Chesapeake Healthy Watersheds Assessment:

Assessing the Health and Vulnerability of Healthy Watersheds within the Chesapeake Bay Watershed

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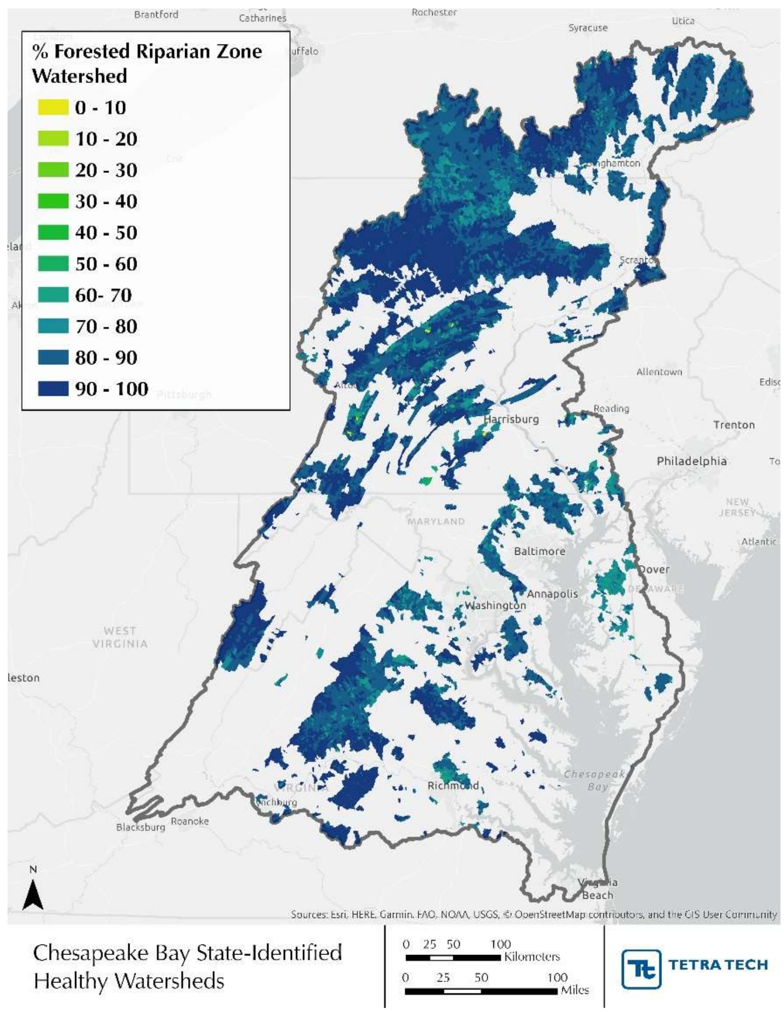
May 20, 2020



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Acknowledgments

The authors wish to thank the staff of the Chesapeake Bay Program and other partner agencies for assistance throughout the project and in particular for providing geospatial data and technical review. This project has been funded wholly or in part by the United States Environmental Protection Agency under assistance agreement CB96341401 to the Chesapeake Bay Trust. The contents of this document do not necessarily reflect the views and policies of the Environmental Protection Agency, nor does the EPA endorse trade names or recommend the use of commercial products mentioned in this document.

Executive Summary

The Chesapeake Bay Program, through its Maintain Healthy Watersheds Goal Implementation Team, has a goal of maintaining the long-term health of watersheds identified as healthy by its partner jurisdictions. Quantitative indicators are important to assess current watershed condition, track future condition, and assess the vulnerability of these state-identified watersheds to future degradation. Building upon the U.S. Environmental Protection Agency (EPA) Preliminary Healthy Watershed Assessment (PHWA) framework, a set of candidate metrics characterizing multiple aspects of landscape condition, hydrology, geomorphology, habitat, biological condition, and water quality were assembled and evaluated for integration into an overall watershed health index. Geospatial analyses were structured, where possible, to leverage data from EPA StreamCat, the National Fish Habitat Partnership, the Chesapeake Bay Watershed Model for nutrient loads, Chesapeake Bay high-resolution land use / land cover data, and other regional data sources. In addition, a set of vulnerability metrics were derived representing aspects of land use change, water use, wildfire risk, and climate change. Metric values were compiled for the nearly 84,000 NHDPlus (v.2) catchments Bay-wide and were used to assess conditions and vulnerability within the catchments associated with the current set of state-identified healthy watersheds. Metrics were combined into sub-indices and an overall Watershed Health index. These indicators will be available to federal, state, and local managers as a geospatial tool, providing critical information for maintaining watershed health. The Chesapeake Healthy Watersheds Assessment (CHWA) provides a framework for tracking condition at future intervals, with the ability to integrate new data that become available.

The assessment framework, metrics, and geodatabase created for the CHWA are intended to be useful for a variety of management applications. Primarily, the assessment will support the Chesapeake Bay Program and its jurisdiction partners in detecting signals of change in the state-identified healthy watersheds, providing information useful to support strategies to protect and maintain watershed health. In particular, indicators of vulnerability may help to provide an "early warning" to identify factors that could cause future degradation, allowing for steps to be taken to head off these potential negative effects. The CHWA will also be integrated with other Bay Program efforts in support of stream and watershed health.

1. Introduction - Purpose and Objectives

The U.S. Environmental Protection Agency (EPA 2019a) defines a healthy watershed as one in which natural land cover supports:

- dynamic hydrologic and geomorphic processes within their natural range of variation,
- habitat of sufficient size and connectivity to support native aquatic and riparian species, and
- physical and chemical water quality conditions able to support healthy biological communities.

Through its Healthy Watersheds Program, EPA promotes the protection of healthy watersheds through a variety of assessment and management approaches (EPA 2012). Protection of healthy watersheds is an integral component of overall strategy to meet the goal of the Clean Water Act, specifically "…to restore and maintain the chemical, physical, and biological integrity of the Nation's waters." EPA's Healthy Watersheds efforts are intended to "protect and maintain remaining healthy watersheds having natural, intact aquatic ecosystems; prevent them from becoming impaired; and accelerate restoration successes." (EPA 2012)

The Chesapeake Bay Program (CBP) recognizes the importance of conserving healthy watersheds within the Chesapeake Bay region as part of the overall Bay restoration effort. In addition to clean water and high-quality habitat for aquatic species, healthy watersheds also provide social and economic benefits such as clean drinking water, wildlife habitat, flood protection, and recreation. Conservation of healthy watersheds is a proactive approach that can reduce the need for future and costly restoration of watersheds that become degraded (CBP 2020a).

Through the Maintain Healthy Watersheds Goal Implementation Team (HWGIT), the Bay Program and its partners have established a goal of sustaining the long-term health of watersheds identified as healthy by partner jurisdictions. Quantitative information on watershed health will contribute to an understanding of the current condition of the state-identified healthy watersheds and will help to track conditions in the future. The Healthy Watersheds Outcome Management Strategy (CBP 2020a) identifies efforts underway and planned for achieving the intended outcome: that 100 percent of state-identified currently healthy waters and watersheds remain healthy.

- *Healthy Watersheds Goal: Sustain state-identified healthy waters and watersheds recognized for their high quality and/or high ecological value.*
- *Healthy Watersheds Outcome: 100 percent of state-identified currently healthy waters and watersheds remain healthy.*

- Healthy Watersheds Outcome Management Strategy (CBP 2020a)

To provide information that will help in watershed assessment, this project applied the U.S. Environmental Protection Agency (EPA) Preliminary Healthy Watersheds Assessment (PHWA) framework to develop an approach for characterizing the health of watersheds in the Chesapeake Bay. This effort will support the HWGIT in tracking progress towards the Healthy Watersheds Outcome. Further, this project gathered additional information that can be applied towards assessing vulnerabilities of healthy watersheds to future degradation, and to help target and inform management efforts in these areas. The project had three objectives:

1. To apply the PHWA framework to assess the current condition of state-identified healthy watersheds within the Chesapeake Bay Watershed.

2. To develop an approach to use the PHWA framework to track the health of state-identified healthy watersheds over time to determine if watershed health is being maintained.

3. To apply the PHWA framework to identify vulnerabilities in state-identified healthy watersheds.

Although developed in support of the HWGIT, the Chesapeake Healthy Watersheds Assessment (CHWA) has many cross-connections to other CBP efforts, including stream health, fish habitat assessment, water quality, climate change, and local engagement. Watershed health data developed for this project will be applicable in support of these interrelated programs for Bay protection and restoration.

2. Background: EPA's Preliminary Healthy Watersheds Assessment Framework

The linkages between landscape conditions and stream health have been well documented, at a range of scales from the local reach to broader watershed scale (Allan 2004). A variety of studies have investigated landscape influences on stream and riverine ecology (see review by Steel et al. 2010), particularly with the intent to inform watershed management and conservation activities. Advances in geospatial tools and data visualization bring new opportunities for applying landscape-scale data to inform the management of streams and watersheds to promote healthy conditions.

Recent efforts by EPA's Healthy Watersheds program have brought together key, nationally consistent data to assess watershed health and vulnerability. The approach provided by the nationwide PHWA (EPA 2017) includes an index of watershed health, incorporating six key ecological attributes inherent in the definition of healthy watersheds: landscape condition, geomorphology, habitat, water quality, hydrology, and biological condition (Figure 1). In addition, the PHWA vulnerability index incorporates a limited number of potential stressors representing three categories: land use change, water use, and wildfire risk. In April 2017, EPA rolled out the PHWA, with a set of 48 statewide and 85 ecoregional-scale assessments of watershed health and vulnerability across the conterminous United States. The PHWA was intended to serve as a useful framework that could be built upon by states and regions. To support further use and refinement, EPA produced state-specific PHWA geodatabases including a suite of indicators at the 12-digit hydrologic unit code (HUC) scale.

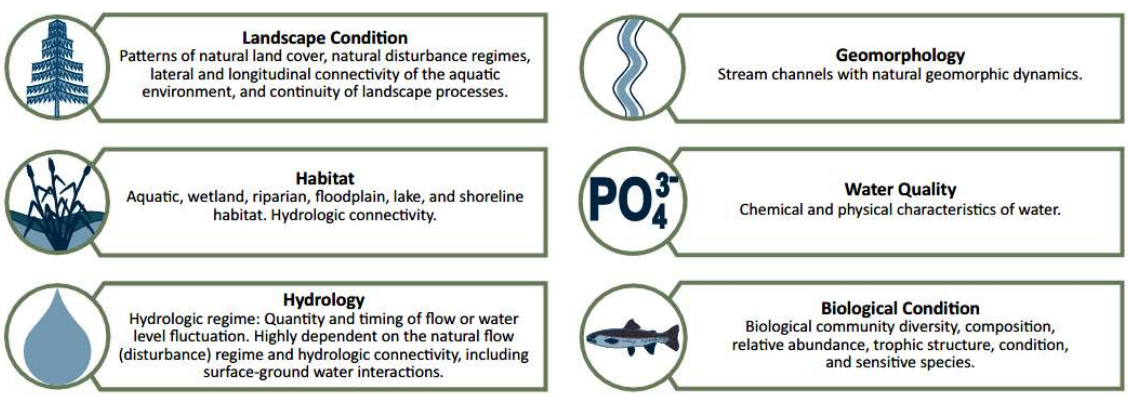


Figure 1: Six attributes of watershed health described in EPA's Identifying and Protecting Healthy Watersheds: Concepts, Assessments, and Management Approaches (EPA 2012).

EPA's PHWA employed a suite of metrics in each of the six overall categories for watershed health (Figure 2). PHWA metrics were designed to be used individually or combined into six sub-indices representing those categories and a final, overall index of watershed health. The PHWA also compiled vulnerability metrics in three categories (Figure 3).

