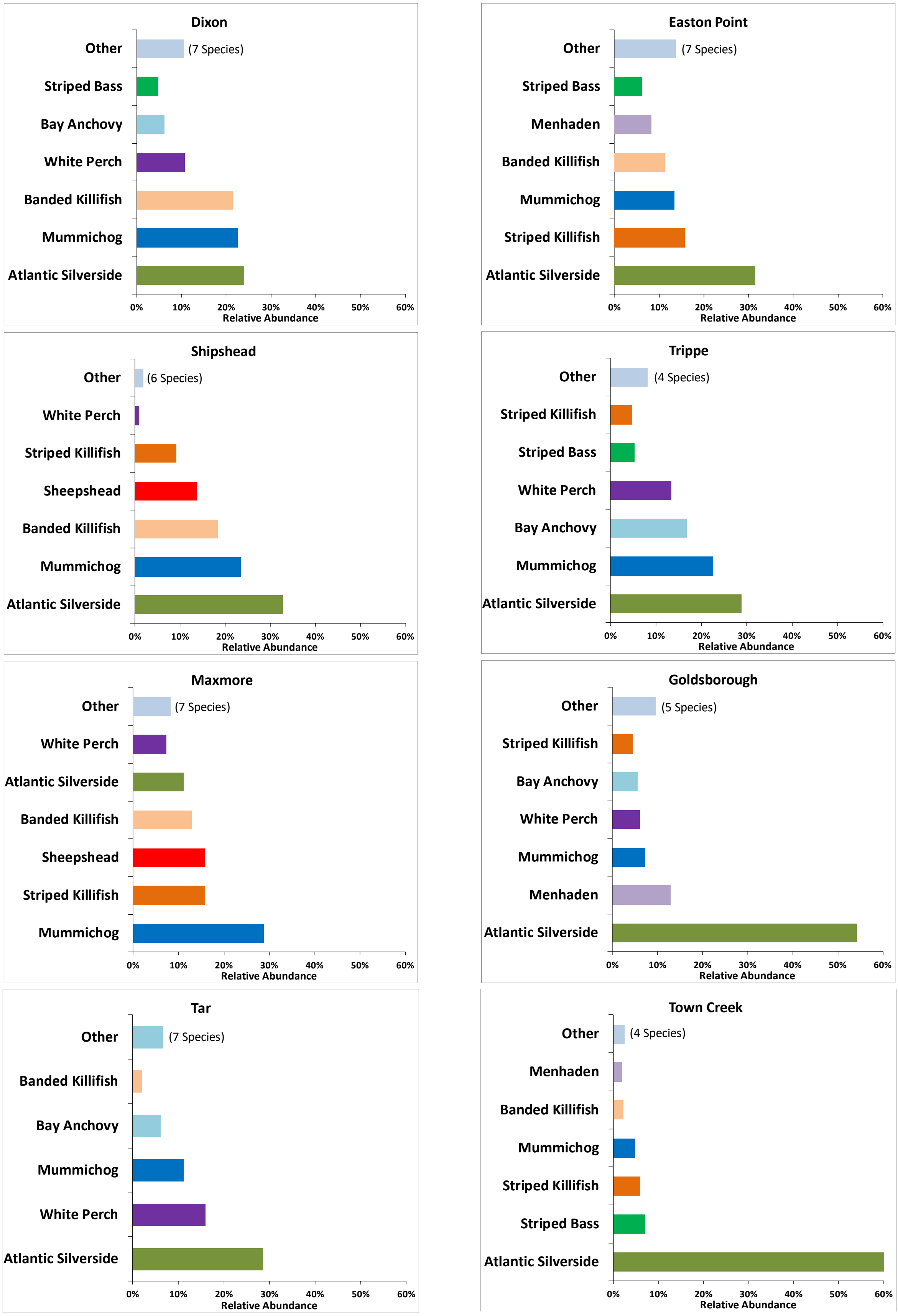


Figure F8. Average relative abundance of the six most abundant species collected by seine at each of the eight sub-watershed sampling stations in the Tred Avon River in 2017 and the total relative abundance of all other species (TA1 Easton Point; TA2 Dixon; TA3 Shipshead; TA4 Maxmore; TA5 Trippe; TA6 Goldsborough; TA7 Tar; TA8 Town Creek). Relative abundance is the percent composition of a fish species kind relative to the total number of fish species in the area. 'Sheepshead' refers to sheepshead minnow. Sub-watersheds are arranged in a clockwise fashion starting with the most northwesterly station (TA2 Dixon Creek) (Fig. WS1).

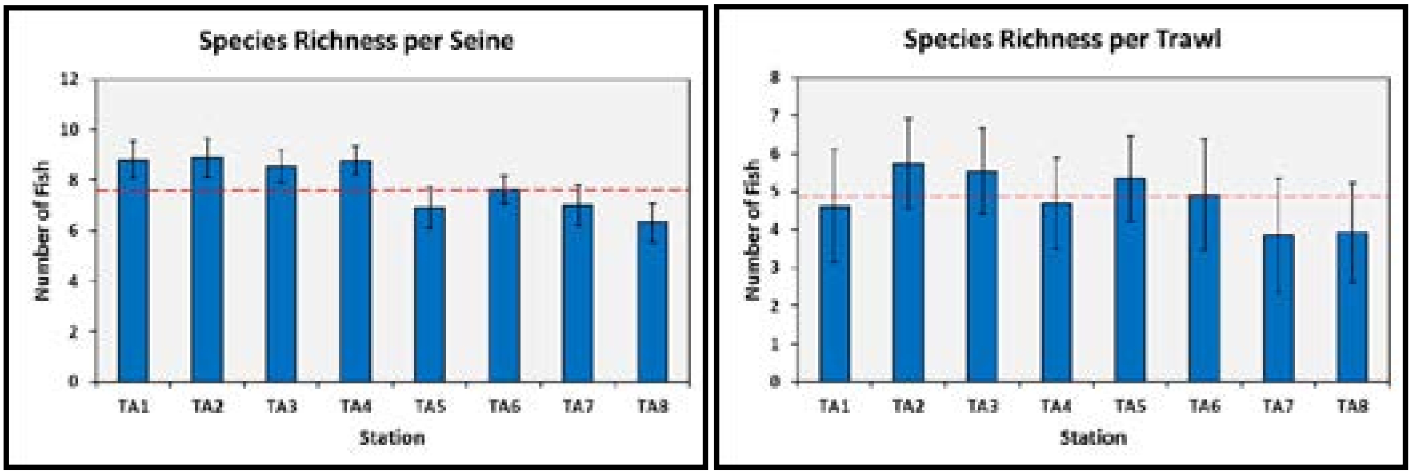


Figure FC9. Comparison of average species richness in shallow nearshore waters using a seine (left) and open waters using a trawl (right) in 2015–2017 at the eight sub-watershed sampling stations in the Tred Avon River (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). The red line represents mean species richness. Error bars represent 95 percent confidence intervals.

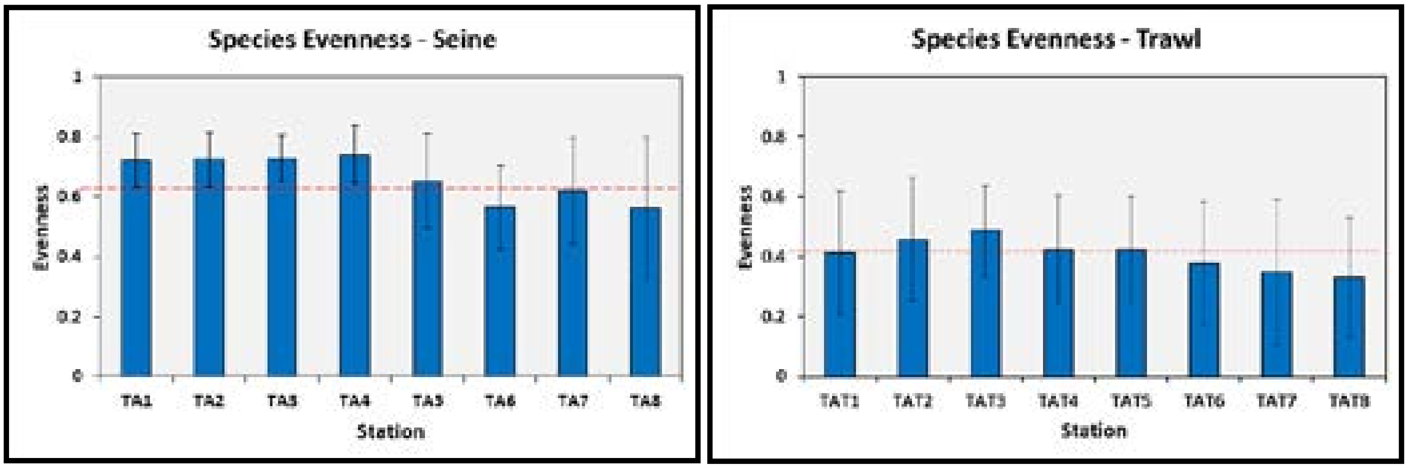


Figure FC10. Comparison of average species evenness in shallow nearshore waters using a seine (left) and open waters using a trawl (right) in 2015–2017 at the eight sub-watershed sampling stations in the Tred Avon (TA1 Easton Point; TA2 Dixon Creek; TA3 Shipshead Creek; TA4 Maxmore Creek; TA5 Trippe Creek; TA6 Goldsborough Creek; TA7 Tar Creek; TA8 Town Creek). The red line represents the mean evenness score. Error bars represent 95 percent confidence intervals.

Image FC3. Atlantic silversides (*Menidia menidia*) were the most prevalent fish in nearshore shallow seine hauls (left) while bay anchovies (*Anchoa mitchilli*) dominated the open water trawls (right) in the Tred Avon River. The bay anchovy is shown lying next to the larger hogchoaker (*Trinectes maculatus*) in the image on the right.

Impact of Low Dissolved Oxygen on Fish

Low dissolved oxygen events at Easton Point (TA1) appeared to influence fish richness and abundance in this study. During one-half of the fish community sampling dates in 2015–2017, dissolved oxygen levels in bottom waters were below the U.S. EPA criteria of 5.0 milligrams per liter (EcoCheck 2011), a frequently used Chesapeake Bay oxygen goal. Multiple fish species appeared to react to low dissolved oxygen levels by moving away from the location as seen by the lower number of fish caught in trawls at Easton Point (TA1). The abundance of white perch remained high at Easton Point (TA1) in spite of low dissolved oxygen levels suggesting this species may be able to better tolerate low oxygen levels. However, since white perch have a strong tendency for site fidelity, this fish is vulnerable to local stressors such as low dissolved oxygen (McGrath and Austin 2009).

Aquatic organisms including benthos, fish, and crabs get the oxygen needed for respiration by removing oxygen from water as it flows across their gills which then passes into the blood or hemolymph. Excess nutrients in the water, or eutrophication, can fuel the growth of algae blooms which sink and become decomposed by bacteria while consuming oxygen. Algae-consuming bacteria are most active at high summer temperatures and can create hypoxic (low oxygen) areas making it harder for aquatic organisms to get the oxygen needed to survive.

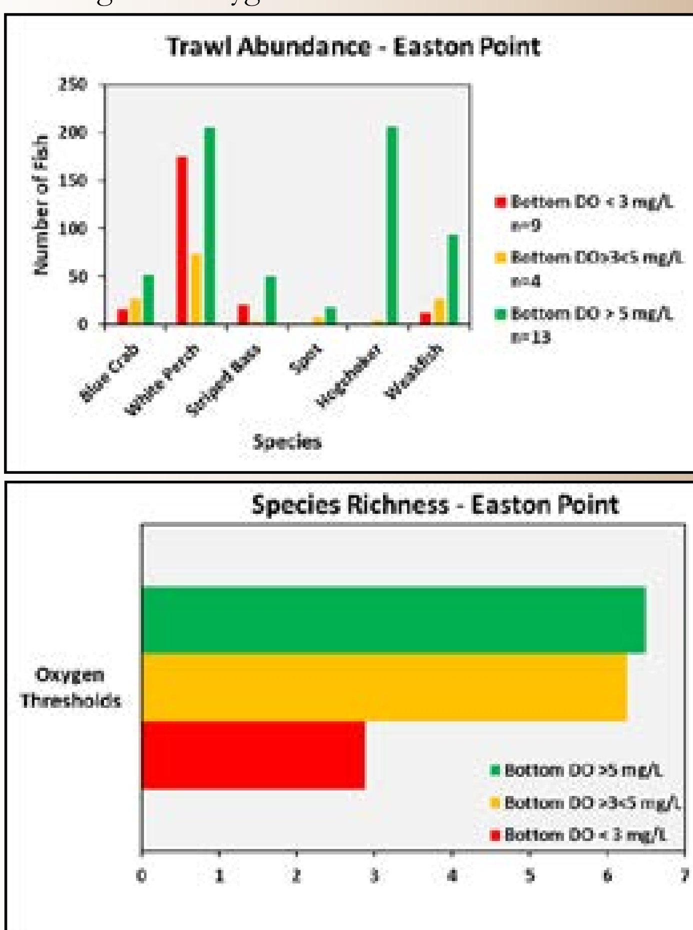


Figure FCBP1. Fish abundance and species richness comparisons with dissolved oxygen levels for species caught in open water using a trawl at Easton Point (TA1) (mg/L = milligrams per liter).

Fish Community Composition Findings

- Species richness and diversity (evenness) increased slightly in the upper Tred Avon sub-watersheds (TA1-TA4), this may be due to slightly lower salinities, or proximity to lower salinity waters, allowing for the presence of species with lower salinity preferences. It should be noted; however, that the salinities only varied between 10.7 and 12.5 parts per thousand among sub-watersheds based on average seasonal water quality measurements (WQPB1).

- Tred Avon River has a similar distribution of nearshore fish species with 5-6 species being observed at all stations. The Atlantic silverside was the most abundant nearshore fish species observed in seine hauls.

- The abundance of fish in seine hauls reflected inter-annual variability and generally decreased during the study period. The upper Tred Avon River sub-watersheds (TA1–TA4) had higher seine abundances.

- Trippe Creek (TA5) seine hauls contained relatively low numbers of fish in both 2016 and 2017.

- Tar Creek (TA7) supports the greatest abundance of menhaden in seine hauls.

- The dominant species caught by trawl in each of the eight selected sub-watersheds of the Tred Avon River (TA1–TA8) was the bay anchovy; bay anchovy abundance composed 80 percent of all trawl landings. The bay anchovy is the most abundant fish in Chesapeake Bay and a favored prey of large predatory fish such as bluefish, weakfish, and striped bass and seabirds (Lippson and Lippson 2006).

- The absence of fish during frequent low dissolved oxygen events at Easton Point (TA1) may be related to the relatively high proportion of impervious surface (22 percent) in this urban sub-watershed of the Tred Avon River (Fig. FCPB1; Fig. WQPB2).

Image FC4. NOAA scientists at Cooperative Oxford Laboratory conducting field collections for fish community composition during the Tred Avon ecological assessment.

Fish Health Assessment

Image FH1. Scientists prepare blood and gill tissue samples to assess the health of white perch (*Morone americana*) in the Tred Avon River.

Background

Fish are good indicators of environmental stress because their health reflects habitat conditions. Key biological functions such as respiration, electrolyte and acid-base balance, and waste elimination occur in exchange with the surrounding water across their thin, fragile gills. Declines in water quality, loss of critical habitat, exposure to contaminants and other stressors can have a direct effect on the physiology of fish by disrupting single or multiple physiological processes and biological functions. Stress in fish may also be a predisposing factor to disease (Roberts 2012).

A variety of indicators have been used to estimate general health of fish populations, including individual bioindicator variables (e.g. changes in biological, physiological or histopathological conditions), integrative indices composed of multiple indicators, and community or population level responses to environmental stresses. In this study, we examined fish health by applying an integrative index, the Health Assessment Index (HAI) tool (Adams et al. 1993), which includes a suite of lesion observations and physiological indicators for rapid assessment in the field. In partnership with Maryland Department of Natural Resources, we applied an HAI modified for improved application in the Chesapeake Bay (Mark Matsche, personal communication), to assess the health of white perch (*Morone americana*) in the Tred Avon River.

We selected white perch as the target of the fish health assessment for several reasons: 1) it is nearly ubiquitous in the Tred Avon River and throughout Chesapeake Bay, 2) an adult fish is large enough for comprehensive tissue sampling, and 3) the fish has a relatively small home range and generally remains within its native river (Mansueti 1961; Bowen 1987; McGrath and Austin 2009). Moreover, white perch occupy both nearshore and open water habitats which offers a composite picture of estuarine conditions.

Our goal for this assessment was to evaluate fish health in different areas in the Tred Avon River. We collected white perch annually (2015–2017) during a weeklong effort each fall and show the data for 2016–2017. In the fall of 2015, we were unable to catch white perch from each of the eight selected sub-watersheds in the Tred Avon River as the fish were unevenly distributed and primarily located in the mainstem of the river. As a result, white perch collections in 2016 and 2017 focused on the mainstem of the river with two specific locations in the upper river (near Easton Point, TA1) and the lower river (near the mouths of Trippe Creek,TA5, and Goldsborough Creek,TA6. These regions are demarcated by a line running east to west at Double Mills Point (Fig. WS1).

Methods

Eighty adult white perch (40 male and 40 female) were caught in 2016 and 2017 from both the upper (TAU) and lower (TAL) sections of the Tred Avon River using baited fishing lines (Fig. WS1). Fish were held briefly in a live-well onboard the vessel and promptly bled for hematological assays. A gill biopsy was removed and examined for parasites using a microscope, and the gender and length of each fish was recorded. The fish were then transported on ice to the Cooperative Oxford Laboratory for processing to determine their condition, bioenergetics, and reproductive status (Fig. FH1).

Table FH1. Bioindicators used in the Health Assessment Index (HAI) for white perch (*Morone americana*) in the Tred Avon River.

Functional group	Indicator	Approach	Indication
Condition	Lesions External parasites Internal parasites Gill micro parasites	Necropsy Necropsy Necropsy Gill biopsy	Tissue damage/parasitism Macro parasitism-relative intensity Macro parasitism-relative intensity Microscopic parasite-relative intensity
Bioenergetics	Mesenteric fat	Necropsy	Energy storage
Hematology	White blood cell count Neutrophil:Lymphocyte	Hematology Hematology	Infection/parasitism/disease/stress Infection/disease/stress

The HAI value was calculated by evaluating the presence and severity of lesions in the eyes, skin, gills, heart, liver, spleen, intestine, and kidney of each fish, as well as the presence of internal and external parasites (Adams et al. 1993). Each observation was scored according to the severity of the lesion or the relative number of parasites: 0 (no lesion or parasites), 10 (mild lesion or few parasites), 20 (moderate lesion or parasites), or 30 (severe lesion or numerous parasites). However, each organ can have a score higher than 30 if more than one type of lesion is present. The HAI score for each fish is the sum of all lesion or parasite scores for that fish. A low HAI score indicates better health, while a higher HAI score indicates poorer health.

Two hematologic assessments measured the physiological condition of fish, total white blood cell (WBC) counts and neutrophil to lymphocyte ratio (NLR). An increase in the NLR ratio and a decrease in total WBC signals general or chronic stress (Noga 2006).

- Total WBC count is the total number of leucocytes (lymphocytes, neutrophils, and granulocytes) in a liter of blood. An increase in the production of WBC may indicate that an organism is trying to fight an infection, while decreases in WBC counts have been associated with chronic disease, parasitism and environmental stress (Hrubec and Smith 2000).

- NLR is the ratio of the numbers of neutrophils and lymphocytes in blood specimens. An increase in neutrophils, often with a decrease in lymphocytes, in the blood of fish and other animals is typically associated with a wide variety of acute stressors, infection, or trauma (Campbell 2006; Noga 2000).

Fulton's Condition Factor (Ricker 1975) was used to measure the robustness of fish growth. This factor is calculated from the relationship between the weight of a fish and its length, with the intention of describing the "condition" of that individual.

Mesenteric fat was assessed in white perch as a measure of lipid storage. 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. This approach assumes that a majority of fish collected from habitats in good condition possess abundant fat reserves relative to fish collected from habitats in degraded condition (AFS; Goede and Barton 1990).

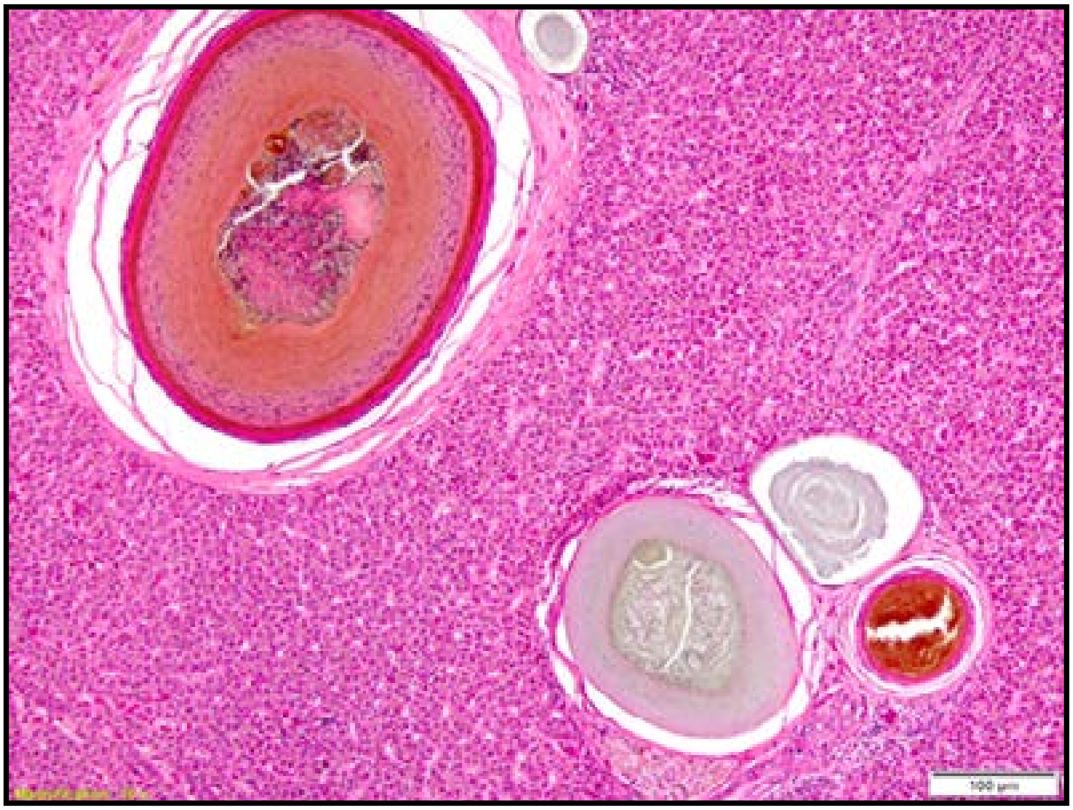


Image FH2. Microscopic image of lesions associated with inflammatory responses to parasites in liver tissue of white perch (*Morone americana*). Micrograph by Mark Matsche, Maryland Department of Natural Resources.

Results

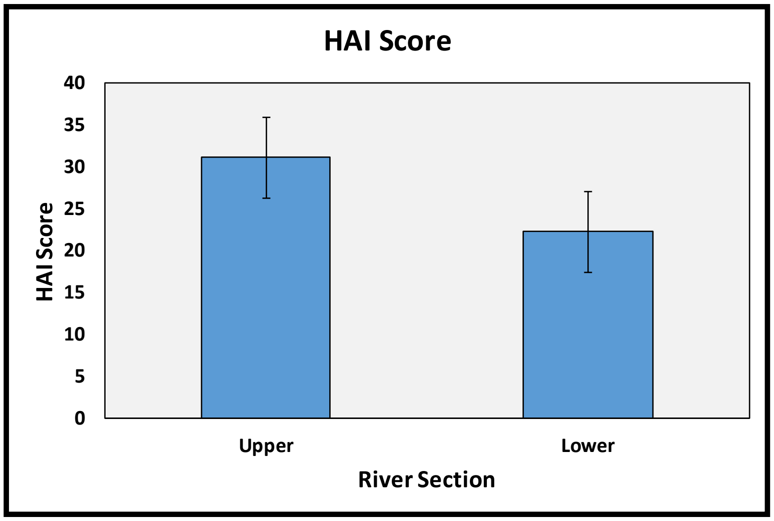


Figure FH1. Comparison of Health Assessment Index (HAI) scores for adult white perch (*Morone americana*) caught by hook and line from upper and lower regions of Tred Avon River (Fig. WS1). Error bars represent 95 percent confidence intervals.