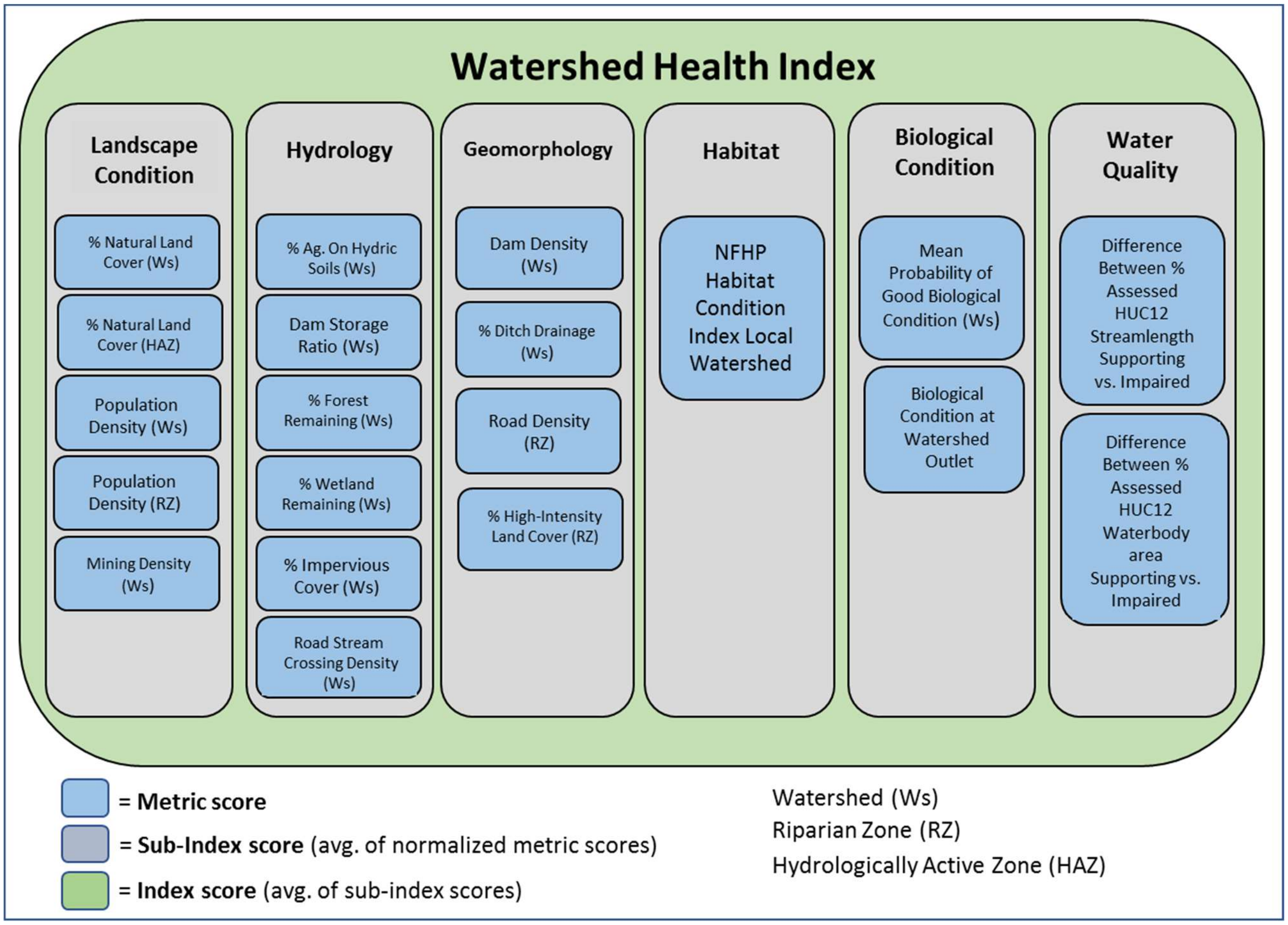


Figure 2: EPA's PHWA Watershed Health Index and sub-index structure with component metrics in each of six categories (Source: EPA 2017).

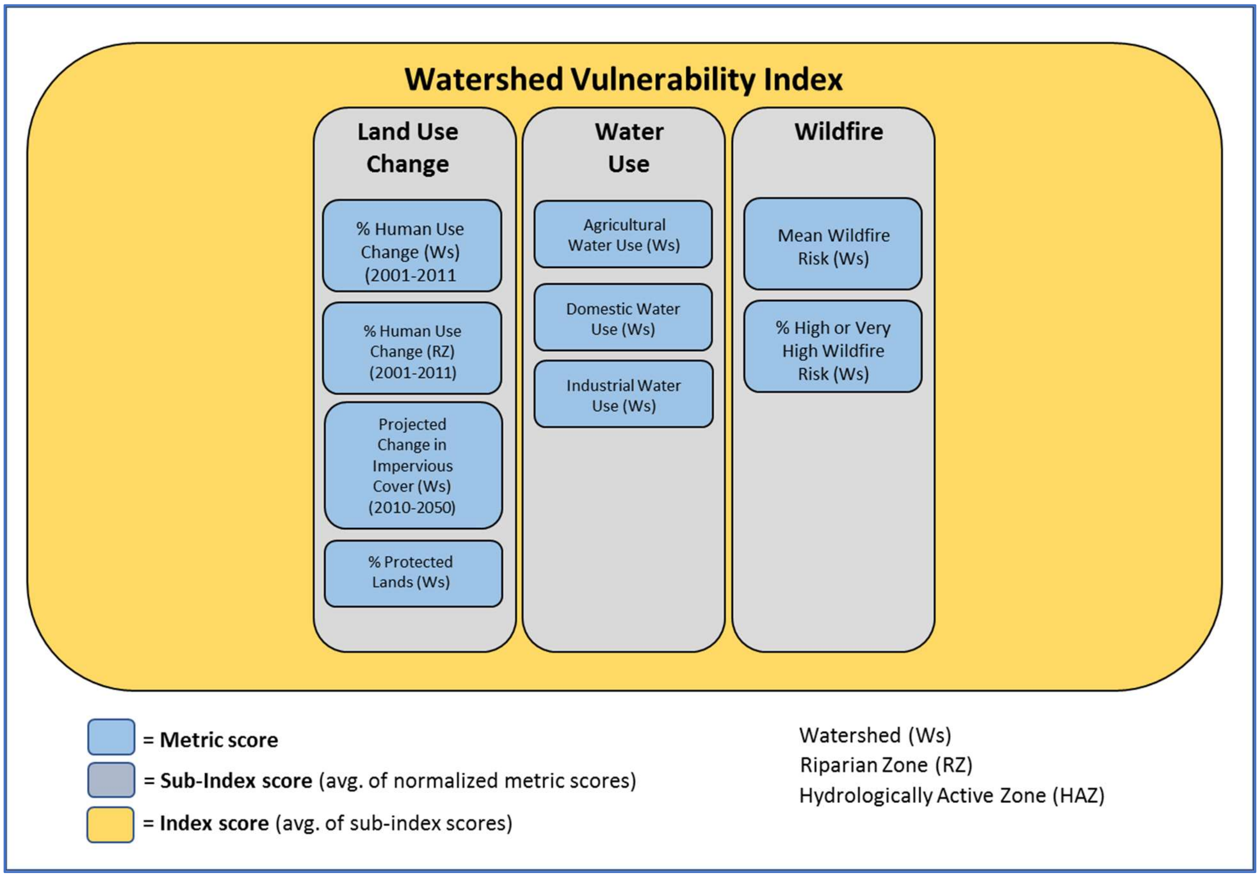


Figure 3: EPA's PHWA Watershed Vulnerability Index and sub-index structure with component metrics (Source: EPA 2017).

3. State-Identified Healthy Watersheds within the Chesapeake Bay Watershed

Each of the Chesapeake Bay jurisdictions have set their own definitions of “healthy waters and watersheds”, and a map of these state-identified healthy waters and watersheds is maintained by the Bay Program (CBP 2019). These waters and watersheds, as identified in 2017, will serve as the baseline from which watershed health will be assessed and progress toward the healthy watershed outcome will be measured. Individual jurisdictions have defined their healthy waters and watersheds, as shown in Table 1. In addition to region-wide efforts, individual jurisdictions have their own programs to support protection of high-quality waters and watersheds. The HWGIT encourages these efforts and also seeks to provide data and tools to assist in tracking the status of conditions in the healthy watersheds and in identifying signals of change and vulnerability.

Table 1: Individual jurisdictions’ definitions of healthy waters and watersheds (CBP 2019)

Jurisdiction	Definition of Healthy Waters or Watersheds
New York	Waterbodies that have been categorized as "No Known Impact" because monitoring data and information indicate an absence of use restrictions are considered healthy.
Pennsylvania	Waters and watersheds that have been classified as High Quality or Exceptional Value are considered healthy.
Maryland	Tier II Waters: streams and their catchments are designated Tier II when their biological characteristics are significantly better than minimum water quality standards.
West Virginia	Waters that have been designated Tier 3 are known as outstanding national resource waters and are considered healthy.
Virginia	Waters and watersheds that are identified as having high aquatic integrity according to the Virginia Department of Conservation and Recreation's Division of Natural Heritage Healthy Waters Program are defined as ecologically healthy waters.
Delaware	Currently no healthy watersheds defined. All of the state's tributaries to the Chesapeake Bay are impaired by nitrogen, phosphorus, sediment and/or bacteria, and will only be considered healthy when their Total Maximum Daily Loads (TMDLs) are achieved and their surface water quality standards are met.
District of Columbia	Because the District primarily urbanized, it has not currently identified healthy watersheds.

4. Interagency Coordination in Development of the Chesapeake Healthy Watersheds Assessment

The development of the Chesapeake Healthy Watersheds Assessment was sponsored by the CBP and involved coordination with Bay Program staff, the HWGIT, and a core group of state and federal partners, including state data contacts. GIT and core group members are listed in Appendix A. Throughout the course of the project, meetings were held to provide updates and seek input from GIT members and core group partners. Summaries and presentations from the following meetings are included in Appendix B of this report:

- Project kickoff meeting, October 27, 2017
- Core group meeting, December 18, 2017
- HWGIT meeting, January 24, 2018
- Core group meeting, October 22, 2018
- HWGIT meeting, June 6, 2019

5. Scale of Analysis

Although the national PHWA provided data at the 12-digit HUC scale, initial inspection of healthy watershed examples within the Chesapeake Bay Watershed indicated that a finer scale of analysis would be needed to for the CHWA. Analysis needed to be appropriate for assessing the state-identified healthy watersheds, as many of these watersheds are themselves smaller than a 12-digit HUC. Even for larger healthy watersheds, managers of state programs had expressed interest in having access to environmental and landscape data on the particular sub-areas within those watersheds to inform management and decision-making processes, and especially, to help locate and address land-based stressors that may be affecting watershed health.

For the current analysis conducted for the Chesapeake Healthy Watersheds Assessment, the geographic units selected were catchments from the National Hydrography Dataset Plus Version 2 (NHDPlus) geospatial dataset developed by EPA and USGS. These NHDPlus catchments represent the direct drainage area of individual NHDPlus stream reaches and therefore allowed assessment of conditions at a finer scale than provided by the PHWA. Within the Chesapeake Bay Watershed, the average area of a 12-digit HUC is 89.97 square kilometers (34.74 square miles = 22,233.6 acres), while the average area of an NHDPlus catchment is 2.04 square kilometers (0.79 square miles = 505.6 acres). If needed, catchment data can be aggregated up to larger landscape units. Using the NHDPlus catchments as the basic unit of analysis provides data to characterize watershed health and vulnerability within a spatial framework that supports watershed protection and planning across various spatial scales and hydrologic units.

An initial step was to prepare a map representing the drainage areas of the healthy watersheds in Chesapeake Bay Watershed (Figure 4), created from the state-identified waters and watersheds provided by the Bay Program. A further step was to identify those NHDPlus catchments associated with each of the state-identified healthy watersheds, so that catchment-specific data can be examined for these watersheds of interest, either individually or as a group. However, metrics were computed for all catchments across the entire Bay watershed, not only for those within healthy watersheds.