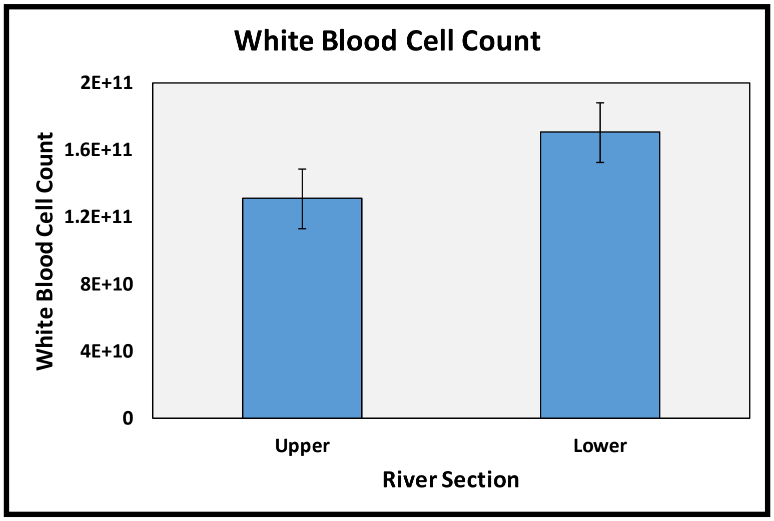


Figure FH2. Comparison of white blood cell counts for adult white perch (*Morone americana*) caught by hook and line from upper and lower regions of Tred Avon River. Error bars represent 95 percent confidence intervals.

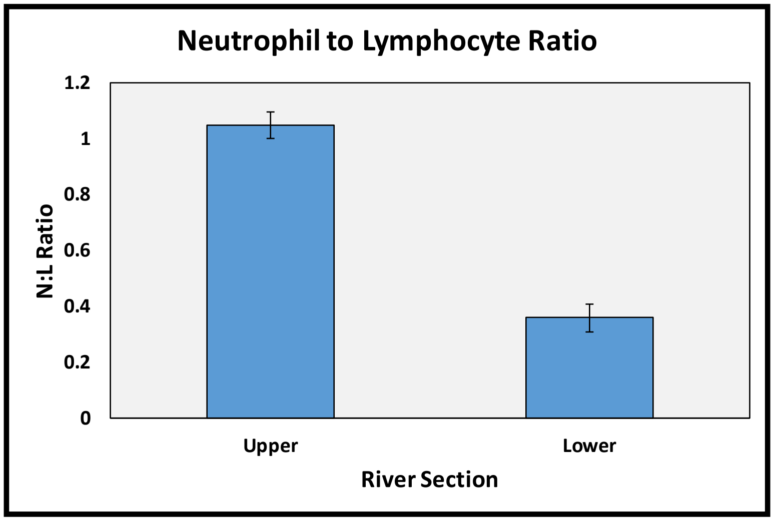


Figure FH3. Comparison of neutrophil to lymphocyte ratio (NLR) in adult white perch (*Morone americana*) caught by hook and line from upper and lower regions of Tred Avon River. Error bars represent 95 percent confidence intervals.

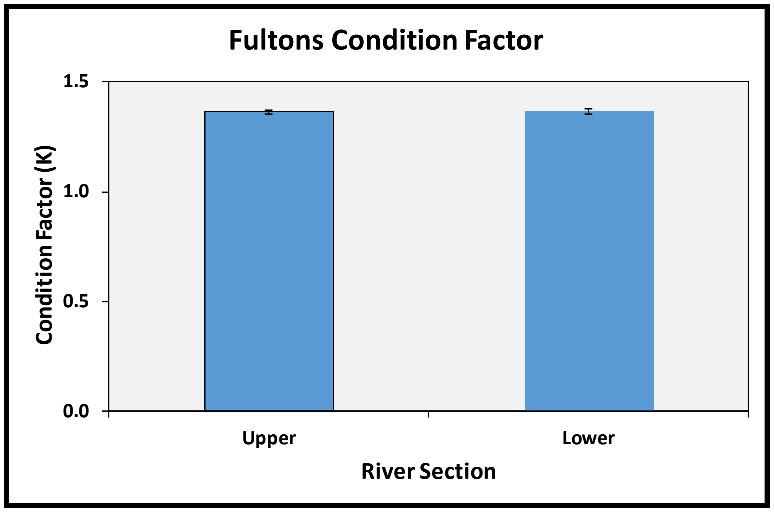


Figure FH4. Fulton's Condition Factor in adult white perch (*Morone americana*) collected in 2016 and 2017 from the upper and lower Tred Avon River [K=100 x weight in grams per length cubed in centimeters]. Error bars represent 95 percent confidence intervals.

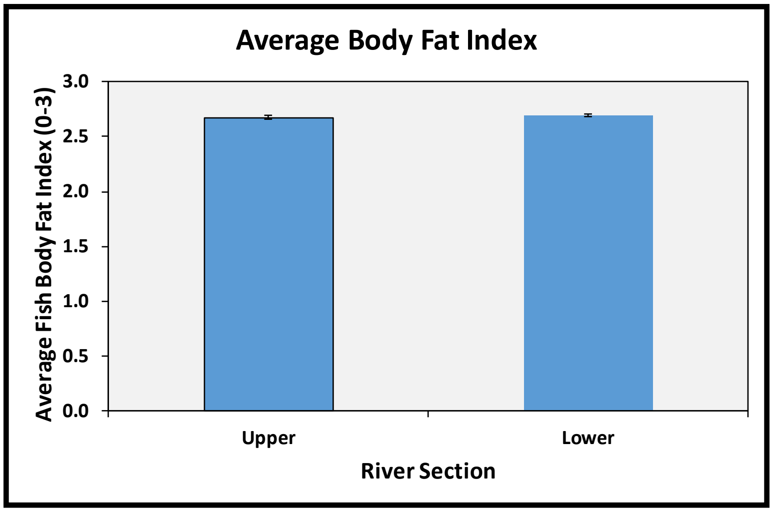


Figure FH5. Average Body Fat Index in adult white perch (*Morone americana*) collected in 2016 and 2017 from upper and lower sections of the Tred Avon River. Error bars represent 95 percent confidence intervals.

Image FH3. A syringe is used to withdraw blood from caudal blood vessel of white perch (*Morone americana)* for hematological assays (Table FH1). Photograph by Mark Matsche, Maryland Department of Natural Resources.

Fish Health Assessment Findings

- Multiple indicators of health (HAI, histopathology, hematology) reveal that white perch in the upper Tred Avon River are under greater stress than those in the lower Tred Avon.

- The HAI scores were higher in white perch in the upper Tred Avon River (TAU) indicating a higher incidence of lesions compared to fish examined from the lower Tred Avon River (TAL) (Fig. FH1). The higher HAI scores in the TAU fish were attributed to increased prevalence and severity of lesions in the heart and intestine from parasitic infections.

- Fulton's condition factor, which is a measure of the robustness of fish growth, the amount of stored energy as body fat, and gonadal development is similar between white perch caught in the upper and lower sections of the Tred Avon River (Fig. FH2). There were, however, other signs of increased stress including smaller spleens, increased splenic macrophage aggregate volume, liver enlargement, and higher incidence of liver and heart histopathology lesions among upper river fish.

- The hematology results indicate a marked decrease in total WBC (Fig. HF4) and increased NLR (Fig. FH5) among upper river fish, which is often a signal of general or chronic stress in fish.

- White perch from the upper Tred Avon River (TAU) have a greater burden of parasites compared to lower river fish, which may be a consequence of decreased condition of fish. Parasites observed included microscopic gill parasites, and, nematodes and digenean trematodes in internal organs.

- White perch in the Tred Avon River have slightly higher fitness levels then those observed in previous studies in other river systems in Chesapeake Bay (Leight et al. 2014), potentially indicating better habitat and food availability in the Tred Avon River than the Magothy, Rhode, and Corsica Rivers.

OYSTER ECOSYSTEM SERVICES

Background

We evaluated the potential capacity for nutrient removal directly from the water by oysters through their filtration of the water as they feed. This is considered an 'ecosystem service' since it removes nutrients from the water and could complement land-based nutrient management measures that are already in place in the Choptank Habitat Focus Area (HFA; Ferreira et al. 2011). Our evaluation includes separate analyses of the Tred Avon River, Harris Creek, and Little Choptank River which are areas within the Choptank HFA. We used an aquaculture production model (Farm Aquaculture Resource Management [FARM]; www.farmscale.org; Ferreira et al. 2007; 2009) to estimate the ecosystem service of nitrogen removal that is provided by restored oyster reefs and oyster aquaculture. An analysis that calculates the economic costs avoided as a result of conducting some activity was used to estimate the ecosystem service of nutrient removal by oysters.

Sixty-five percent of U.S. estuaries, including the Choptank River and other parts of the Chesapeake Bay, are moderately to severely degraded by nutrient inputs from agricultural and urban runoff, atmospheric deposition, and wastewater treatment plants (WWTP; Bricker et al. 2007; 2008). Nutrient related water quality degradation, called eutrophication, is among the most serious threats to the function and services supported by coastal ecosystems. As discussed in the water quality chapter, indicators of these eutrophic conditions include excessive algal blooms, hypoxia (Diaz and Rosenberg 2008), and loss of seagrass habitat from cloudy waters (Orth and Moore 1984) that can have cascading effects on fisheries (e.g. Brietburg et al. 2009; Lipton and Hicks 2003; Mistiaen et al. 2003). Nutrient management measures in the Choptank River watershed have resulted in improved water quality in the past five years as indicated, in part, by a resurgence of seagrass beds and improved water clarity (Murphy et al. 2017; MidShore Riverkeepers, undated) but there is still moderate impairment as shown by the water clarity and chlorophyll indicators described in this report.

Recent studies have shown that removal of nutrients directly from the water through filtration by bivalve shellfish (oysters, clams, mussels) can complement land-based nutrient management measures (Bricker et al. 2018; Reistma et al. 2018). We focused on oysters, specifically on the Eastern oyster (*Crassostrea virginica*) which is the local species of interest. Planting oysters in aquaculture farms and on restored reefs improves water quality because they filter suspended sediment and chlorophyll from the water, removing nutrients as well as improving water clarity. This filtering also short-circuits organic degradation of nutrient-driven plankton blooms by bacteria, which reduces the occurrence of low dissolved oxygen events. Nutrients are sequestered into oyster tissue and shell, and the community of bacteria supported by the presence of oysters also enhances nitrogen removal from the aquatic system through reduction of nitrogen to gas form (denitrification; Kellogg et al. 2013; Carmichael et al. 2012; Pollack et al. 2013; Humphries et al. 2016; Reitsma et al. 2018). The use of oyster cultivation for nutrient remediation, called 'bioextraction,' has been demonstrated by recent studies and the economic value of the ecosystem service represented by the water cleaning service has also been estimated (e.g. Lindahl et al. 2005; Rose et al. 2014, 2015; Ferreira and Bricker 2016; Ferreira et al. 2011).

In the northeast United States, government agencies at the local, state, and federal levels have been exploring the use of shellfish aquaculture as a nutrient management measure (Bricker et al. 2015; Rose et al. 2014; Kellogg et al. 2014; Oyster BMP Panel 2016). Several U.S. policies promote shellfish aquaculture and ecosystem service valuation (2011 U.S. NOAA Marine Aquaculture Policy and National Shellfish Initiative, 2015 Obama Administration Ecosystem Services Memorandum). Studies have shown that the costs and removal efficiencies of nitrogen through shellfish cultivation compare favorably with Best Management Practices (BMPs) that have been approved by local and federal agencies and can legally be used by jurisdictions to fulfill nutrient reduction requirements necessary to achieve water quality goals (Stephenson et al. 2010; Rose et al. 2015). Nutrient BMPs are nutrient management practices that are used to reduce the impact of nutrients on coastal water quality, such as improvements to wastewater treatment processing, and using hay bales, drainage ponds and riparian buffer strips of vegetation to reduce runoff from roads into a waterbody. Recently, the use of harvested oyster tissue was approved as a nutrient BMP in the Chesapeake Bay Region (Oyster BMP Panel 2016), and in Massachusetts, harvest of oysters and clams is already being used to fulfill mandated nutrient reductions (Reitsma et al. 2018; Town of Mashpee Sewer Commission 2015). Here we estimate the potential contribution to nutrient removal in the Tred Avon River and other tributaries in the Choptank HFA and the economic value represented by that removal.

Simulated oyster aquaculture farm site: Harris Creek

Harris Creek, a small sub-system of the Choptank HFA was selected to represent oyster related nitrogen removal due to the presence of oyster aquaculture (54.5 lease acres), conditions favorable to oyster reproduction (USACE 2014) and importantly, an extensive oyster reef restoration that was completed in 2015. Historically, Choptank River supported a robust *Crassotrea virginica* population but, as in other areas of the Chesapeake, oyster populations are now less than 1% of historic levels (Bricker et al. 2014; NOAA 2018). Following President Obama's 2009 Executive Order 13508 for Chesapeake Bay Protection and Restoration, the Maryland Interagency Working group (MIW) committed to large-scale oyster restorations in 10 Chesapeake Bay tributaries to be completed by 2025 (Oyster Metrics Workgroup 2011). Harris Creek was the first tributary chosen based on criteria including water quality, available restorable bottom, protection from harvest, and historical spat set. The 350 acre restoration is the largest successful oyster reef restoration in the world (CBF 2018). Restoration in Tred Avon and Little Choptank are not yet complete (Table OE1).

Pollution discharge to Choptank HFA, including to Harris Creek, Tred Avon and Little Choptank, is primarily from non-point agricultural sources (Dorfman et al. 2016). Nitrogen inputs for 2012, estimated by the Phase 5 Chesapeake Bay Model (USEPA 2010), were 32.6 metric tons per year (S. Ravi and G. Shenk, Chesapeake Bay Program, personal communication) for Harris Creek, 1.8 percent of the total to all of Choptank HFA (1,812 metric tons per year). Inputs to Tred Avon and Little Choptank Rivers were 97.7 and 98.3 metric tons per year, respectively (USEPA 2010; S. Ravi and G. Shenk, Chesapeake Bay Program, personal communication).

Table OE1. Areas of targeted oyster reef restoration and aquaculture leases in Choptank Habitat Focus Area (HFA) (sources: reef restoration, USACE 2012; CBF 2016 – note that only Harris Creek reef restoration is complete; aquaculture lease areas, Karl Roscher, Maryland Department of Natural Resources, personnel communication).

Oyster Areas (acres)	Harris Creek	Tred Avon River	Little Choptank River	Choptank River HFA
Targeted restored oyster reef	350	147	440	937
Aquaculture	54.5	98	47.2	528

OYSTER ECOSYSTEM SERVICES DEFINITIONS

Avoided costs analysis. This is an analytical approach used to assign a dollar value to the removal of nutrients from the water by oysters. First, an estimate is made of the amount of nutrient that is removed from the water by harvested oysters which contain nutrients in their tissue and shell. The dollar value represented by that amount of nutrients is determined by using the costs of other nutrient removal methods to remove that same amount of nutrients. The cost of nutrient removal by wastewater treatment, agricultural and urban Best Management Practices are typically used to determine value. The value of the nutrients removed by harvesting oysters is considered to be the cost that is avoided by using oysters instead of the other methods.

Best Management Practices (BMPs) are practices that have proven successful in preventing nutrients from reaching coastal waters. There is a list of BMPs that are approved by state and local jurisdictions for use in nutrient removal plans that are required in order to be compliant with legally mandated nutrient removal. Examples of approved BMPs are: planting vegetated buffers or using hay bales at the edges of farm fields and urban parking lots; improving removal efficiency of wastewater treatment processes. A recently approved BMP in the Chesapeake Bay region is harvested oyster tissue.

Diploid and triploid oysters. Oysters that can reproduce are called diploid and are naturally occurring while triploid oysters have been genetically modified so that they cannot reproduce. Triploid oysters are used in aquaculture because they do not use any energy for reproduction and thus grow faster and reach harvest size earlier than diploid oysters.

Nutrient credit trading program. The trading concept depends on the determination of the amount of nutrients that can be discharged to a waterbody without causing negative impacts. Once that threshold is known, the dischargers of nutrients to the waterbody are each assigned a limit that they are allowed to discharge so that the total amount of nutrients does not go over the threshold. If one discharger cannot meet their requirement, they can purchase 'credits' from another discharger who discharges less than the allowed amount. Because oyster growers only remove nutrients from the waterbody, there is discussion that they be 'credited' with the removal and be able to sell those credits or receive payment for the nutrient removal provided by their oyster harvest.

Methods

Farm Aquaculture Resource Management (FARM) Model

Ecosystem services of oyster-related nitrogen removal were quantified by applying the local scale FARM model (Ferreira et al. 2007, 2009; Silva et al. 2011; www.farmscale.org). To provide a more complete picture of nitrogen removal by oysters, both aquaculture and restored reef areas were included in the estimate. We assumed that bottom culture and restored reefs had the same growth and nutrient removal capability since both operations used spat-on-shell and minimal handling of oysters during the cultivation cycle. Nitrogen was the nutrient of interest because it is typically the limiting nutrient in estuaries (Malone et al. 1996). The FARM model takes into account food conditions inside a farm (or reef), shellfish ecophysiological characteristics (e.g. how much food they filter from the water in a given time period, how much of that food (i.e. phytoplankton and detrital particulates) becomes part of tissue and shell and how much is excreted or expelled, and how much water they filter in a specified time period), and farming practices (e.g. farm size, seeding density, mortality) to estimate oyster production and nitrogen removal. The model was calibrated to Chesapeake Bay to provide improved estimates given the particularly plankton and suspended solids rich Bay waters (Cubillo et al. 2017). The model was also updated to provide the capability to simulate oyster growth and nutrient removal for both triploid (unable to reproduce) and diploid (able to reproduce by spawning) oysters. The diploid model was used here because we simulate growth of bottom spat-on-shell which is the method used by the majority of Maryland growers (>80 percent, Karl Roscher, personnel communication) and diploid spat-on-shell is used in restoration.

Areal removal rates (i.e. kilograms of nitrogen removed per acre per year) were determined for a simulated site in Harris Creek and assumed to be representative of rates in all of Choptank HFA. These local scale (i.e. for one farm) results were extended to other parts of the Choptank using lease areas used for aquaculture and the area of restored reefs (Table OE1) to provide system-scale estimates of nitrogen removal by sequestration into tissue and shell (Bricker et al. 2014, 2015, 2018). While only the Harris Creek restoration is complete, the total areas targeted for restoration were used to provide an estimate of potential removal once reef restorations in all areas are complete. Additional assumptions used for upscaling were: i) there are no additional reasons that identified bottom area could not be cultivated; ii) all lease areas within a zone have the same oyster growth and nitrogen removal rates despite potential differences in water quality among aquaculture farm locations; iii) and there is no interaction among (potential) adjacent farms (i.e. no food depletion).

To determine the total oyster-related nitrogen removal ecosystem service we also calculated potential oyster-related denitrification losses. Areas of bottom oyster aquaculture and restored reefs (Table OE1) were used to estimate denitrification losses using the areal rate determined by a previous study of the Choptank River (225 kilograms nitrogen removed per acre per year; Kellogg et al. 2013).

Data and Model Inputs

Data from the Chesapeake Bay Program Water Quality Database and Dorfman et al. (2016) for years 2010–2015 for Choptank River sampling station EE2.1, the closest station to the simulation site, were used for FARM model inputs. Five years of data were used to avoid biases due to anomalous wet or dry years. Statistical analyses using Jonckheere-Terpstra and Mann-Kendall tests (Zar 1999) were performed on monthly measures of chlorophyll *a*, dissolved oxygen, salinity, temperature, dissolved inorganic nitrogen, particulate organic matter, and total suspended solids. Since no time trends were detected in these variables in the specified timeframe, all data were used as inputs.

Other inputs used were: current speed data from the NOAA Tidal Current Predictions Bald Eagle Point station for 2017, oyster seed weight of 0.12 grams and 70 grams weight for a 3 inch (7.62 centimeter) harvest size oyster based on oyster sizes in Harris Creek (Paynter et al. 2014). Oyster mortality was set to 75 percent, based on mortalities reported by Maryland oyster growers (Don Webster, Regional Extension Specialist, University of Maryland Sea Grant Extension, personal communication). A seeding density of 247 oysters per square meter was used for bottom aquaculture simulations based on densities typically used by Maryland growers (Don Webster, Don Webster, Regional Extension Specialist, University of Maryland Sea Grant Extension, personal communication). A seed planting density of 140 oysters per square meter was used for restored oyster reefs, based on the five year post-restoration target density of 50 oysters per square meter indicating restoration success (Maryland Interagency Oyster Restoration Workgroup of the Sustainable Fisheries Goal Implementation Team restoration plans).

Image OE1. A cage of farmed oysters (*Crassostrea virginica*) is hauled from the bottom of an aquaculture lease site in the Maryland portion of the Chesapeake Bay (left). In this image, Captain Donny Simmons (left) and David Tippett (right) are working from the vessel *Miss Sallie*. Market-sized oysters are being culled from bottom cages by Captain Simmons for commercial sale (center). After cages have been washed and scraped to remove fouling organisms, juvenile oysters (right) are returned to the cages and replaced on the lease bottom to grow.

Ecosystem Service Valuation

An intriguing aspect of the potential use of oyster bioextraction as a BMP is the potential economic value of the nutrient removal ecosystem service that could be paid to growers if they were part of a nutrient credit trading program (Ferreira and Bricker 2016; Lindahl et al. 2005). The way these programs work is that a threshold of nitrogen load to a water body is determined by the U.S. EPA and the state, above which water quality impairment occurs. Each of the nitrogen dischargers to that water body is assigned an amount of nitrogen that it can discharge (called credits) that together do not go over the specified threshold; it is designed to protect the waterbody from degradation. If one discharger is unable to keep discharge at the assigned level, that discharger can buy the extra 'credits' from another discharger that does not discharge the entire amount it has been allotted. This framework creates an economic market for the trading of nutrient credits that helps to achieve the water quality goal in an efficient and cost effective manner (Stephenson et al. 2010; Ferreira and Bricker 2016).

To determine the market value of the nutrient removal by the oysters, we used the cost avoided or replacement cost method (King and Mazzotta 2000). The method assumes that if shellfish are no longer present, the nitrogen removal services they provide would need to be replaced by WWTP upgrades, and/or implementation of agricultural and urban BMPs. The costs of nitrogen removal by these technologies provides a useful estimate of the value of nitrogen removal by bioextraction. The values used here (ranging from $5.90 – $159 per pound per year) were determined for Long Island Sound, however, we believe that they represent a reasonable estimate of costs in the Chesapeake Bay region (Bricker et al. 2015, 2018; Table OE2).

Table OE2. Costs of implementation of incremental reductions from wastewater treatment plants (WWTP) at three levels of effluent nitrogen (N) concentration, and of agricultural and urban best management practices (BMP). Data from Evans 2008; results are reported in 2013 U.S. dollars; adapted from Bricker et al. 2018.

Alternative Nutrient Reduction Measure	Average Cost ($/pound/year) ($/kilogram/year)
WWTP 8 milligrams N/liter	14.63 32.19
WWTP 5 milligrams N/liter	16.82 37.00
WWTP 3 milligrams N/liter	44.81 98.58
Agricultural BMP	5.90 12.98
Urban BMP	159 349

Results

Nutrient Removal by Oyster Filtration and Denitrification – Aquaculture and Restored Reefs

The FARM model simulation provided a removal estimate of 199 kilograms per acre per year by sequestration of nitrogen into tissue and shell of restored oyster reefs, and removal of 332 kilograms per acre per year by bottom oyster aquaculture. Estimates from Kellogg et al. (2013) of 225 kilogram nitrogen removed per acre per year were used to determine the removal by oyster associated denitrification. These areal rates of removal were used with the areas of aquaculture and restored reefs within each of the study areas to estimate the annual total nitrogen removal (Table OE3).

Oyster related nitrogen removal for Tred Avon and for all of Choptank are equivalent to 84 percent and 38 percent, respectively. The estimated removal of nitrogen by restored oyster reefs and aquaculture through sequestration into tissue and shell and denitrification in Harris Creek (179 metric tons per year) is equivalent to more than five times the nitrogen input (32.6 metric tons per year), and for Little Choptank the nitrogen removal is more than twice the incoming nitrogen (98.3 metric tons per year). Note that these are not closed systems thus it is possible to remove more nitrogen than is discharged to the system from the watershed. This suggests that oyster related removal could play a significant role in water quality improvement in Choptank HFA and the three sub-systems, and that these oyster related ecosystem services could be important in a comprehensive nutrient management program in the Choptank HFA.

Table OE3. FARM estimated removal rates (via assimilation into tissue and shell, and denitrification) in restored reefs and aquaculture areas in Tred Avon, Little Choptank, Harris Creek and and all of the Choptank Habitat Focus Area (HFA). Estimated nitrogen (N) removal by sequestration into tissue and shell by restored reefs is 199 kilograms per acre per year and by bottom oyster aquaculture is 332 kilograms per acre per year. Denitrification removal is estimated to be 225 kilograms nitrogen removed per acre per year (Kellogg et al. 2013).

Oyster Type	Tred Avon River (1000 kg N/yr	Little Choptank River (1000 kg N/yr)	Harris Creek (1000 kg N/yr)	Choptank HFA (1000 kg N/yr)
Aquaculture	32.5	15.7	18.1	175
Restored reefs	29.3	87.6	69.7	186
Denitrification associated removal	55.1	110	91.0	330
TOTAL REMOVAL	117	213	179	691

Economic Value of the Nutrient Removal Ecosystem Service

An economic value was estimated using the avoided costs analysis based on costs of implementation of agricultural and urban best management practices, and costs of incremental reductions from WWTPs, and of agricultural and urban best management practices. The costs range from $359–$13.00 per kilogram per year ($159–$5.90 per pound per year; Table OE4).