Other state and regional efforts to characterize and identify healthy watersheds have also selected NHDPlus catchments as the basic geographic unit for analysis. Examples include Tennessee’s statewide assessment of watershed health and vulnerability (Matthews et al. 2015) and the Alabama-Mobile Bay healthy watershed assessment (Cadmus Group 2014a) – both were based on NHDPlus catchments. Similarly, Wisconsin’s statewide assessment of watershed health and vulnerability (Cadmus Group 2014b) employed state-specific boundaries at a catchment scale, using reach-scale watershed segments from the Wisconsin Department of Natural Resources 24K hydro geodatabase.

As described in the Tennessee healthy watersheds assessment (Matthews et al. 2015), using the NHDPlus catchment scale provides a spatial framework for watershed protection planning at a variety of scales and offers several advantages:

> NHDPlus is a medium-resolution dataset of all stream reaches in the nation and their corresponding catchments. Each NHDPlus catchment represents the direct, or local, drainage area for an individual stream reach and has a common identifier (COMID) assigned to it in the dataset. A separate table identifies the “from” and “to” COMID for every catchment in the dataset, giving

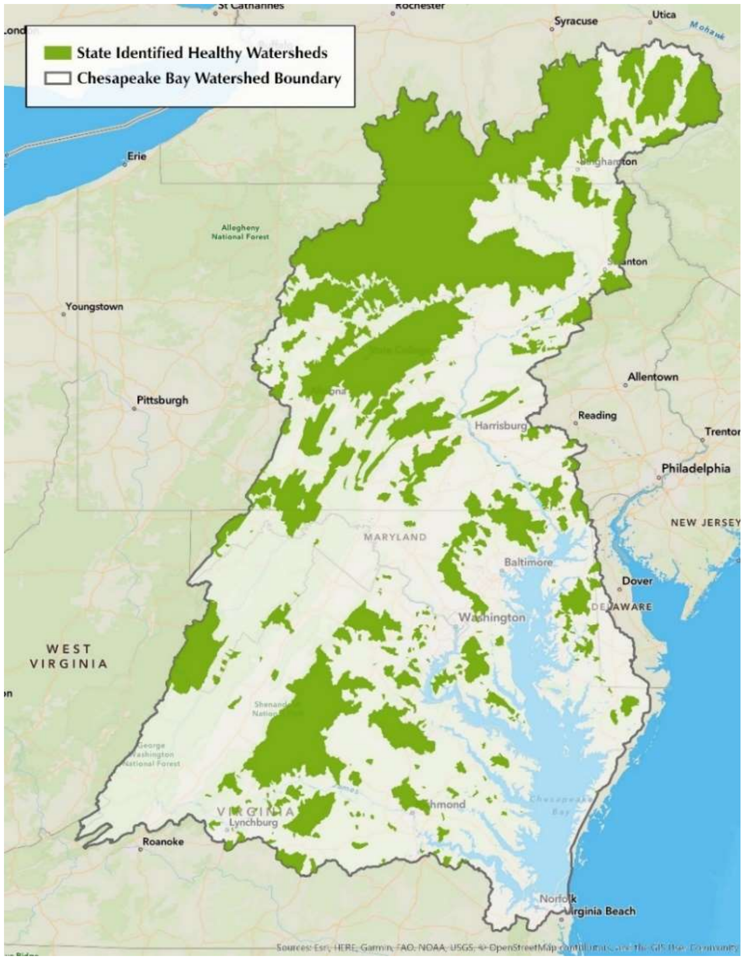


Figure 4: Drainage areas of state-identified healthy waters and watersheds in the Chesapeake Bay Watershed.

a complete picture of the hydrologic relationships between every catchment in the stream network at the 1:100,000 scale.

The hydrologic relationships in NHDPlus allow for calculations of watershed characteristics (e.g., drainage area, stream length, land use) at both the incremental (within catchment boundaries) and cumulative scales (within all upstream catchments) for any stream reach. Cumulative values are included in the Assessment because of the potential for upstream conditions to influence the health of a given stream reach. For example, high percent imperviousness in the cumulative watershed is expected to influence downstream biological communities even though the incremental imperviousness for the catchment may be low. In addition to its analytical benefits, NHDPlus catchments can be aggregated to larger watershed scales. This allows for flexible reporting of results at other watershed scales appropriate for multiple management or communication objectives.

Watershed health and vulnerability metrics were quantified on a catchment-by-catchment basis. The NHDPlus dataset supports aggregation of incremental-to-cumulative data by storing a unique numeric identifier for each catchment as well as upstream/downstream catchments.

For the Chesapeake assessment, working at the NHDPlus catchment scale provided the benefits described above and also enabled the leveraging of data and approaches from the EPA's Stream-Catchment (StreamCat) Dataset (Hill et al. 2016) in compiling catchment-scale metric data. Developed by EPA's Office of Research and Development (ORD), the StreamCat dataset (https://www.epa.gov/national-aquatic-resource-surveys/streamcat) is an extensive collection of landscape metrics for 2.6 million streams and associated catchments within the conterminous U.S., including both natural and human-related landscape features. Of particular importance, StreamCat data are summarized both for individual stream catchments and for cumulative upstream watersheds (Figure 5), based on the NHDPlus Version 2 geospatial framework (EPA 2019b).

Using the same approach, most of the metrics included in the Chesapeake Healthy Watersheds Assessment were computed as integrating conditions throughout the entire upstream watershed. For certain applications of the data, use of catchment-specific (not watershed) data may also be of interest. For example, data on landscape conditions by individual catchments may be useful to help understand the various stressors acting in different parts of a watershed, whereas values that integrate conditions across the entire upstream watershed may blur or smooth these differences.

As in the national PHWA, certain CHWA metrics were computed for the riparian area only, defined as the area within approximately 100 meters on either side of the stream-line. Other metrics were computed for slight variations of this defined riparian area, known as the hydrologically connected or hydrologically active zone, as defined in the PHWA (Table 2 and Figure 6).

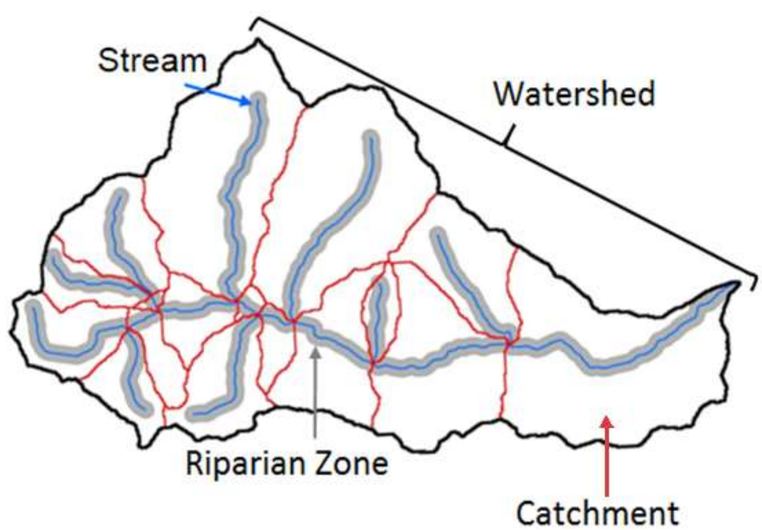


Figure 5: Diagram of catchment and watershed terms as used in StreamCat and the Chesapeake Healthy Watersheds Assessment. A riparian buffer area is here defined as land within approximately 100 meters on each side of stream. Diagram modified from StreamCat documentation (EPA 2019b).

Table 2: EPA StreamCat/PHWA definitions for riparian zone, hydrologically connected zone, and hydrologically active zone. (Source: PHWA MD dataset, MD_PHWA_TabularResults_170518)

Riparian Zone (RZ)	The Riparian Zone (RZ) is the corridor of land adjacent to surface waters. The RZ is delineated for the United States in a geospatial grid dataset depicting surface water features and adjacent buffer areas. The RZ grid was generated by creating a 108-meter buffer around surface waters in the Water Mask grid. The buffer includes areas on both sides of surface waters and the buffer size of 108 meters was selected based on the spatial resolution of the Water Mask grid to approximate a 100-meter buffer. The spatial resolution of the RZ grid is 30 meters.
Hydrologically Connected Zone (HCZ)	The Hydrologically Connected Zone (HCZ) is comprised of wet areas with high runoff potential that are contiguous to surface water. The HCZ is delineated for the United States for indicator calculations in a geospatial grid dataset depicting surface water features and wet areas that are contiguous to surface water. The HCZ grid was generated using the Wetness Index and Water Mask grids. The Wetness Index grid was first used to identify wet areas based on topography (i.e., low-lying, low-slope areas), defined as pixels with a Wetness Index of 550 or greater. The HCZ was then delineated as wet pixels in the Wetness Index grid that were also contiguous to surface water in the Water Mask. Wet pixels that were isolated from surface water were not included in the HCZ grid. The spatial resolution of the HCZ grid is 30 meters.
Hydrologically Active Zone (HAZ)	The Hydrologically Active Zone (HAZ) is a geospatial grid dataset that combines the Riparian Zone grid and the Hydrologically Connected Zone grid. (See also Riparian Zone and Hydrologically Connected Zone definitions).

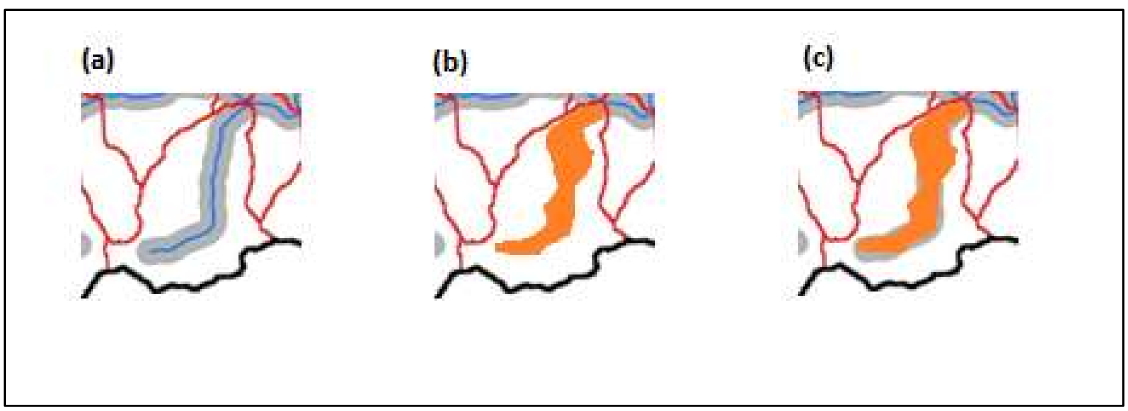


Figure 6: Depiction of EPA StreamCat/PHWA definitions for (a) riparian zone, (b) hydrologically connected zone, and (c) hydrologically active zone.

6. Developing an Assessment of Watershed Health

For the Chesapeake Healthy Watersheds Assessment, candidate metrics in each of the six categories describing ecological attributes of watershed health condition were considered and evaluated as potential indicators of watershed health. Input from CBP partners, HWGIT members, and state data contacts was gathered to inform the process of proposing and selecting candidate metrics. Candidates included the original suite of PHWA metrics, calculated at the catchment rather than HUC-12 scale, along with Chesapeake Bay Watershed-specific renditions of those metrics, based upon regional rather than national data sets, when available. In addition, new metrics were proposed and considered, including those based on additional demographic, geomorphic, habitat, and biological data, as well as nutrient load data from SPARROW and the Chesapeake Bay Watershed Model.

Ecological filters were applied to reduce the original set of candidate metrics to a final recommended suite. Criteria for selecting metrics included availability of data at an appropriate scale (generally at the catchment or finer level), coverage of the entire study area, and low redundancy with other potential metrics (Figure 7). Data that did not provide broad spatial coverage but were more limited in scope, such as site-specific monitoring data, were not included in the current analysis. Future management efforts directed toward maintenance of conditions in healthy watersheds may benefit from more localized data. Data were compiled and watershed health metrics were developed for each of the 83,623 NHDPlus catchments within the Chesapeake Bay Watershed.