In the Tred Avon River, the total value of the nitrogen removal by sequestration into oyster tissue and shell in restored reefs and oyster farms and associated denitrification is estimated to range from $1.5–$41 million per year. Nitrogen removal by oysters in all of Choptank HFA has an estimated value of $15–$404 million per year, depending on the alternative management measure used for the valuation. It should be noted that in a nutrient credit trading program this is the amount that would potentially be paid to oyster growers as compensation for the nitrogen removal service provided by their oysters. Although currently there are no nutrient credit programs that pay for ecosystem services, the Chesapeake Bay Program has taken a first step by approving the assignment of nitrogen removal 'credits' for harvested oyster tissue that can be used to fulfill mandated nutrient reductions (Oyster BMP Panel 2016). The potential payment to oyster growers for the nutrient removal service is under discussion.These optimistic results show that oysters can provide domestic seafood product as well as contribute to water quality improvements.

Image OE2. Adult oysters (*Crassostrea virginica*) are grown from spat in bottom cages at aquaculture lease sites in the Maryland portion of Chesapeake Bay.

Table OE4. Avoided costs valuation of the estimated nitrogen removal by sequestration into tissue and shell of oysters in aquaculture leases and restored reefs and by denitrification. Values are based on costs of removal by wastewater treatment (WWTP), urban and agricultural BMPs (Table OE2).

Oyster Type	Tred Avon River ($millions/yr)	Little Choptank River ($millions/yr)	Harris Creek ($millions/yr)	Choptank HFA ($millions/yr)
Aquaculture Removal	0.422 – 11.4	0.203 – 5.48	0.235 – 6.33	8.88 – 239
Restored reef removal	0.389 – 10.2	1.14 – 30.6	0.904 – 24.4	1.85 – 49.8
Denitrification removal	0716 –19.3	1.42 – 38.3	1.81 – 31.8	4.28 – 115
TOTAL VALUE	1.52 – 40.9	2.76 – 74.5	2.32 – 62.6	15.0 – 404

Oyster Ecosystem Services Findings

- Oyster aquaculture and reef restoration are promising and valuable nitrogen removal mechanisms (via sequestration into tissue and shell and associated denitrification) and could contribute in a positive way to nutrient management in Tred Avon River and Choptank River HFA. Note also that additional related ecosystem services such as concurrent sediment removal and increased water clarity were not quantified but potentially have a significant value particularly if water clarity improves and seagrasses are able to regrow. Additionally, bioextractive removal of nitrogen by clam populations was not estimated thus the potential removal by oysters may be only a conservative estimate.

- The FARM model simulation provided a removal estimate of 199 kilograms per acre per year by sequestration of nitrogen into tissue and shell of restored oyster reefs, and removal of 332 kilograms per acre per year by bottom oyster aquaculture. Estimates from Kellogg et al. (2013) of 225 kilogram nitrogen removed per acre per year were used to determine the removal by oyster associated denitrification.

- In Tred Avon River, the estimated removal of 117 metric tons of nitrogen by oyster aquaculture and restored reefs has an estimated value of $1.5–$41 million per year.

- In the greater Choptank HFA, the removal of an estimated 691 metric tons of nitrogen by oyster aquaculture and restored reefs has an estimated value of $15–$404 million per year.

- The concept of using bioextractive removal of nutrients from the water column is beginning to be formally recognized with 'credits' being given for harvest of oyster tissue in the Chesapeake region, but payment to oyster growers for the ecosystem service of nitrogen removal is still under discussion.

SYNTHESIS

Our three-year ecological assessment provides valuable insights into conditions within the Tred Avon River, a river that supports important natural resources, and is the site of an extensive oyster restoration project. The Tred Avon River watershed is a good example of an area where multiple types of land use are competing for space and where urbanization is slowly replacing farm fields and forests.

Key Findings

The Tred Avon River is in relatively good condition based on the variables and criteria we used for this assessment but there are signs of degradation which could worsen with increasing population growth and land development.

Several Chesapeake Bay–wide issues were clearly detected in some of the sub-watersheds in theTred Avon River, including excess nutrients, high chlorophyll *a* concentrations, seasonally decreased oxygen levels in bottom waters, and poor water clarity. As was detected in previous studies (Leight et al. 2015) for other watersheds of the Chesapeake Bay and has been highlighted in report cards (UMCES 2018) for the Chesapeake Bay overall, sub-watersheds of the Tred Avon River have poor water clarity and several sub-watersheds suffer from excessive nutrient concentrations.

Signs of degradation were particularly evident at the most upstream station, Easton Point (TA1), which was impacted by multiple stressors – low dissolved oxygen in bottom waters, the presence of chemical contaminants above low-level NOAA thresholds, high levels of nutrients, high chlorophyll *a* concentrations, high fecal bacterial counts, and poor water clarity. These impacts were seen in the benthic community (organisms living in or on the bottom) and corresponded with signs of stress in the health of white perch. In addition, there was evidence at this Tred Avon sub-watershed that most fish species, with the notable exception of white perch, move out of our trawl location during low dissolved oxygen events. Multiple anthropogenic stressors are present at Easton Point (TA1) due to higher levels of development and impervious surface than is present in the other Tred Avon sub-watersheds we assessed.

Multiple species of fish reacted to low dissolved oxygen levels by moving away from Easton Point (TA1), as seen by the lower number of fish caught in trawls during low dissolved oxygen events. The abundance of white perch remained high at Easton Point (TA1) in spite of low dissolved oxygen levels suggesting that this species may be able to better tolerate low oxygen levels than other species. However, our fish health assessment revealed that white perch caught near Easton Point (TA1) showed physiological signs of stress including signs of hypoxia exposure. Since white perch have a strong tendency for site fidelity, this fish is vulnerable to local stressors such as low dissolved oxygen (McGrath and Austin 2009).

The absence of fish during frequent low dissolved oxygen events at Easton Point (TA1) may be related to the relatively high proportion of impervious surface (22 percent) in this sub-watershed of the Tred Avon River. Frequent low dissolved oxygen events were not observed in other sub-watersheds assessed in the Tred Avon where impervious surface is 3–4 percent at stations TA2-TA7 and 18 percent at Town Creek (TA8). Uphoff et al. (2011) observed that mean bottom dissolved oxygen levels are 3 times more likely to be hypoxic in Chesapeake Bay watersheds having greater than 10 percent impervious surface. Additionally, the proportion of bottom trawls containing indicator species (white perch, striped bass, spot, blue crabs) significantly decreased during low dissolved oxygen events (Uphoff et al. 2011). The impervious surface thresholds developed by Uphoff et al. (2011) are based on studies in nine tributaries of the Chesapeake Bay, including the Choptank River, while we compared sub-watersheds within the Tred Avon River, a tributary of the Choptank (WS1). Future studies may look to quantify the extent of the influence of Easton Point's (TA1) relatively high impervious surface levels throughout the Tred Avon River.

In contrast, our other sub-watershed with relatively notable land development, Town Creek (TA8), did not exhibit similar signs of stress as Easton Point (TA1). Town Creek (TA8) showed degraded water clarity in the water column and chemical contaminants in the sediments, likely due to the relatively dense boating and marina facilities. However, these stresses did not appear to greatly impact the benthic community or the mummichog population, which was abundant and had chemical contaminant concentrations in their tissues at similar levels observed in mummichogs examined at the remaining sampling stations (TA2–TA7).

The contaminant levels in the Tred Avon River sediments were similar to most samples from the Eastern Shore of Maryland and middle reaches of the mainstem Chesapeake Bay when compared with chemical contaminant levels measured in 210 sediment samples from the mainstem and the lower sections of most rivers of the Chesapeake Bay (Hartwell and Hameedi 2007). However, contaminant levels at Easton Point (TA1) and Town Creek (TA8) sediments are more typical of some western shore stations, but well below that of stations in the highly industrialized Patapsco (MD) and Elizabeth (VA) Rivers.

In addition to poor environmental conditions at Easton Point (TA1), signs of degradation were also evident at Trippe Creek (TA5) which had marginal nutrient grades (total nitrogen and phosphorus), occasional exceedances of the indicator bacteria criteria, and degraded benthos. Trippe Creek (TA5) is surrounded by a moderate level of crop fields, relative to the other Tred Avon River sub-watersheds, and a golf course, which may have contributed to the presence of some stressors.

Oyster aquaculture and reef restoration are promising and valuable nitrogen removal mechanisms (via sequestration into tissue and shell and associated denitrification) and could contribute in a positive way to nutrient management in Tred Avon River and Choptank River HFA since the Chesapeake Bay Program has approved oyster tissue as a nutrient best management practice in the Chesapeake Bay region.

Other Notable Observations

- In Tar Creek (TA7), seine samples were dominated by menhaden with few other species present, unlike the other seven sub-watersheds assessed in the Tred Avon River. The reason for this difference is uncertain but may be related to the proximity of this creek to the mouth of the Tred Avon River.

- Both the fish Health Assessment Index (HAI) and benthic index of biotic integrity (B-IBI) detected significant differences among sub-watersheds within the Tred Avon River, underscoring the utility of these indices and the importance of within-river sampling resolution.

- The draft comprehensive plan by the U.S. Army Corps of Engineers (USACE 2018) highlights the Tred Avon River watershed as an area with numerous opportunities for natural resource conservation and habitat preservation (e.g. restored shorelines, wetlands and marshes, creation of riparian buffers). While the overall condition of the Tred Avon River is good, conservation of this watershed will be necessary to prevent any exacerbation of stressor impacts.

Implications

Estuaries are challenged by a complex mixture of land based influences, as a wide array of human pressures compromise their ecological integrity (Fisher et al. 2010; Leight et al. 2014). These negative impacts will likely escalate as populations in coastal zones rise, unless there is effective management of these influences. Some stress is expected in estuaries which are dynamic by nature and thus have evolved a degree of resiliency. However, degradation of the environment caused by other stressors, such as land development, may lead to less resilient conditions. Minimizing adverse impacts to the aquatic environment will help to preserve the resilience and sustainability of aquatic ecosystems such as Chesapeake Bay.

This study detected high nutrient concentrations in the Tred Avon River, potentially due to land use and water flow. Based on previous work, an indicator of severe nutrient pollution in a watershed may be derived from a combination of factors including high population density (greater than 100 persons per square kilometer), slow water flow (greater than 10 days residence time) and percent of urban and agricultural land use (greater than 40 percent) (Bricker et al. 2014). While the population density of the Choptank River watershed is currently estimated at 50 persons per square kilometer (Fleming et al. 2017), the residence time is about 19 days and land use is estimated to be 62 percent urban and agriculture (Bricker et al. 2007). As population growth continues to expand along the Choptank River and the larger Chesapeake Bay, it will be critical to focus future research efforts on determining how to minimize the negative impacts of land development to maintain sustainable and resilient aquatic ecosystems.

Management of a healthy ecosystem requires information about the complex, and often non-linear, relationship between stressors, such as land use activities, and natural resources, with the goal of achieving a resilient and productive environment (Leight et al. 2014). The overall goal of the Tred Avon ecological assessment is to provide local managers and decision makers with the information necessary to make informed decisions on the environmental influence of ecosystem condition in small watersheds with relatively differing land use characteristics. Although negative impacts of land development were apparent at Easton Point (TA1), the data obtained from the Tred Avon River ecological assessment can further inform future land use decisions in surrounding areas. The data collected from the sub-watersheds of the Tred Avon River, as well as the data obtained in our previous assessments to compare different river systems (Leight et al. 2014, 2015), will be helpful in addressing the impacts of land use activities at local and regional levels. Insights gained from this ecological assessment are relevant not only to the Tred Avon watershed but also to the Choptank and other watersheds of the Chesapeake Bay and along the nation's coasts.

Several management implications can be drawn from the Tred Avon ecological assessment. Primary among them is the need for resource managers to persist in current efforts to reduce non-point introduction of nitrogen, phosphorous and sediments to Chesapeake Bay and related successes in reaching restoration goals. Since high nutrients and some contaminants can be transported to aquatic ecosystems via runoff, it will be important to target management measures not only to areas where runoff is a concern but to also apply strategies that would reduce both nutrients and contaminants in sediments. (Leight et al. 2014).

Another management implication of this assessment is the need for critical habitat preservation to support diverse and healthy fish and shellfish populations particularly in spawning areas such as the Choptank River. This may be achieved by the testing and/or application of innovative management measures such as oyster aquaculture, oyster reef restoration, and setting thresholds for land development (Uphoff et al. 2011).

Given the dynamic nature of population growth and land development in the Tred Avon watershed, as well as the extensive effort to repopulate oysters in the river, the data collected over this three-year study provides a valuable baseline against which current and future restoration efforts can be measured.

Analysis of the indicators of ecosystem condition in the Tred Avon River and their relationship to human activities provides insights into the trade-offs between development on land and the condition of the aquatic ecosystem. This information is critical to striking a balance between supporting the needs of increasing population growth and protecting vital ecosystem services that have benefited generations of communities residing locally or in other regions of the Chesapeake Bay.

Results from the Tred Avon ecological assessment support earlier conclusions drawn by Fisher et al. (2010) regarding the level of degradation in Chesapeake Bay and the continued need for management (USACE 2018). Recommendations to manage water quality on a watershed scale (Fisher et al. 2010) are currently being implemented through the Chesapeake Bay Watershed Agreement (CBP 2014) which requires jurisdictions to develop Watershed Implementation Plans (WIPs), now entering Phase III. Additional recommendations by Fisher et al. (2010) to reduce caps for wastewater discharges, decrease fertilizer applications on agriculture areas and lawns, and increase stream buffers and winter cover crops on farms remain relevant. Accordingly, stakeholder input into USACE's recent comprehensive plan for the Chesapeake Bay resulted in an inventory of management opportunities and actions at the watershed scale which will help to facilitate restoration, protection, and conservation activities throughout the Chesapeake Bay (USACE 2018). Results from our ecological assessment support these suggestions for management at the watershed scale in the Tred Avon River and other impacted watersheds in the Chesapeake Bay as well as similarly challenged coastal ecosystems located nationally and internationally.

Image SY1. Workboat on the Tred Avon River.

Chemical Contaminants in Sediments

Chemical Contaminant	Units	ERL Value	ERM Value
Arsenic	µg/g	8.2	70
Cadmium	µg/g	1.2	9.6
Chromium	µg/g	81	370
Copper	µg/g	34	270
Lead	µg/g	46.7	218
Mercury	µg/g	0.15	0.71
Silver	µg/g	1	3.7
Zinc	µg/g	150	410
Total PCBs	ng/g	22.7	180
4,4'-DDE	ng/g	2.2	27
Total DDTs	ng/g	1.6	46.1
Acenaphthene	ng/g	16	500
Acenaphthylene	ng/g	44	640
Anthracene	ng/g	85	1100
Fluorene	ng/g	19	540
2-Methylnaphthalene	ng/g	70	670
Naphthalene	ng/g	160	2100
Phenanthrene	ng/g	240	1500
Benzo(a)anthracene	ng/g	261	1600
Benzo(a)pyrene	ng/g	430	1600
Chrysene	ng/g	384	2800
Dibenz(a,h)anthracene	ng/g	63.4	260
Fluoranthene	ng/g	600	5100
Pyrene	ng/g	665	2600

Note: ug/g = micrograms per gram

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Image PA1. NOAA Cooperative Oxford Laboratory staff and interns in 2016.

Aamir, M., S. Khan, J. Nawab, Z. Qamar, and A. Khan. 2016. Tissue distribution of HCH and DDT congeners and human health risk associated with consumption of fish collected from Kabul River, Pakistan. Ecotoxicology and Environmental Safety. 125:128-134.

Able, KW. and M.P. Fahay. 2010. Ecology of estuarine fishes. Johns Hopkins University Press. 584 pp.

Adams S., A. Brown, and R. Goede. 1993. A quantitative health assessment index for rapid evaluation of fish condition in the field. Transactions of the American Fisheries Society 122:63-73.

AFS (American Fisheries Society). 1990. Methods for fish biology. C.B. Schreck and P.B. Moyle (eds) American Fisheries Society, Bethesda, MD. 684 pp.

APHA. 1992. Standard Methods for the examination of water and wastewater, 18th ed., American Public Health Association, American Water Works Association and Water Environmental Federation, Washington D.C.

APHA. 1998. Standard Methods for the examination of water and wastewater, 20th ed., American Public Health Association, American Water Works Association and Water Environmental Federation, Washington D.C.

Anderson, J.R., E.E. Hardy, J.T. Roach, and R.E. Witmer. 1975. A land use and land cover classification system for use with remote sensor data. U.S. Geological Survey Professional Paper 964, A revision of the land use classification system as presented in U.S. Geological Survey Circular 671.

Balthis, L., J. Hyland, C. Cooksey, E. Wirth, M. Fulton, J. Moore, and D. Hurley. 2012. Support for Integrated Ecosystem Assessments of NOAA's National Estuarine Research Reserve System (NERRS): Assessment of Ecological Condition and Stressor Impacts in Subtidal Waters of the Sapelo Island National Estuarine Research Reserve. NOAA Technical Memorandum NOS NCCOS 150. NOAA Center for Coastal Environmental Health and Biomolecular Research, Charleston, SC.

Beckvar, N., T.M. Dillon, and L.B. Read. 2005. Approaches for linking whole-body fish tissue residues of mercury or DDT to biological effects thresholds. Environmental Toxicology and Chemistry. 24(8): 2094–2105.

Berman, M.R., Berquist, H., Killeen, S., Nunez, K., Rudnicky, T., Schatt, D.E., Weiss, D. and K. Reay, 2005. Talbot County, Maryland - Shoreline Situation Report, Comprehensive Coastal Inventory Program, Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, 23062.

Bowen, B.W. 1987. Population structure of the white perch, Morone americana, in lower Chesapeake Bay as inferred from mitochondrial DNA restriction analysis. M.A. Thesis, Virginia Institute of Marine Science, Gloucester Point, Virginia.

Breitburg D.L., D.W. Hondorp, L.A. Davias, and R.J. Diaz. 2009. Hypoxia, nitrogen, and fisheries: Integrating effects across local and global landscapes: Annual Review of Marine Science 1(1):329-349.

Bricker, S.B., J.G. Ferreira, C. Zhu, J.M. Rose, E. Galimany, G. Wikfors, C. Saurel, R. Landeck Miller, J. Wands, P. Trowbridge, R. Grizzle, K. Wellman, R. Rheault, J. Steinberg, A. Jacob, E.D. Davenport, S. Ayvazian, M. Chintala, and M.A. Tedesco. 2018. The role of shellfish aquaculture in reduction of eutrophication in an urban estuary. Environmental Science and Technology. 52:73−183.

Bricker, S.B., J.G. Ferreira, C. Zhu, J.M. Rose, E. Galimany, G.H. Wikfors, Saurel, C.R. Landeck Miller, J. Wands, P. Trowbridge, R.E. Grizzle, K. Wellman, R. Rheault, J. Steinberg, A.P. Jacob, E.D. Davenport, S. Ayvazian, and M.A. Tedesco. 2015. An ecosystem services assessment using bioextraction technologies for removal of nitrogen and other parameters in Long Island Sound and Great Bay/Piscataqua Region. NCCOS Coastal Ocean Program Decision Analysis Series No. 194; U.S. EPA ORD, Atlantic Ecology Division: Narragansett, RI.

Bricker S.B., B. Longstaff, W. Dennison, A. Jones, K. Boicourt, C. Wicks, and J. Woerner. 2007. Effects of Nutrient Enrichment in the Nation's Estuaries: A Decade of Change, National Estuarine Eutrophication Assessment Update. NOAA Coastal Ocean Program Decision Analysis Series No. 26. National Centers for Coastal Ocean Science, Silver Spring, MD. 322 pp. http://ccma.nos.noaa.gov/news/feature/Eutroupdate.html

Bricker, S. B., B. Longstaff, W. Dennison, A. Jones, K. Boicourt, C. Wicks and J. Woerner. 2008. Effects of Nutrient Enrichment in the Nation's Estuaries: A Decade of Change. Harmful Algae 8:21-32.

Bricker, S.B., K.C. Rice, and O.P. Bricker III. 2014. From Headwaters to Coast: Influence of Human Activities on Water Quality of the Potomac River Estuary. Aquatic Geochemistry 20:291-324.

Buchheister, A., C.F. Bonzek, J. Gartland and R. Latour. 2013. Patterns and drivers of the demersal fish community of Chesapeake Bay. Marine Ecology Progress Series. 481:161-180.

Campbell, T. 2006. Hematology of fish. In: Thrall, M., Baker, D., Campbell, T., DeNicola, D., Fettman, M., Lassen, E., Rebar, A. and Weiser, G., Ed. Veterinary hematology and clinical chemistry. Blackwell Publishing, Ames, p. 277-289.

Carmichael, R. H., W. Walton, and H. Clark. 2012. Bivalve-enhanced nitrogen removal from coastal estuaries. Canadian Journal of Fisheries and Aquatic Sciences. 69:(7):1131−1149.

CBF (Chesapeake Bay Foundation). 2014. Nitrogen & Phosphorus. http://www.cbf.org/how-we-save-the-bay/issues/agriculture/nitrogen-phosphorus. *Accessed 06/17/2015.*

CBF. (Chesapeake Bay Foundation). 2016. Chesapeake Bay Foundation State of the Bay Report http://www.cbf.org/about-the-bay/state-of-the-bay-report/). *Accessed 09/04/2018.*

CBF (Chesapeake Bay Foundation). Undated. Oyster Restoration on Harris Creek: A New Day, A New Way for Oyster Restoration. http://www.cbf.org/how-we-save-the-bay/programs-initiatives/maryland/oyster-restoration/oyster-restoration-on-harris-creek.html.

CBF (Chesapeake Bay Foundation). 2018. Oyster Restoration on Harris Creek: A New Day, A New Way for Oyster Restoration. http://www.cbf.org/how-we-save-the-bay/programs-initiatives/maryland/oyster-restoration/oyster-restoration-on-harris-creek.html Accessed 9/12/2018.

CBF (Chesapeake Bay Foundation). 2018. Oyster Restoration on Harris Creek: A New Day, A New Way for Oyster Restoration. http://www.cbf.org/how-we-save-the-bay/programs-initiatives/maryland/oyster-restoration/oyster-restoration-on-harris-creek.html. *Accessed 9/12/2018.*

Changing Chesapeake. 2018. http://www.chesapeakedata.com/changingchesapeake/ *Accessed 06/28/2018.*

CBP (Chesapeake Bay Program). 2012. Chesapeake Bay watershed. https://www.chesapeakebay.net/discover/watershed. *Accessed 07/16/2018.*

CBP (Chesapeake Bay Program). 2016. 2015 Oyster Restoration Implementation Update. Compiled by the Maryland Oyster Restoration Interagency Workgroup of the Goal Implementation Team.

CBP (Chesapeake Bay Program). 2018a. Facts and Figures. https://www.chesapeakeBay.net/discover/facts. *Accessed 06/29/2018.*

CBP (Chesapeake Bay Program). 2018b. Population. https://www.chesapeakeBay.net/state/population. *Accessed 06/29/2018.*

CBP (Chesapeake Bay Program). 2018. Chemical contaminants. https://www.chesapeakebay.net/issues/chemical_contaminants. *Accessed 6/29/2018.*

CBP (Chesapeake Bay Program). 2018. Dissolved Oxygen. https://www.chesapeakebay.net/discover/ecosystem/dissolved_oxygen. *Accessed 06/20/2018.*

CRC (Chesapeake Research Consortium). 2018. http://chesapeake.org/2018/08/07/2018-bay-report-card. *Accessed 08/07/2018.*

CRS (Congressional Research Service). 2018. Chesapeake Bay Restoration: Background and Issues for Congress. https://crsreports.congress.gov. *Accessed 09/14/2018.*

Crum, K.P. R.G. Baloouskus, and T.E. Targett. 2018. Growth and movements of mummichogs (*Fundulus heteroclitus*) along armored and vegetated estuarine shorelines. Estuaries and Coasts 41:S131-S143.

Cubillo, A.M., S.B. Bricker, M. Parker, and J.G. Ferreira. 2017. NCCOS Ecological Assessment to Support NOAA's Choptank Complex Habitat Focus Area: Eutrophication and Shellfish Aquaculture/Restoration Ecosystem Services Modeling. Final report in fulfillment of Purchase Order JHT16P6090 to NOAA NCCOS July 2017.

Currin, C., J. Davis, L.C. Baron, A. Malhotra, and M. Fonseca. 2015. Shoreline change in the New River estuary, North Carolina: Rates and consequences. Journal of Coastal Research. 31(5):1069-1077.

Dauer, D.M., S.B. Weisberg and J.A. Ranasinghe. 2000. Relationships between benthic community condition, water quality, sediment quality, nutrient loads, and land use patterns in Chesapeake Bay. Estuaries 23(1):80-96.