A final recommended suite of metrics for assessing watershed health is presented in Figure 8, with a summary of these metrics and data source information in Table 3. Further details can be found in Appendix C and in metadata within the accompanying geodatabase.

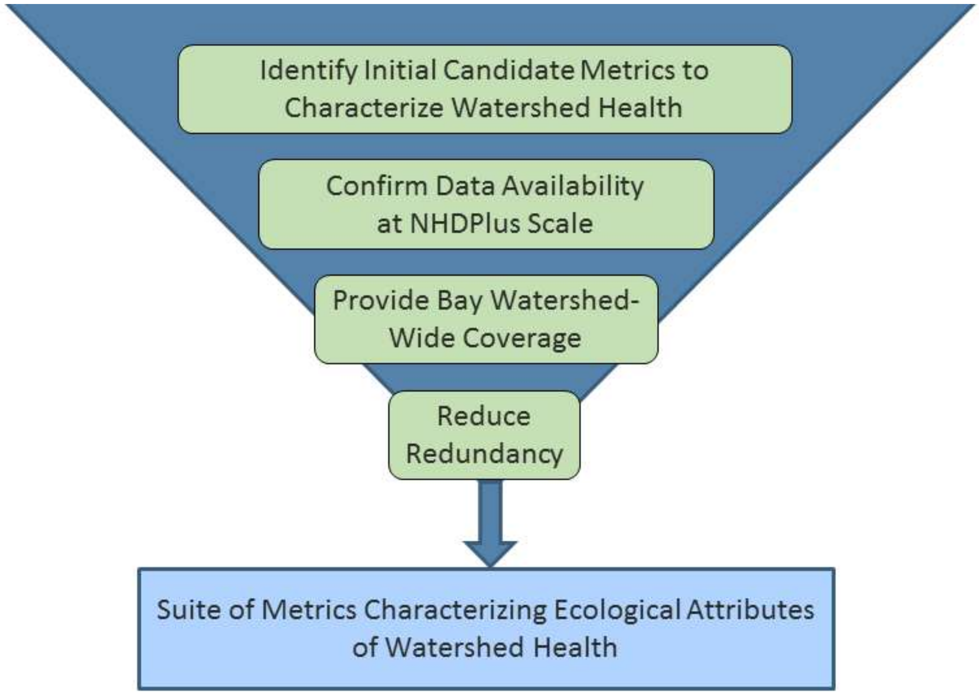


Figure 7: Filters applied to select candidate metrics characterizing watershed health

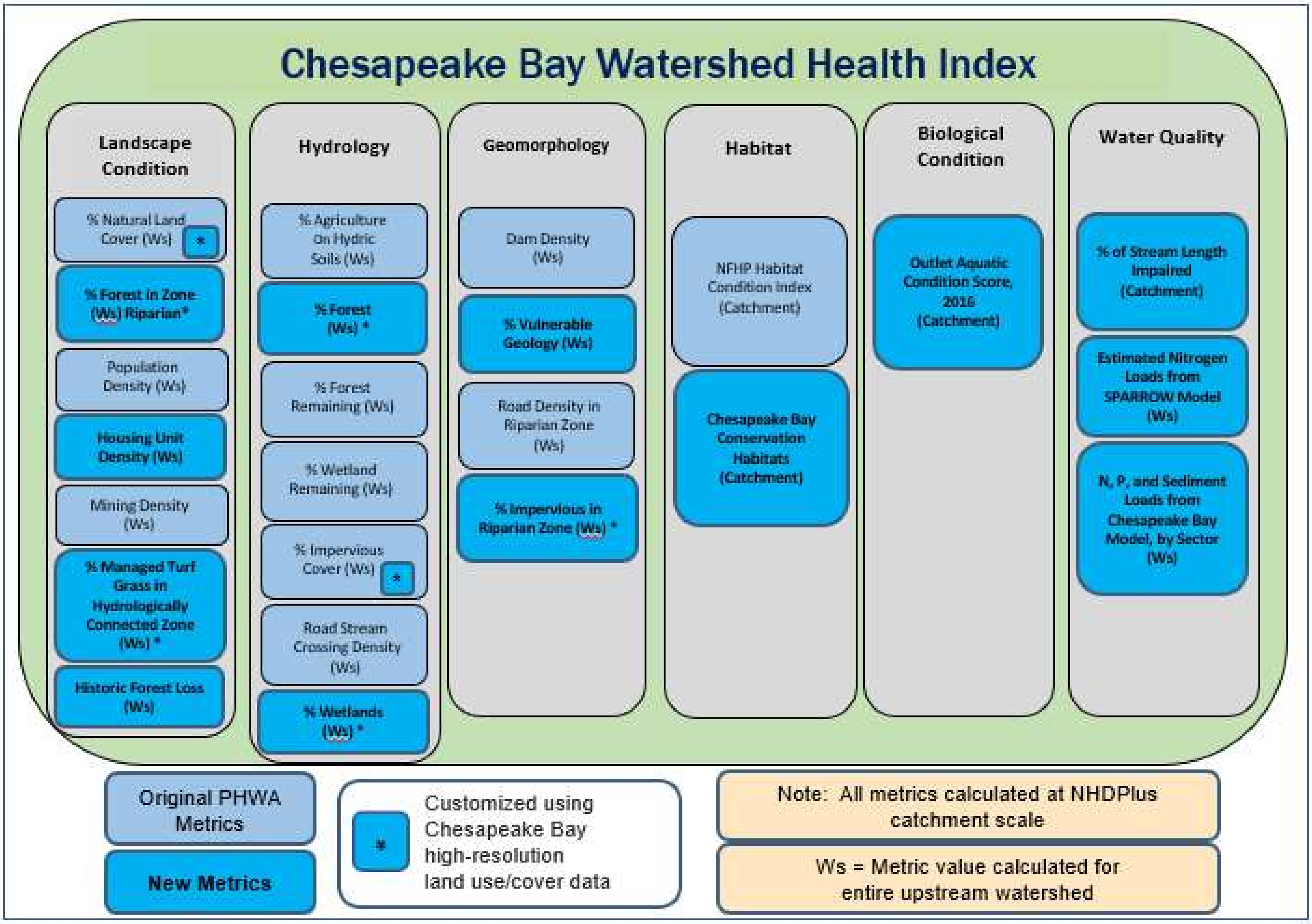


Figure 8: Recommended suite of metrics indicative of watershed health for catchments in Chesapeake Bay Watershed. Light blue boxes are metrics from the original, national PHWA, but developed here at the catchment scale. Bright blue boxes indicate new or modified metrics.

Table 3: Recommended watershed health metrics for catchments in Chesapeake Bay watershed

Sub-Index	Metrics	Notes: Data Source
Landscape Condition	% Natural Land Cover in Watershed	CBP high-resolution land use/land cover data, 2013
	% Forest in Riparian Zone in Watershed	CBP high-resolution land use/land cover data, 2013
	Population Density in Watershed	StreamCat, 2010 census data
	Housing Unit Density in Watershed	StreamCat, 2010 data
	Mining Density in Watershed	StreamCat
	% Managed Turf Grass in Hydrologically Connected Zone (HCZ) in Watershed	CBP high-resolution land use/land cover data, 2013
	Historic Forest Loss in Watershed	LANDFIRE. Reflects forest loss from European colonization to 2010. 2014 data.
Hydrology	% Agriculture on Hydric Soil in Watershed	EPA EnviroAtlas
	% Forest in Watershed	CBP high-resolution land use/land cover data, 2013
	% Forest Remaining in Watershed	LANDFIRE, 2014 data
	% Wetlands Remaining in Watershed	LANDFIRE, 2014 data
	% Impervious in Watershed	CBP high-resolution land use/land cover data, 2013
	Density Road-Stream Crossings in Watershed	StreamCat, 2010 data
	% Wetlands in Watershed	CBP high-resolution land use/land cover data, 2013
Geomorphology	Dam Density in Watershed	StreamCat, 2013 data
	Vulnerable Geology in Watershed	CBP
	Road Density in Riparian Zone, in Watershed	StreamCat
	% Impervious in Riparian Zone in Watershed	CBP high-resolution land use/land cover data, 2013
Habitat	National Fish Habitat Partnership (NFHP) Habitat Condition Index in Catchment	NFHP 2015 data (from USGS)
	Chesapeake Bay Conservation Habitats in Catchment	Landscope / Nature's Network Conservation Design for the Northeast

Table 3: Recommended watershed health metrics for catchments in Chesapeake Bay watershed

Sub-Index	Metrics	Notes: Data Source
Biological Condition	Outlet Aquatic Condition Score in Catchment	EPA Office of Research and Development, StreamCat-based model of National Rivers and Streams Assessment (NRSA) biological condition, 2016
Water Quality	% of Stream Length Impaired in Catchment	EPA ATTAINS
	Estimated Nitrogen Load from SPARROW Model (lbs/acre/yr), in Watershed	CBP SPARROW model
	Nitrogen, Phosphorus, and Sediment Load from Chesapeake Bay Watershed Model, by Sector (Developed Land, Agriculture, Wastewater, Septic, and Combined Sewer Overflow, CSO), in Watershed (13 separate metrics)	CBP Model (Phase 6)

Metric data by catchment were assembled into the project geodatabase. Each catchment (designated with a unique identifier, COMID) has data for all of the selected metrics, as well as other attributes such as catchment area, a flag indicating whether the catchment is located within a healthy watershed, whether located at its outlet, and the identity of that healthy watershed. Metrics are organized under the six topic areas described above. Data are available for all catchments, not just those within state-identified healthy watersheds.

As an example of results that can be derived from CHWA data, descriptive statistics for watershed health metrics in the state-identified healthy watersheds are shown in Appendix D (Table D-1). The values presented in Table D-1 are for catchments at the outlet of each state-identified healthy watershed. For metrics designated as watershed-wide, these data reflect conditions throughout the upstream area of the healthy watershed. For example, the mean percent natural land cover upstream of state-identified healthy watersheds is 67% (ranging from 1% to 100%), while the mean percent impervious cover is 3% (range 0% to 50%). Table D-1 is provided as an example of the type of summary statistics that can be derived from the CHWA. Further breakdowns by state or for particular types of catchments can also be produced.

The CHWA geodatabase provides a useful means for visualizing data at broad scales (i.e., across the entire Chesapeake Bay Watershed, an entire state, or a large river basin) or at a local scale. For example, the metric for Percent Forest in Riparian Zone (Watershed) can be displayed for all catchments throughout the Chesapeake Bay Watershed or for only those catchments within the state-identified healthy watersheds (Figure 9). As expected, many of the state-identified healthy watersheds have high values for the Percent Forest in Riparian Zone metric, with a mean of 88%, and a range 22% to 99%. Low values for Percent Forest in Riparian Zone are within areas dominated by urban or agricultural land uses.

The Percent Forest in Riparian Zone is a metric describing landscape condition and was created using the Chesapeake Bay Program's high-resolution land use / land cover data, in combination with a mask including a 100-m buffer on each site of stream. Values were calculated for the entire upstream riparian area in the watershed. The map below depicts the Percent Forest in Riparian Zone (Watershed) for all catchments within the state-identified healthy watersheds. Riparian forest cover is generally high within the catchments associated with state-identified healthy watersheds, although a few gaps appear, which would be candidates for consideration as locations for forest buffer improvements.