Diaz, R.J. and R. Rosenberg. 2008. Spreading dead zones and consequences for marine ecosystems: Science 321:926-929.

Dorfman, D.S., A. Mabrouk, L. Bauer, D.M. Nelson, C. Clement, and L. Claflin. 2016. Choptank Ecological Assessment: Digital Atlas - Baseline Status Report. NOAA Technical Memorandum NOS NCCOS 213. Silver Spring, MD. 173 pp.

Durell, E.Q., and C. Weedon, 2017. http://dnr.maryland.gov/fisheries/Pages/striped-bass/juvenile-index.aspx. *Accessed 06/29/2018.*

EcoCheck. 2011. Sampling and data analysis protocols for Mid-Atlantic tidal tributary indicators. Wicks E.C., Andreychek M.L., Kelsey R.H., and Powell S.L. (eds). IAN Press, Cambridge, Maryland, USA.

Evans, B.M. 2008. An Evaluation of Potential Nitrogen Load Reductions to Long Island Sound from the Connecticut River Basin. Report Submitted to New England Interstate Water Pollution Control Commission, Lowell, MA.

Ferreira, J.G. and S.B. Bricker. 2016. Goods and services of extensive aquaculture: shellfish culture and nutrient trading. Aquaculture International. DOI 10.1007/s10499-015-9949-9

Ferreira J.G., A.J.S. Hawkins, S.B. Bricker. 2007. Farm-scale assessment of shellfish aquaculture in coastal systems – the Farm Aquaculture Resource Management (FARM) model: Aquaculture 264:160–174.

Ferreira J.G., A. Sequeira, A.J.S. Hawkins, A. Newton, T.D. Nickell, R. Pastres, J. Forte, A. Bodoy, and S.B. Bricker. 2009. Analysis of coastal and offshore aquaculture: Application of the FARM model to multiple systems and shellfish species: Aquaculture 292:129-138.

Ferreira, J.G., A. Hawkins and S. B. Bricker. 2011. The role of shellfish farms in provision of ecosystem goods and services. In: S. E. Shumway. Shellfish Aquaculture and the Environment. Hoboken, NJ: Wiley-Blackwell.

Fisher, T.R., J.D. Hagey, W.R. Boynton, and M.R. Williams. 2006. Cultural eutrophication in the Choptank and Patuxent estuaries of Chesapeake Bay. Limnology and Oceanography 51:435-447.

Fisher, T.R., T.E. Jordan, K.W. Staver, A.B. Gustafson, A.I. Koskelo, R.J. Fox, A.J. Sutton, T. Kana, K.A. Beckert, J.P. Stone, G.McCarty, and M.Lang. 2010. The Choptank Basin in transition: intensifying agriculture, slow urbanization, and estuarine eutrophication, pps. 135-165, IN: M. J. Kennish and H. W. Paerl (eds), Coastal Lagoons: Systems of Natural and Anthropogenic Change, CRC Press.

Fleming, C.S., M.K. Dillard, S.D. Regan, M. Gorstein, E. Messick, and A. Blair. 2017. A Coastal Community Vulnerability Assessment for the Choptank Habitat Focus Area. NOAA Technical Memorandum NOS NCCOS 225. Silver Spring, MD. 92 pp.Footner, H. 1972. Rivers of the Eastern Shore: Seventeen Maryland Rivers. Tidewater Publishers, Centreville, MD. 375 pp.

Footner, H. 1979. Rivers of the Eastern Shore. Schiffer Publishing Ltd. 381 pp.

Fulton, M.H., J.L. Hyland, P.B. Key, E.F. Wirth, L. Balthis, C. Cooksey, K. Chung, and A.K. Leight. 2007. Characterization of toxic impacts on living marine resources in tidal rivers of the Chesapeake Bay. NOAA Technical Memorandum NOS NCCOS 64. 80 pp.

Goede, R.W. and B.A. Barton, 1990. Organismic indices and an autopsy-based assessment as indicators of health and condition in fish. In: Adam, S.M., Ed., Biological Indicators of Stress in Fish, American Fisheries Society, Bethesda, 93-108.

Hartwell, S.I. and J Hameedi. 2007. Magnitude and Extent of Contaminated Sediment and Toxicity in Chesapeake Bay. NOAA Technical Memorandum NOS NCCOS 47. 234 pp.

Hrubec, T., and S. Smith. 2000. Hematology of fish. In Feldman, B., Zinkl, J., and N. Jain, Ed., Schalm's veterinary hematology, 5th edition. Lippincott Williams and Wilkins, Baltimore, p. 1120-1125.

Humphries, A.T., S.G. Ayvazian, J.C. Carey, B.T. Hancock, S. Grabbert, D. Cobb, C.J. Strobel, and R.W. Fulweiler. 2016. Directly Measured Denitrification Reveals Oyster Aquaculture and Restored Oyster Reefs Remove Nitrogen at Comparable High Rates. Frontiers in Marine Science 3:74: 1-10. doi: 10.3389/fmars.2016.00074

Hyland, J.L., W.L. Balthis, V.D. Engle, E.R. Long, J.F. Paul, J.K. Summers, and R.F. Van Dolah. 2003. Incidence of stress in benthic communities along the U.S. Atlantic and Gulf of Mexico coasts within different ranges of sediment contamination from chemical mixtures. Environmental Monitoring and Assessment 81:149-161.

James-Pirri, M.J., K.B. Raposa, andJ.G. Catena, J.G. 2001. Diet composition of mummichogs, *Fundulus heteroclitus,* from restoring and unrestricted regions of a New England (USA) salt marsh. Estuarine Coastal and Shelf Science 53(2):205-213.

Kellogg, M.L., J.C. Cornwell, M.S. Owens, and K.T. Paynter. 2013. Denitrification and nutrient assimilation on a restored oyster reef. Marine Ecology Progress Series 480: 1-19 doi: 10.3354/meps10331

Kellogg, M.L., A.R. Smyth, M.W. Luckenbach, R.H. Carmichael, B.L. Brown, J.C. Cornwall, M.F. Piehler, M.S. Owens, D.J. Dalrymple and C.B. Higgins. 2014. Use of oysters to mitigate eutrophication in coastal waters. Estuarine Coastal and Shelf Science 151:156-168.

King, D. M. and M.J. Mazzotta. 2000. Ecosystem Valuation. Methods, Section 1. Market Price Method. Available online at http://www.ecosystemvaluation.org/market_price.htm. *Accessed February 28, 2012.*

King, R.S., J.R. Beaman, D.F. Whigham, A.H. Hines, M.T. Baker, and D.E. Weller. 2004. Watershed Land Use Is Strongly Linked to PCBs in White Perch in Chesapeake Bay Subestuaries. Environmental Science and Technology 38: 6546-6552.

Kornis, M.S., D. Breitburg, R. Balouskus, D.M. Bilkovic, L.A. Davias, S. Giordano, K. Heggie, A.H. Hines, J.M. Jacobs, T.E. Jordan, R.S. King,, C.J. Patrick, R.D. Sietz, H. Soulen, T.E. Targett, D.E. Weller, D.F. Whigham, and J. Uphoff Jr. 2017. Linking the abundance of estuarine fish and crustaceans in nearshore waters to shoreline hardening and land cover. Estuarines and Coasts 40:1464-1486.

Lancia, R.A., W.L. Kendall, K.H. Pollock, and J.D. Nichols. 2005. Estimating the number of animals in wildlife populations. In: Techniques for wildlife investigations and management. Braun, C.E. (ed), pp. 1-153. Wildlife Society. Bethesda, Maryland.

Lefcheck, J.S., R.J. Orth, W.C. Dennison, D.J. Wilcox, R.R. Murphy, J. Keisman, C. Gurbisz, M. Hannam, J.B. Landry, K.A. Moore, C.J. Patrick, J. Testa, D.E. Weller, and R.A. Batiuk. 2018. Long-term nutrient reductions lead to the unprecedented recovery of a temperate coastal region. Proceedings of the National Academy of Sciences of the United States of America 115(14):3658-3662.

Leight, A.K., W.H. Slacum, E.F. Wirth, and M.H. Fulton. 2011. An assessment of benthic condition in several small watersheds of the Chesapeake Bay, USA. Environmental Monitoring and Assessment 176: 483-500.

Leight A., J. Jacobs, L. Gonsalves, G. Messick, S. McLaughlin, J. Lewis, J. Brush, E. Daniels, M. Rhodes, L. Collier, and B. Wood. 2014. Coastal Ecosystem Assessment of Chesapeake Bay Watersheds: A story of three rivers. NOAA Technical Memorandum NOS NCCOS 189. 95 pp.

Leight A., R. Trippe III, L. Gonsalves, J. Jacobs, S. McLaughlin, and G. Messick. 2015. Coastal Ecosystem Assessment of Chesapeake Bay Watersheds: Land Use Patterns and River Conditions. NOAA Technical Memorandum NOS NCCOS 207. 59 pp.

Leslie, H. 2018. Value of ecosystem based management. Proceedings of the National Academy of Sciences. www.pnas.org/cgi/doi/10.1073/pnas.1802180115. *Accessed 06/29/2018*.

Lindahl O., R. Hart, B. Hernroth, S. Kollberg, L.O. Loo, L. Olrog, A.S. Rehnstam-Holm, S. Svensson, and U. Syversen. 2005. Improving marine water quality by mussel farming: a profitable solution for Swedish society. Ambio 34(2):131–138.

Lippson, A.J. and R.L. Lippson. 2006. Life in the Chesapeake Bay, Third Edition. Johns Hopkins University Press, Baltimore, Maryland. 325 pp.

Lipton D.W. and R. Hicks. 2003. The cost of stress: Low dissolved oxygen and recreational striped bass (Morone saxatilis) fishing in the Patuxent River. Estuaries 26:310-315.

Llanso, R.J. and D.M. Dauer. 2002. Methods for calculating the Chesapeake Bay Benthic Index of Biotic Integrity. Chesapeake Bay Benthic Monitoring Report. 24 pp.

Long, E.R., L.J. Field, and D.D. MacDonald. 1998. Predicting toxicity in marine sediments with numerical sediment quality guidelines. Environmental Toxicology and Chemistry 17:714-727.

McGrath P. and H.A. Austin. 2009. Site fidelity, home range, and tidal movements of white perch during the summer in two small tributaries of the York River, Virginia. Transactions of the American Fisheries Society 138(5):966-974.

Malone, T. C., D. J Conley, T. R. Fisher, P. M Glibert, L. W Harding, and K. G. Sellner. 1996. Scales of nutrient-limited phytoplankton productivity in Chesapeake Bay. Estuaries 19:371−385.

Manseuti, R.J. 1961. Movements, reproduction, and mortality of the white perch, *Roccus americanus*, in the Patuxent Estuary, Maryland. Chesapeake Science. 2:142-205.

Maryland Department of Planning. 2018. Geospatial and Data Analysis Division. Maryland property view featuring parcel point data records for 2017.

MDE (Maryland Department of the Environment). 2018. https://mdewin64.mde.state.md.us/WSA/FCA/index.html. *Accessed 08/24/2018*.

Messick, G.A., J.M. Jacobs, J.R. Brush, S.M. McLaughlin, A.K. Leight, M.R. Rhodes, D.H. Howard, L. Gonsalves, and E.J. Lewis. 2013. NCCOS coastal ecosystem assessment program: a manual of methods. NOAA Technical Memorandum NOS NCCOS 169. 123 pp.

MidShore RiverKeepers. Undated. https://www.shorerivers.org/choptank/. *Accessed 9/12/2018*.

Murdy, E., R. Baker, and J. Musick. 1997. Fishes of Chesapeake Bay. Washington, D.C.: Smithsonian Institution Press.

Murphy, R. R., E. Trentacoste, and J. Keisman. 2017. Tributary Summary Reports and Syntheses Example concept for Choptank River. Presentation to Chesapeake Bay Science and Technical Committee. Dec 13, 2017. http://www.chesapeake.org/stac/presentations/286_TribSummaries_Choptank_Murphy%20and%20Trentacoste.pdf. *Accessed 9/12/2018*.
Mistiaen J.A., I.E. Strand and D. Lipton. 2003. Effects of environmental stress on Blue Crab (*Callinectes sapidus*) harvests in Chesapeake Bay tributaries. Estuaries 26(2A):316-322.