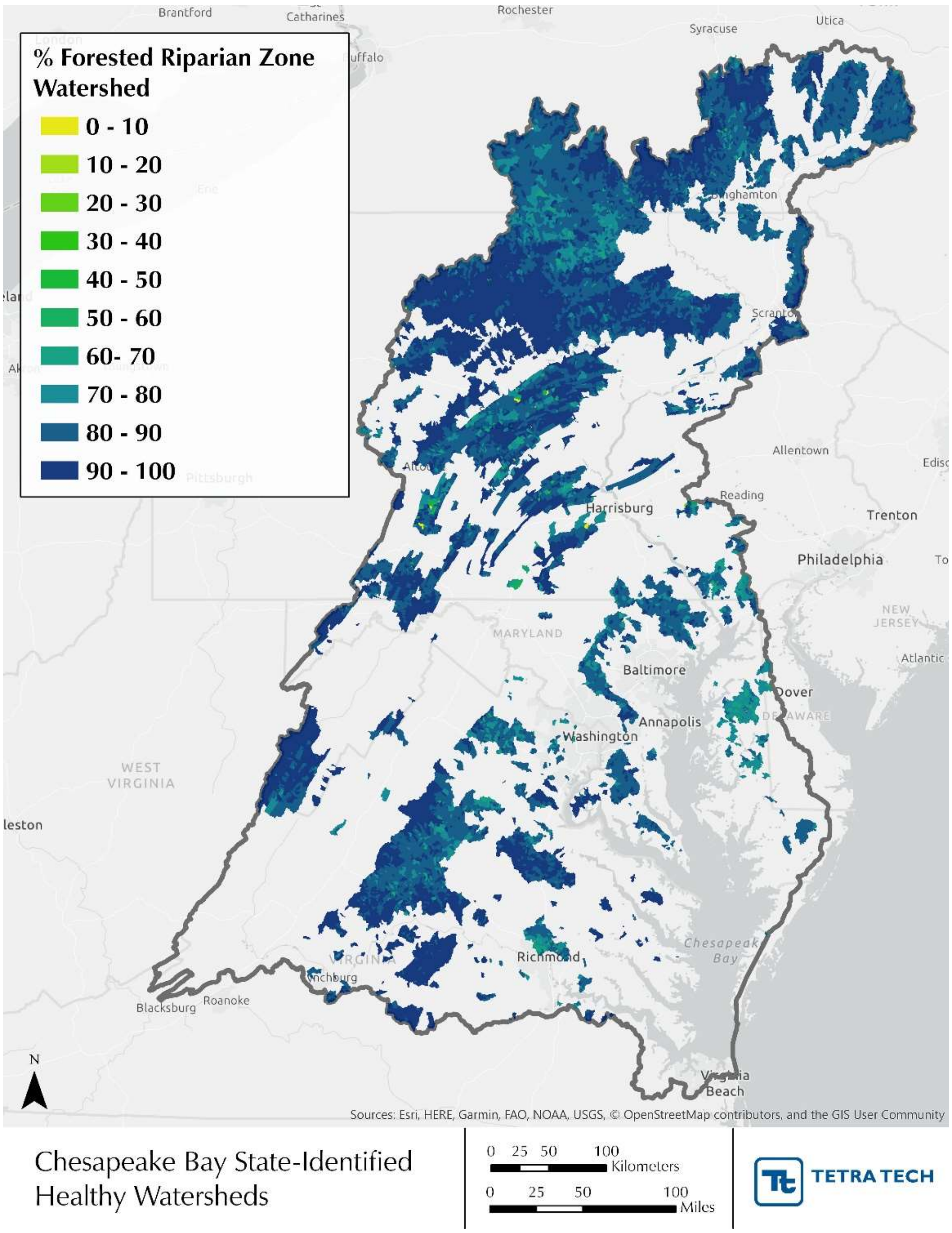


Figure 9: Example watershed condition metric: Percent Forest in Riparian Zone, shown for only the catchments within state-identified healthy watersheds

Depending on the intended application, catchment or watershed data may be most relevant. For some purposes, use of local catchment data, in contrast to values that integrate over the entire upstream watershed, may be appropriate. For example, the metric variation Percent Forest in Riparian Zone (Catchment) represents a slightly different aspect of watershed health than Percent Forest in Riparian Zone (Watershed). The catchment variation of the metric quantifies the extent of riparian forest at the local catchment scale only, rather than across the entire upstream watershed. This variation of the riparian forest metric exhibits greater contrast and more clearly depicts local conditions associated with specific catchments, rather than smoothing those differences.

As described in the following sections, the watershed health metrics were examined in exploratory analyses of correlations and predictive ability. In addition, they were used to create sub-indices of watershed health associated with each of the six aspects of watershed health and an overall watershed health index. Further development of the CHWA offers the opportunity to conduct additional statistical properties of the metrics, test for predictive ability, and adapt the CHWA approach for state-specific management needs (Figure 10). Although the proposed CHWA metrics and indices are subject to further refinement and analysis, they serve as useful tools for beginning to examine conditions throughout the Bay watershed and particularly within the state-identified healthy watersheds.

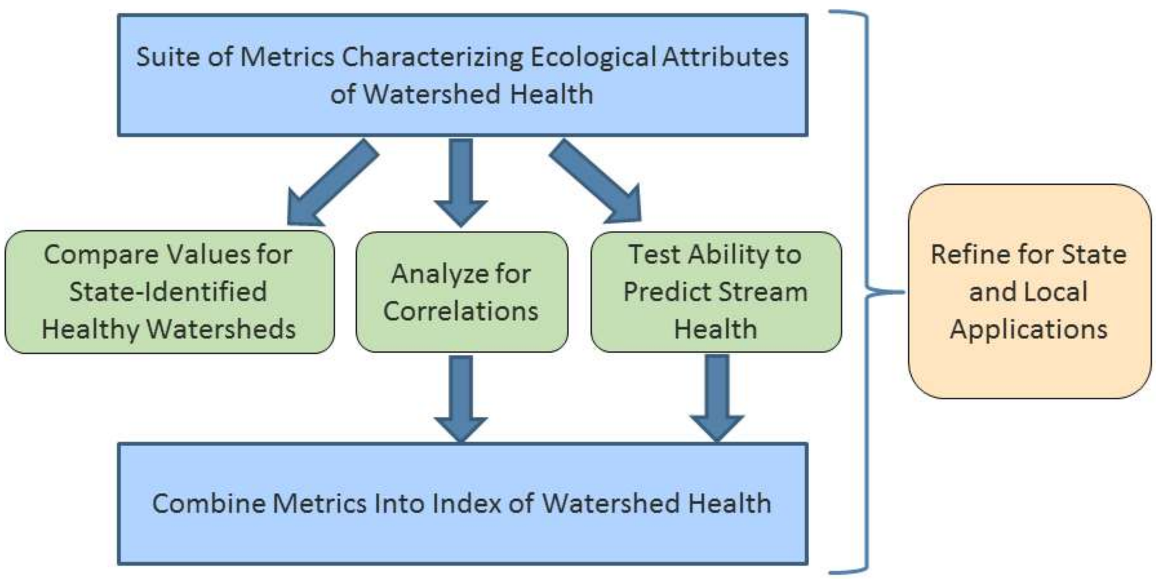


Figure 10: Exploration and refinement of metrics of watershed health. While initial analyses have been completed, additional investigations and refinement are proposed as future steps for the CHWA.

6.1 Distributions of Watershed Health Metric Scores by Catchment

To examine metric values for the state-identified healthy watersheds in relation to other watersheds, box-and-whisker plots were prepared to illustrate the distribution of metric values in different types of catchments. For an initial characterization of conditions using watershed health metrics, catchments were grouped into those outside of state-identified healthy watersheds (n=61,037 total, within Chesapeake Bay Watershed) v. those within healthy watersheds (n=22,586). Catchments within healthy watersheds were further subdivided based on their location either (1) at the outlet of a designated healthy watershed (n=828) or (2) other catchments that are within the drainage area of a healthy watershed, other than the catchment located specifically at the outlet (n=21,758). The first type of healthy watershed catchments may be useful for characterizing the entire area contributing to the healthy watershed, while the second type may help in identifying the heterogeneity of conditions present across the larger area, perhaps to help locate areas where particular stressors are likely to be most influential (e.g., higher percentage of impervious cover affecting a particular tributary branch) or to target management actions (e.g., upgrading stormwater practices in those areas of greater impervious cover). These three catchment types are illustrated in the schematic diagram in Figure 11.

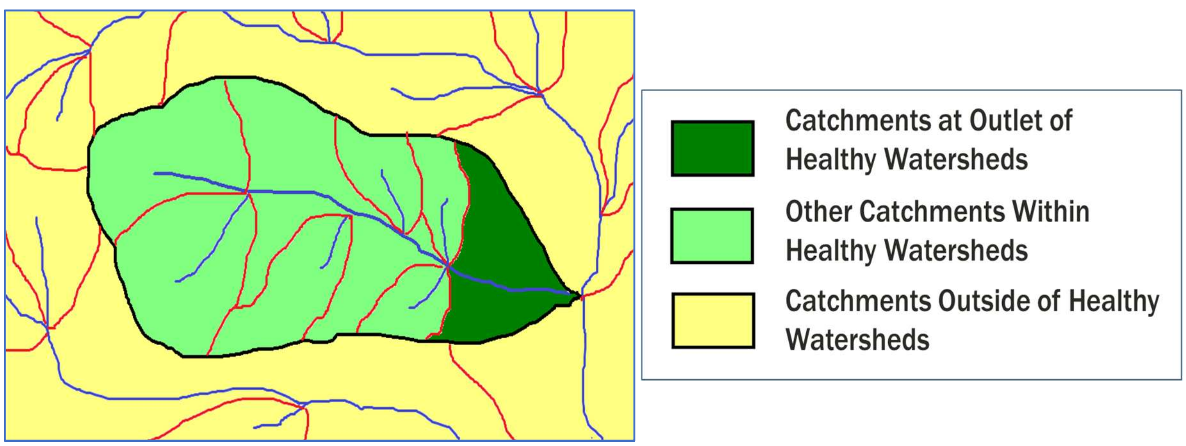
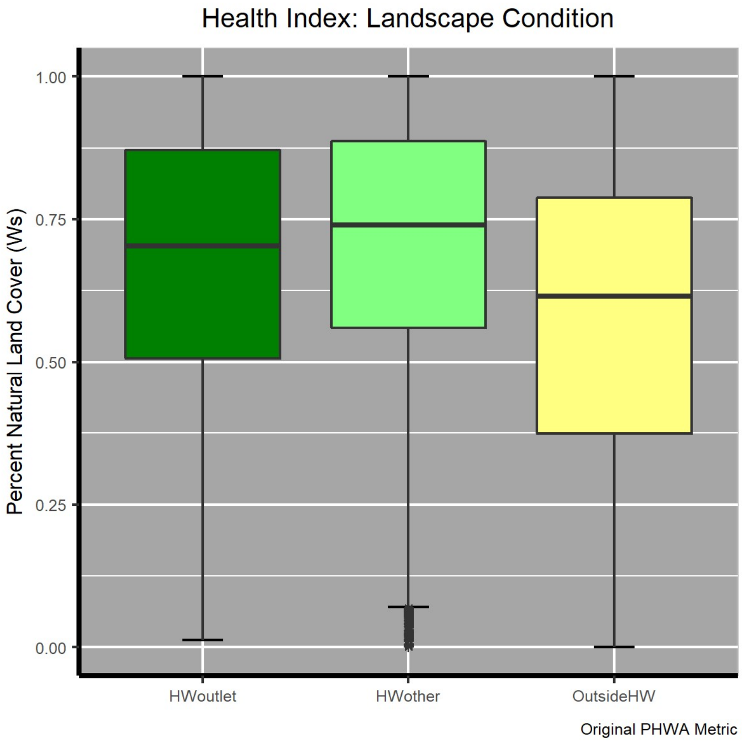


Figure 11: Diagram of catchment labeling as within state-identified healthy watersheds (at outlet and other catchments) v. outside of healthy watersheds.

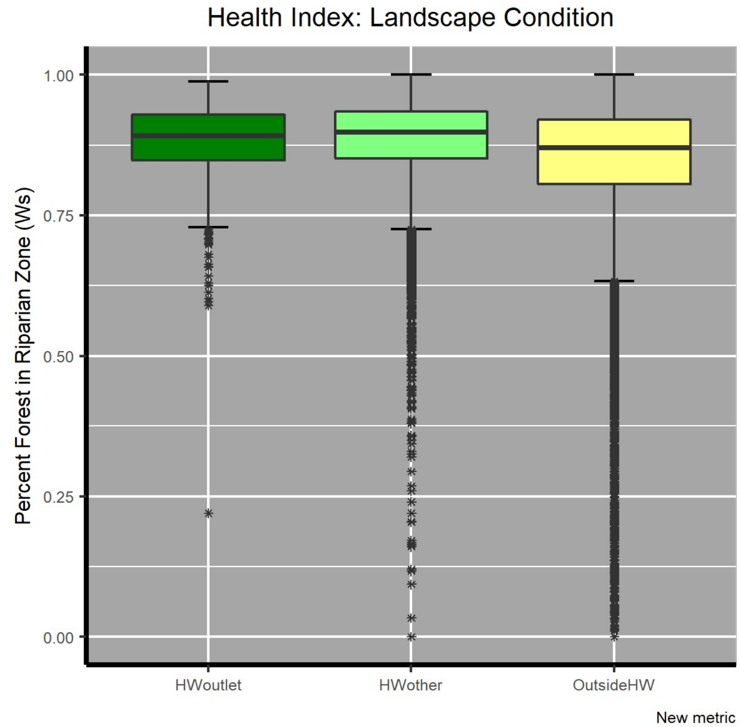
Examples of distributions for watershed health metrics using these groupings are shown in Figures 12-17. Plots for some metrics demonstrated that metric values were distributed differently in state-identified healthy watersheds compared with those outside. For example, the Percent Impervious in Watershed far exceeded 50% in some catchments outside of the state-identified healthy watersheds (to a maximum value of 86%) but was less than 50% in all catchments that were at the outlets of healthy watersheds (Figure 13E).

However, many of the metrics did not exhibit a clear difference between watersheds designated as healthy and those outside. Substantial overlap was apparent between values within and outside of healthy watersheds, rather than the significant difference that might be expected. Several factors are likely contributing to this overlap. First, the state-identified healthy watersheds are not a complete set of all healthy watersheds in the region. There are many areas outside of state-identified healthy watersheds that share similar characteristics of good environmental quality, such as highly forested areas, low amounts of impervious cover, and low population density. In addition, metric formulations that integrate over the entire watershed area reduce the contrast across areas varying in quality and condition. Metrics based on catchment data may provide greater discriminatory power. We recommend that further evaluations be conducted using independent assessments of stream (or watershed) condition, to better evaluate metric performance and predictive ability.

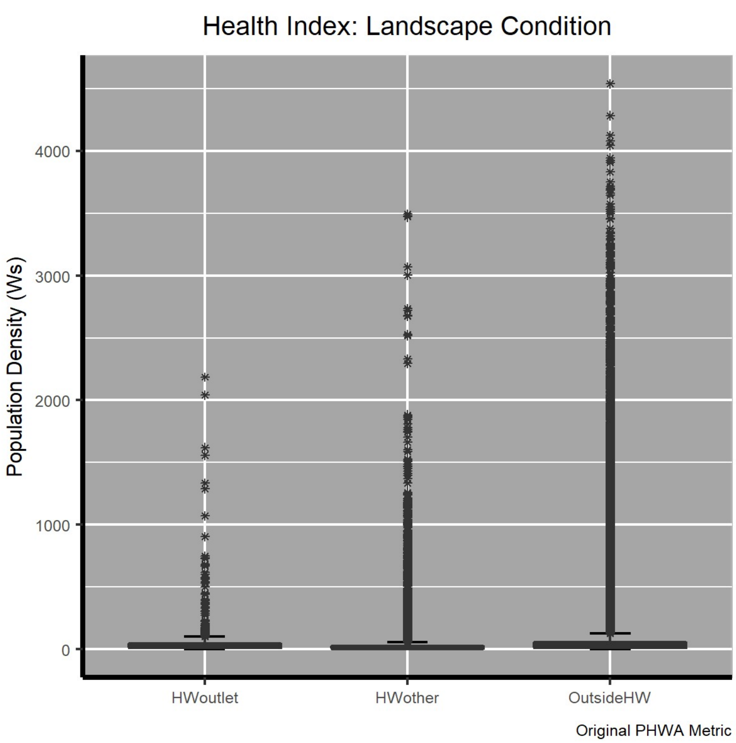
(A)


Health Index: Landscape Condition
Percent Natural Land Cover (Ws)
1.00
0.75
0.50
0.25
0.00
HWoutlet
HWother
OutsideHW
Original PHWA Metric

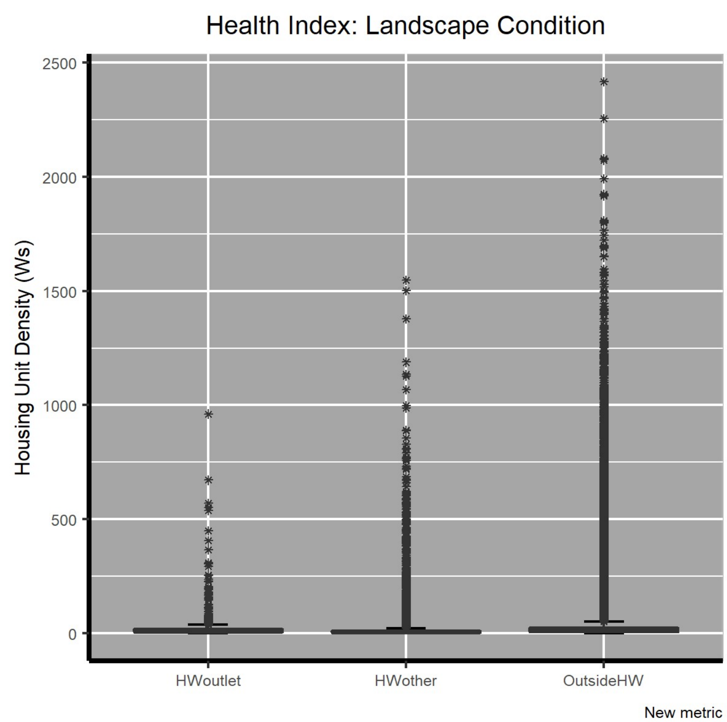
(B)


Health Index: Landscape Condition
Percent Forest in Riparian Zone (Ws)
1.00
0.75
0.50
0.25
0.00
HWoutlet
HWother
OutsideHW
New metric

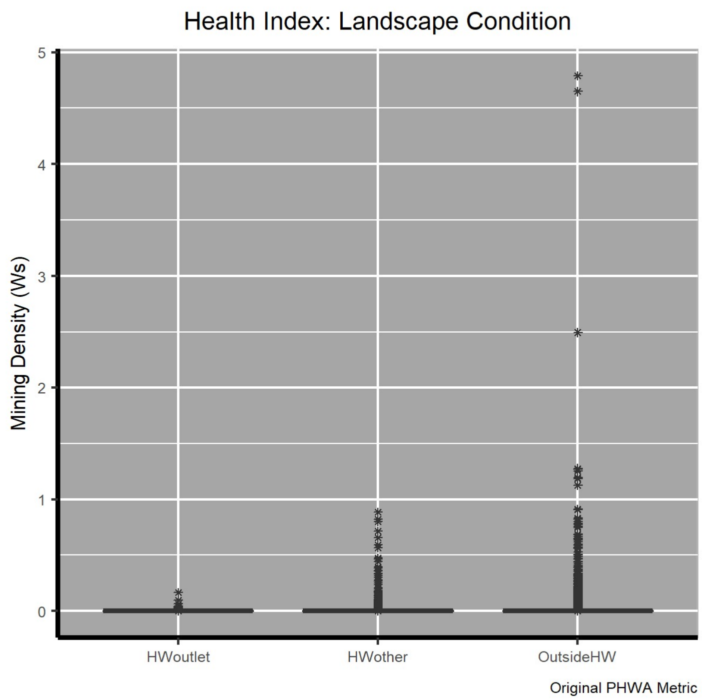
(C)


Health Index: Landscape Condition
Population Density (Ws)
4000
3000
2000
1000
0
HWoutlet
HWother
OutsideHW
Original PHWA Metric

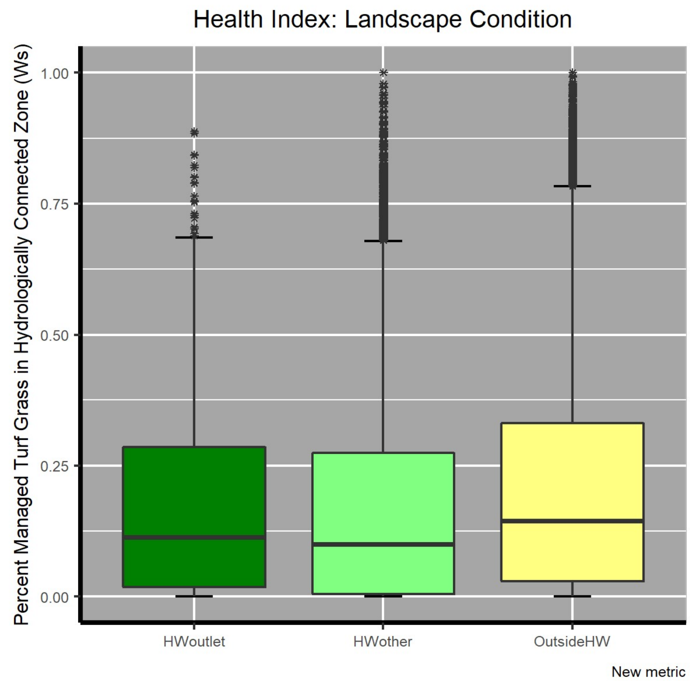
(D)


Health Index: Landscape Condition
Housing Unit Density (Ws)
2500
2000
1500
1000
500
0
HWoutlet
HWother
OutsideHW
New metric

(E)



(F)



(G)