Moyle, P.B., 1994. Biodiversity, biomonitoring, and the structure of stream fish communities, chap 10 of Loeb, S.L., and Spacie, Anne, eds., Biological monitoring of aquatic systems: Boca Raton, Fla., Lewis Publishers, p. 171–186.
https://msa,maryland.gov/msa/mdmanual/36loc/ta/chron/html/tachron.html

Najjar, R.G., C.R. Pyke, M.B. Adams, D. Breitburg, C. Hershner, M. Kemp, R. Howarth, M.R. Mulholland, M. Paolisso, M., D. Secor, K. Sellner, D. Wardrop, and R. Wood. 2010. Potential climate-change impacts on the Chesapeake Bay. Estuarine Coastal and Shelf Science 86(1):1-20.

NCDC (National Climatic Data Center). 2018. U.S. Climate Divisions. https://www.ncdc.noaa.gov/monitoring-refernces/maps/us-climate-divisions.php. *Accessed 06/28/2018*.

NOAA (National Oceanic and Atmospheric Administration). 2008. Dissolved Oxygen. http://oceanservice.noaa.gov/education/kits/estuaries/media/supp_estuar10d_disolvedox.html. *Accessed 06/16/2015*.

NOAA (National Oceanic and Atmospheric Administration/Chesapeake Bay Office). 2015. Tred Avon River oyster restoration tributary plan: A blueprint for sanctuary restoration. https://chesapeakebay.noaa.gov/images/stories/habitats/april2015tredavontribplan.pdf. *Accessed 06/28/2018*.

NOAA (National Oceanic and Atmospheric Administration/Chesapeake Bay Office). 2018. Oysters. http://chesapeakebay.noaa.gov/fish-facts/oysters. *Accessed 06/22/2018*.

NOAA (National Oceanic and Atmospheric Administration/National Ocean Service). 2012. Chlorophyll. http://oceanservice.noaa.gov/education/kits/estuaries/media/supp_estuar10h_clorophyll.html. *Accessed 06/19/2015*.

Noga, E. 2000. Fish leukocyte responses. In: Feldman B, Zinkl J, Jain N (eds) Schalm's veterinary hematology, 5th edition. Lippincott Williams and Wilkins, Baltimore.

Orth, R.J. and K.A. Moore. 1984. Distribution and abundance of submerged aquatic vegetation in Chesapeake Bay: An historical perspective. Estuaries 7(4):531–540.

Oyster BMP Panel. 2016. Panel Recommendations on the Oyster BMP Nutrient and Suspended Sediment Reduction Effectiveness Determination Decision Framework and Nitrogen and Phosphorus Assimilation in Oyster Tissue Reduction Effectiveness for Oyster Aquaculture Practices. Draft report submitted to the Chesapeake Bay Partnership Water Quality Goal Implementation Team, September 22, 2016, available at http://www.chesapeakebay.net/calendar/event/24330/. *Accessed 9/12/2018*.

Oyster Metrics Workgroup. 2011. Restoration Goals, Quantitative Metrics and Assessment Protocols for Evaluating Success on Restored Oyster Reef Sanctuaries Report of the Oyster Metrics Workgroup. Submitted to the Sustainable Fisheries Goal Implementation Team of the Chesapeake Bay Program. https://chesapeakebay.noaa.gov/fisheries-hot-topics/oyster-metrics-report-adopted. *Accessed 9/12/2018*.

Pan, H., J.J. Geng, Y.K. Qin, F.Y. Tou, J.L. Zhou, M. Liu, and Y. Yang. 2016. PCBs and OCPs in fish along coastal fisheries in China: Distribution and health risk assessment. Marine Pollution Bulletin 111(1-2): 483-487.

Paynter, K., A. Michaelis, and A. Handschy. 2014. Paynter Lab Annual Monitoring and Research Summary 2013. Department of Biology, University of Maryland, College Park, MD 20742 and Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, Solomons, MD. Submitted to the Oyster Recovery Partnership.

Pollack, J.B., D. Yoskowitz, H-C. Kim, and P.A. Montagna. 2013. Role and value of nitrogen regulation provided by oysters (Crassostrea virginica) in the Mission-Aransas Estuary, Texas, USA. PLoS ONE 8(6): e65314. doi:10.1371/journal.pone.0065314

Preisendorfer, R.W. 1986. Secchi Disk Science - Visual Optics of Natural-Waters. Limnology and Oceanography. 31(5):909-926.

Prosser, D.J., T.E. Jordan, J.L. Nagel, R.D. Seita, D.E. Weller, and D.F. Whigham. 2018. Impacts of coastal land use and shoreline armoring on estuarine ecosystems: an introduction to a special issue. Estuaries and Coasts 41:S2-S18.

Ranasinghe, J. A., S. B. Weisberg, D. M. Dauer, L. C. Schaffner, R. J. Diaz, and J. B. Frithsen. 1994. Chesapeake Bay Benthic Community Restoration Goals. Prepared for the U.S. EPA Chesapeake Bay Program Office, the Governor's Council on Chesapeake Bay Research Fund, and the Maryland Department of Natural Resources by Versar, Inc., Columbia, MD.

Rapport, D.J., G. Bohm, D. Buckingham, J. Cairns, Jr., R. Costanza, J.R. Karr, H.A.M. deKruijf, R. Levins, A.J. McMichael, N.O. Nielson, and W.G. Whitford. 1998. Assessing ecosystem health. TREE. 13(10):3907-402.

Reitsma, J., D.C. Murphy, A.F. Archer, and R.H. York. 2018. Nitrogen extraction potential of wild and cultured bivalves harvested from nearshore waters of Cape Cod, USA. Marine Pollution Bulletin 116: 175–181.

Ricker, W. E. 1975. Computation and inter-pretation of biological statistics of fishpopulations. Bulletin of the Fisheries Research Board of Canada 191:1-382.

Ringwood, A.H., M.E. DeLorenzo, P.E. Ross, and A.F. Holland. 1997. Interpretation of microtox solid phase toxicity tests: The effects of sediment composition. Environmental Toxicology and Chemistry. 16(6):1135-1140.

Roberts, R.J. 2012. Fish pathology. Wiley Blackwell. 590 pp.

Rose, J. M., S.B. Bricker, M.A. Tedesco, and G.H. Wikfors. 2014. A Role for Shellfish Aquaculture in Coastal Nitrogen Management. Environmental Science and Technology 48:2519−2525.

Rose, J.M. S.B. Bricker, and J.G. Ferreira. 2015. Modeling shellfish farms to predict harvest-based nitrogen removal. Marine Pollution Bulletin 91:185–190.

Shannon, C.E. and W. Weaver. 1949. The mathematical theory of communication. University of Illinois Press, Urbana. 117 pp.

ShoreRivers, Inc. 2018. 2017 Choptank River Report Card. https://www.shorerivers.org/report-cards/ *Accessed 9/30/2018.*

Silva C., J.G. Ferreira, S.B. Bricker, T.A. DelValls, M.L. Martín-Díaz, and E, Yáñez. 2011. Site selection for shellfish aquaculture by means of GIS and farm-scale models, with an emphasis on data-poor environments. Aquaculture 318:444–457.

Spencer, P. and B. McGee. 2016. Ecosystem servie benefits of a cleaner Chesapeake Bay. Coastal Management 44(3):241-258.

Stephenson K., S. Aultman, T. Metcalfe, and A. Miller. 2010. An evaluation of nutrient nonpoint offset trading in Virginia: A role for agricultural nonpoint sources? Water Resource Research 46:WO4519.

TAMS Consultants, Inc. and Menzie-Cura and Associates, Inc. 2000. Revised baseline ecological risk assessment. Hudson River PCBs reassessment. For USEPA Region 2 and U.S. Army Corps of Engineers Kansas City District.

TCHPC (Talbot County Historical Preservation Commission). 2015. 925 Port Street: The Pratt-Hoffman House. Extended Narrative Report.

Town of Mashpee Sewer Commission. 2015. Final Recommended Plan/ Final Environmental Impact Report. Comprehensive Wastewater Management Plan, Town of Mashpee; GHD Inc.: Hyannis, MA.

UMCES (University of Maryland Center for Estuarine Science). 2018. Integration and Application Network. https://ecoreportcard.org/report-cards/chesapeake-bay/health/ *Accessed 8/15/2018*.

Uphoff, J.H., M. McGinty, R. Lukacovic, J. Mowrer and B. Pyle. Impervious surface, summer dissolved oxygen, and fish distribution in Chesapeake Bay subestuaries: Linking watershed development, habitat conditions, and fisheries management. North American Journal of Fisheries Management 31(3):554-566.

USACE (U.S. Army Corps of Engineers). 2012. Chesapeake Bay Oyster Master Plan Appendices.

USACE (U.S. Army Corps of Engineers). 2014. Supplemental Environmental Assessment and Finding of No Significant Impact, Shallow Water Oyster Restoration in Harris Creek Oyster Sanctuary, MD.

USACE (U.S. Army Corps of Engineers). 2018. http://www.nab.usace.army.mil/Missions/Civil-Works/Chesapeake-Bay-Comprehensive-Plan/. *Accessed 6/28/2018*.

USEPA (Environmental Protection Agency). 1995. Environmental Monitoring and Assessment Program (EMAP): Laboratory Methods Manual – Estuaries, Vol. 1: Biological and Physical Analyses. Office of Research and Development, Environmental Monitoring and Systems Laboratory, Environmental Protection Agency, Cincinnati, OH. EPA/620/R-95/008.

USEPA (Environmental Protection Agency). 2004. Water quality standards for coastal and Great Lakes recreation waters; Final Rule. 40 CFR Part 131. Environmental Protection Agency 27 pp.

USEPA (U.S. Environmental Protection Agency). 2010. Chesapeake Bay Phase 5.3 Community Watershed Model. EPA 903S10002 - CBP/TRS-303-10. U.S. Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis MD. December 2010. Values for version 5.3.2 received September 2018 from G. Shenk and S. Ravi, USGS Chesapeake Bay Program Office.

USEPA (Environmental Protection Agency). 2011. New tools measure fish health. Environmental Protection Agency (EPA)/600/F-04/203. Washington DC.

USEPA (Environmental Protection Agency). 2014. 2008-09 NRSA Fish Tissue Data Dictionary for Mercury, Selenium, PBDEs, PCBs, Pesticides, and PFCs September 2014 (https://www.epa.gov/sites/production/files/2014-12/documents/nrsa-data-dictionary-for-fish-tissue-data-9-30-14.pdf). Environmental Protection Agency. *Accessed 6/18/2018.*

USEPA (Environmental Protection Agency). 2018a. https://www.epa.gov/national-aquatic-resource-surveys/indicators-enterococci. *Accessed 08/22/2018.*

USEPA (Environmental Protection Agency). 2018b. Sediment benchmarks for aquatic life (https://archive.epa.gov/emergency/bpspill/web/html/sediment-benchmarks.html#sed2). Environmental Protection Agency. *Accessed 9/24/2018.*

USEPA (Environmental Protection Agency), U.S. Geological Survey, and U.S. Fish and Wildlife Service. 2012. Toxic Contaminants in the Chesapeake Bay and its Watershed: Extent and Severity of Occurrence and Potential Biological Effects, U.S. Environmental Protection Agency Chesapeake Bay Program Office, Annapolis, MD, December, 2012, 175 pp.

USGS (U.S. Geological Service). 2018. https://mi.water.usgs.gov/h2oqual/BactHOWeb.htm. *Accessed 06/18/2018.*

VIMS (Virginia Institute of Marine Science). 2017. http://web.vims.edu/bio/sav. *Accessed 6/29/2018.*

VIMS (Virginia Institute of Marine Science). 2018. http://www.vims.edu/newsandevents/topstories/2018/sav_2017_report.php. *Accessed 08/16/2018.*

Wade, T.J., N. Pai, J.N. Eisenberg, and J.M. Colford, Jr. 2003. Do U.S. Environmental Protection Agency water quality guidelines for recreational waters prevent gastrointestinal illness? A systematic review and meta-analysis. Environmental Health Perspectives 111:1102-1109.

Wagemann, R., E. Trebacz, R. Hunt, and G. Boila. 1997. Percent methylmercury and organic mercury in tissues of marine mammals and fish using different experimental and calculation methods. Environmental Toxicology and Chemistry 16(9):1859–1866.

Wazniak, C.E., M.R. Hall, T.J.B. Carruthers, B. Sturgis, W.C. Dennison, and R.J. Orth. 2007. Linking water quality to living resources in a mid-Atlantic lagoon system, USA. Ecological Applications 17:S64-S78.

Weis, J.S. 2010. Tolerance to Environmental Contaminants in the Mummichog, *Fundulus heteroclitus*, Human and Ecological Risk Assessment: An International Journal, 8:5, 933-953, DOI: 10.1080/1080-700291905756).

Wentworth, C.K. 1922. A scale of grade and class terms for clastic sediments. Journal of Geology. 30:377-392.

Zar, J.H. 1999. Biostatistical Analysis, Fourth edition. Prentice Hall, Upper Saddle River, New Jersey.

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