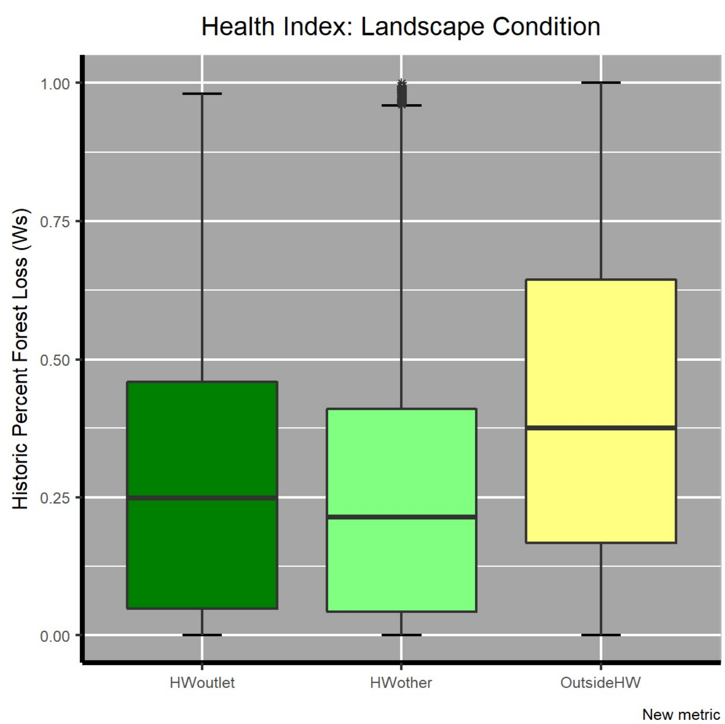
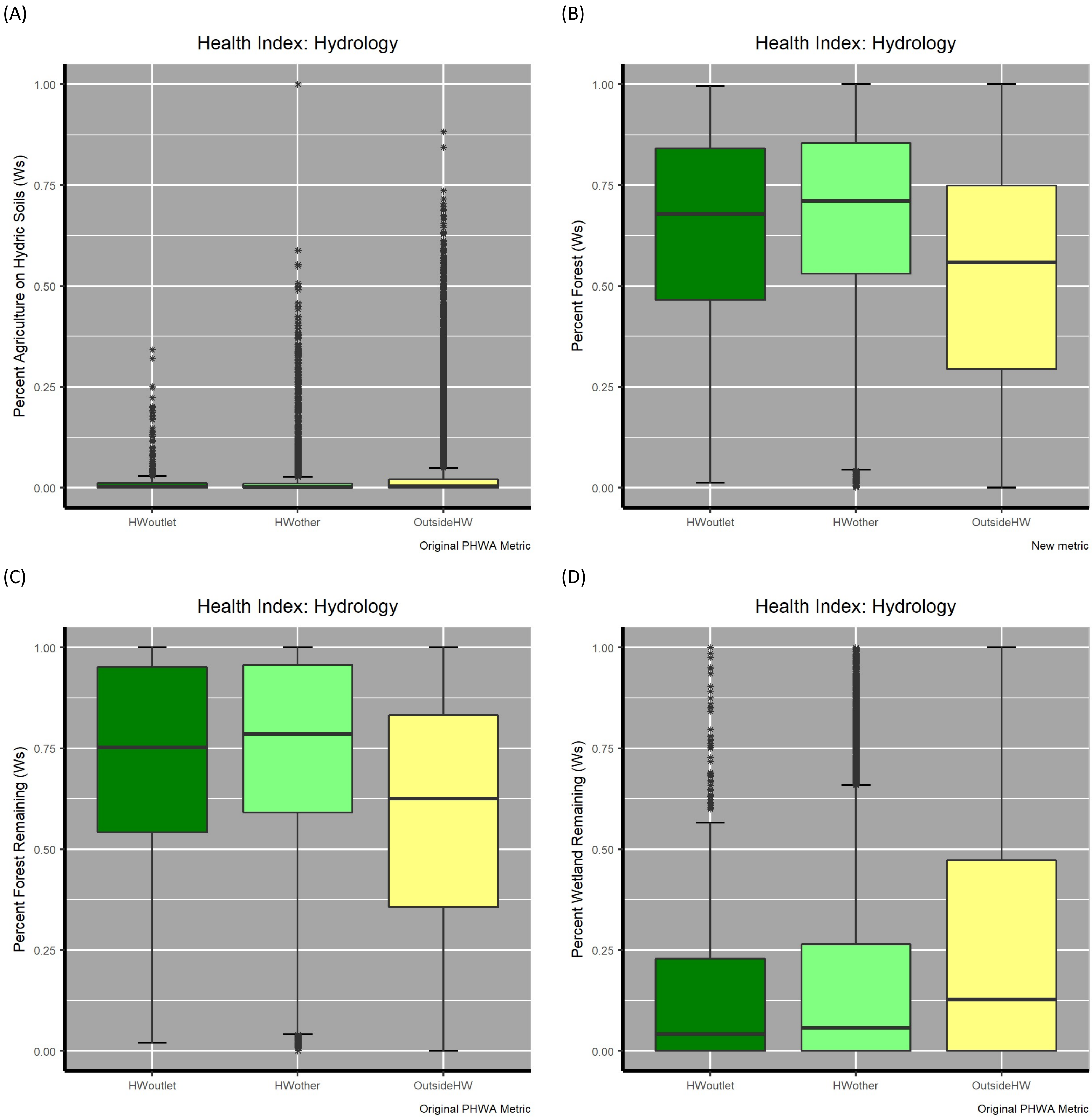
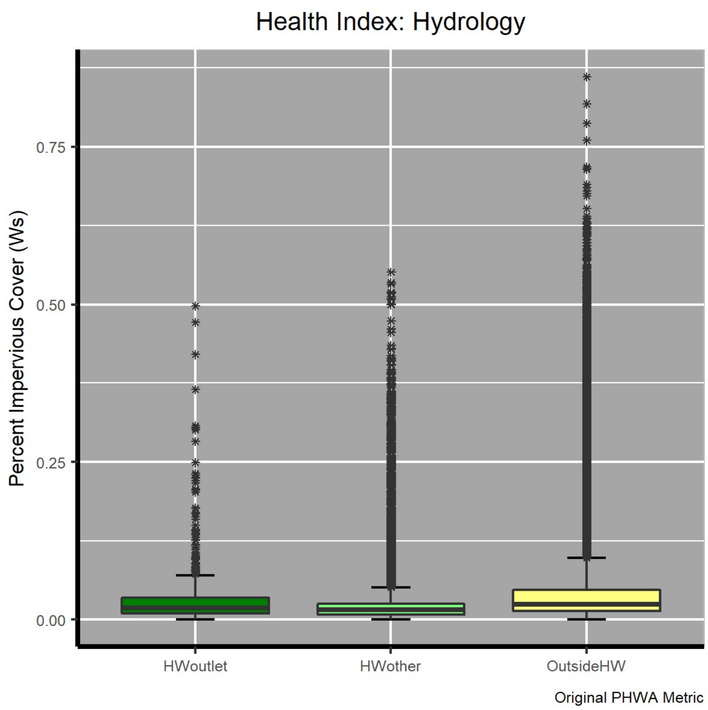


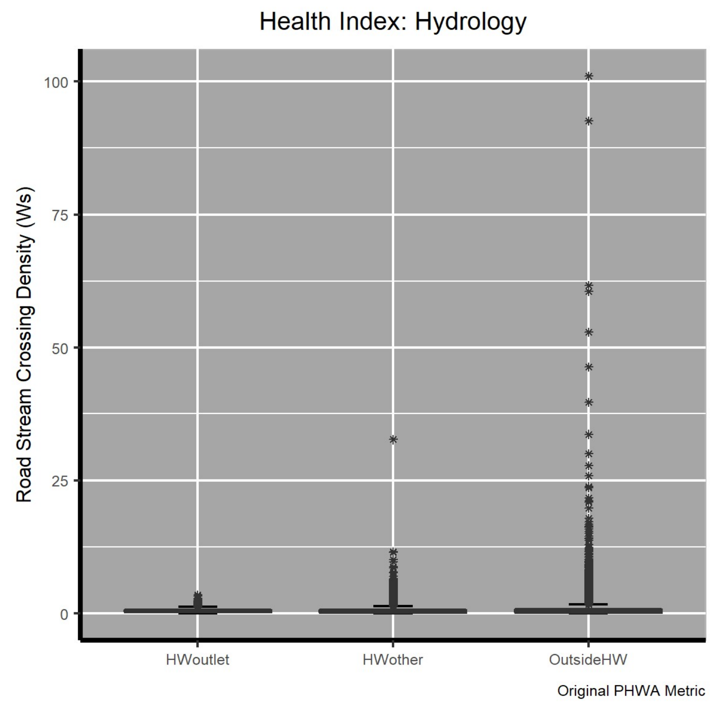
Figure 12: Comparison of distributions for landscape condition metrics for catchments at outlet of state-identified healthy watersheds (dark green), other catchments within those healthy watersheds (light green), and catchments outside of those healthy watersheds (yellow) for (A) Percent Natural Land Cover, (B) Percent Forest in Riparian Zone, (C) Population Density, (D) Housing Unit Density, (E) Mining Density, (F) Percent Managed Turf Grass in Hydrologically Connected Zone, and (G) Historic Percent Forest Loss.


(A)
Health Index: Hydrology
Percent Agriculture on Hydric Soils (Ws)
1.00
0.75
0.50
0.25
0.00
HWoutlet
HWother
OutsideHW
Original PHWA Metric
(B)
Health Index: Hydrology
Percent Forest (Ws)
1.00
0.75
0.50
0.25
0.00
HWoutlet
HWother
OutsideHW
New metric
(C)
Health Index: Hydrology
Percent Forest Remaining (Ws)
1.00
0.75
0.50
0.25
0.00
HWoutlet
HWother
OutsideHW
Original PHWA Metric
(D)
Health Index: Hydrology
Percent Wetland Remaining (Ws)
1.00
0.75
0.50
0.25
0.00
HWoutlet
HWother
OutsideHW
Original PHWA Metric

(E)



(F)



(G)

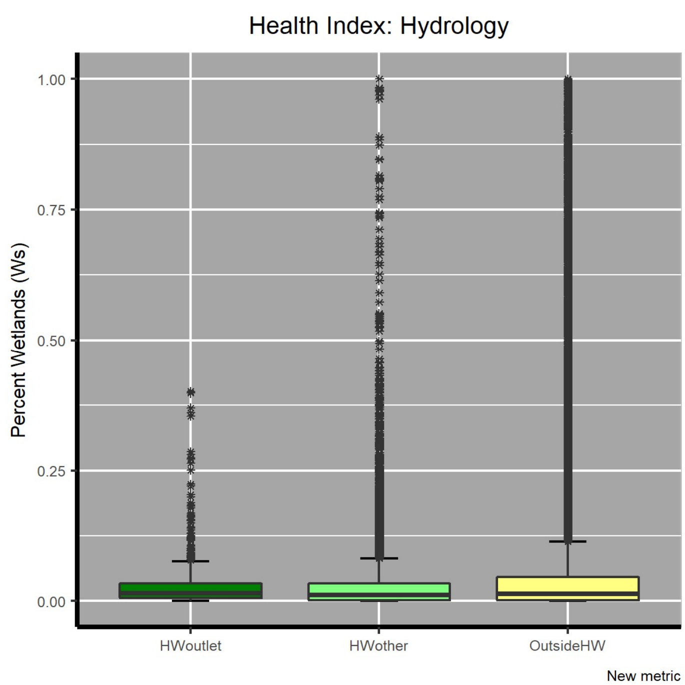


Figure 13: Comparison of distributions for hydrology metrics for catchments at outlet of state-identified healthy watersheds (dark green), other catchments within those healthy watersheds (light green), and catchments outside of those healthy watersheds (yellow) for (A) Percent Agriculture on Hydric Soil, (B) Percent Forest, (C) Percent Forest Remaining, (D) Percent Wetlands Remaining, (E) Percent Impervious, (F) Density of Road-Stream Crossings, and (G) Percent Wetlands.

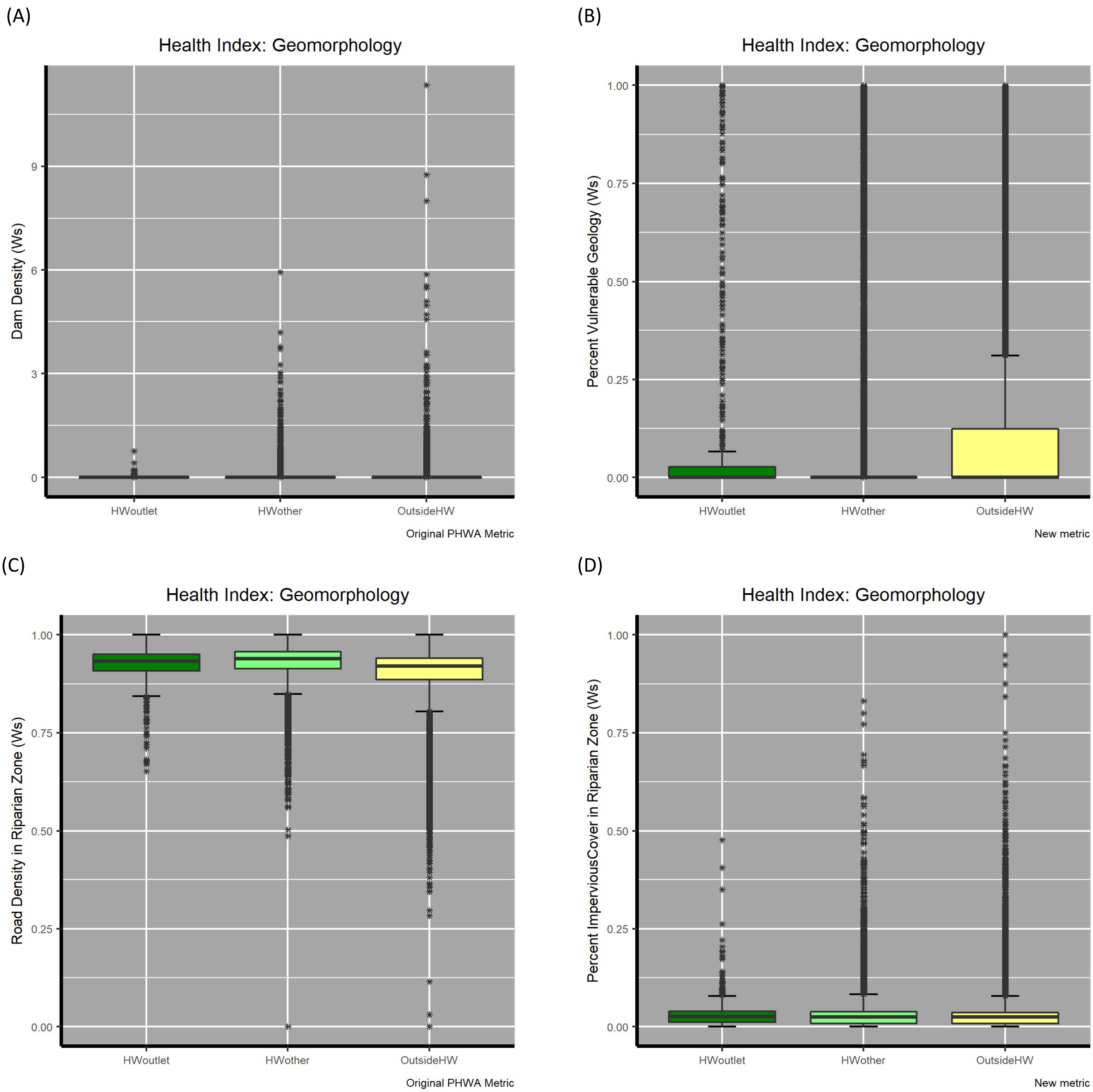
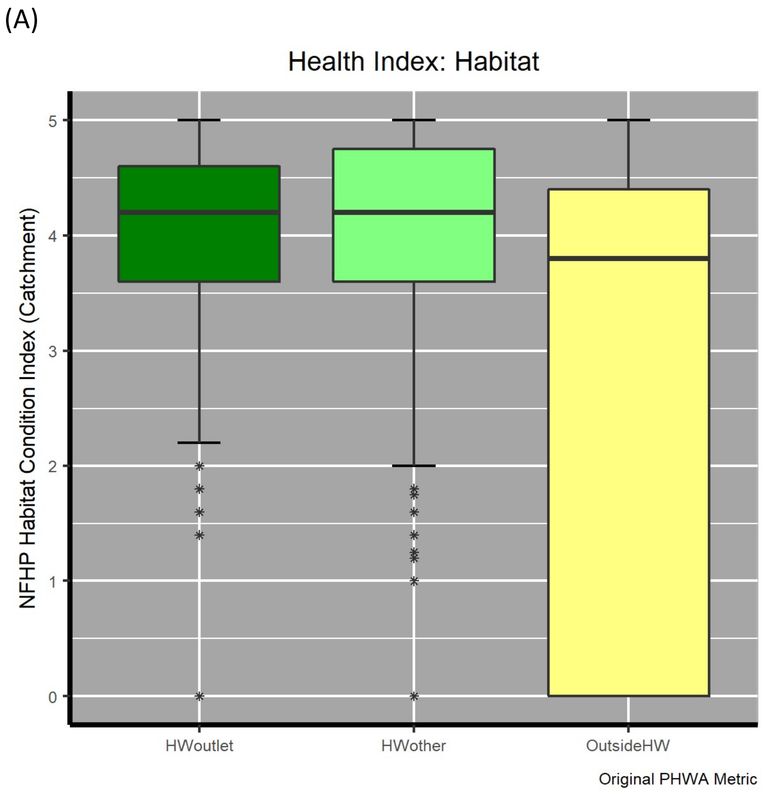


Figure 14: Comparison of distributions for geomorphology metrics for catchments at outlet of state-identified healthy watersheds (dark green), other catchments within those healthy watersheds (light green), and catchments outside of those healthy watersheds (yellow) for (A) Dam Density, (B) Percent Vulnerable Geology, (C) Road Density in Riparian Zone, (D) Percent Impervious in Riparian Zone.



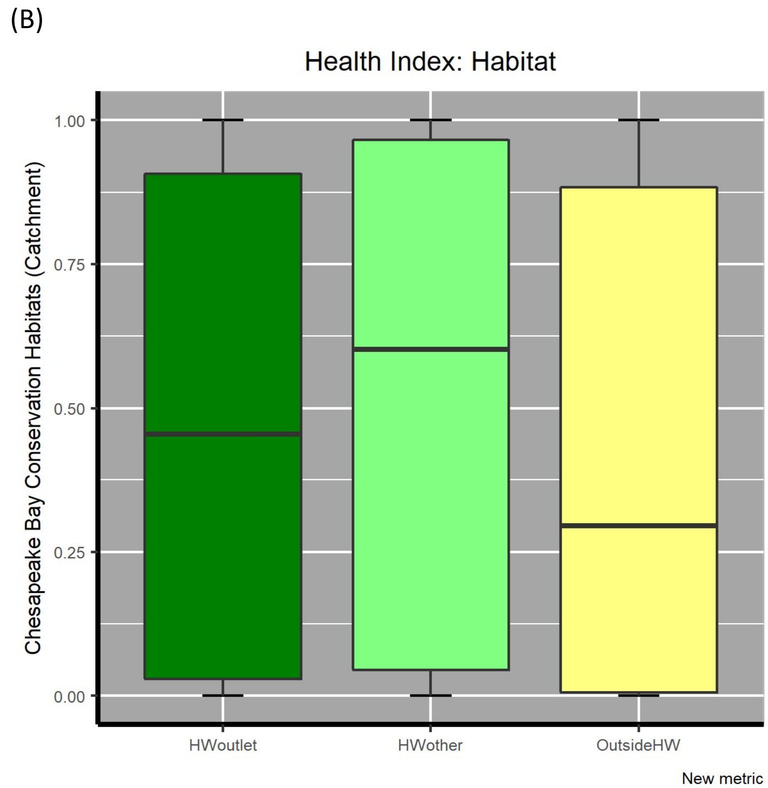


Figure 15: Comparison of distributions for habitat metrics for catchments at outlet of state-identified healthy watersheds (dark green), other catchments within those healthy watersheds (light green), and catchments outside of those healthy watersheds (yellow) for (A) National Fish Habitat Partnership (NFHP) Habitat Condition Index in Catchment and (B) Chesapeake Bay Conservation Habitats in Catchment

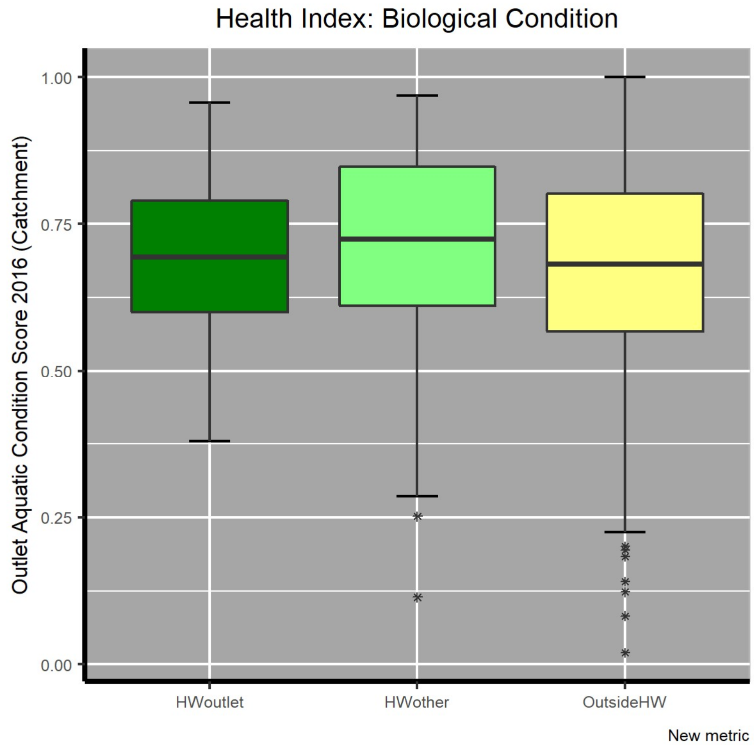
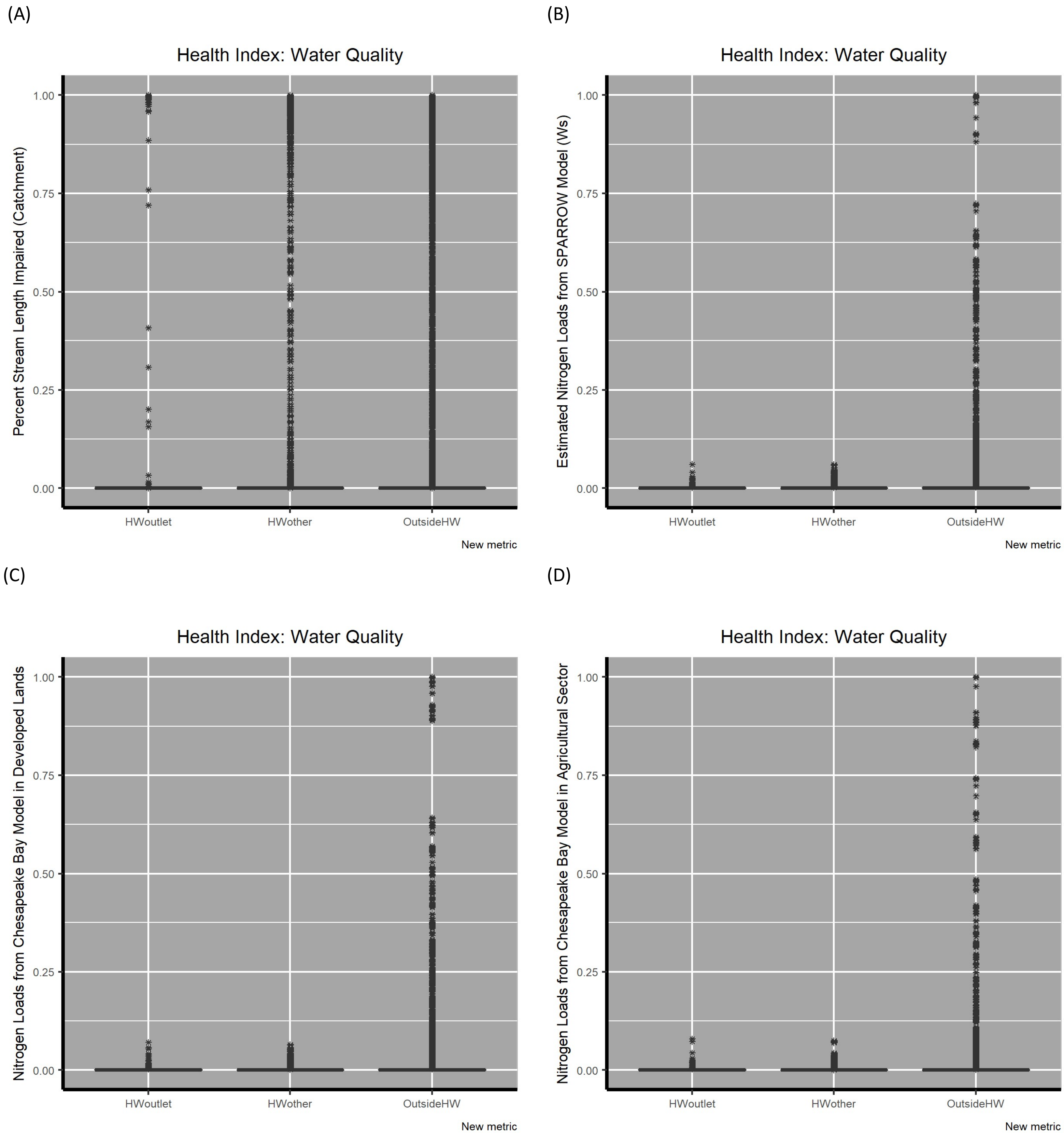
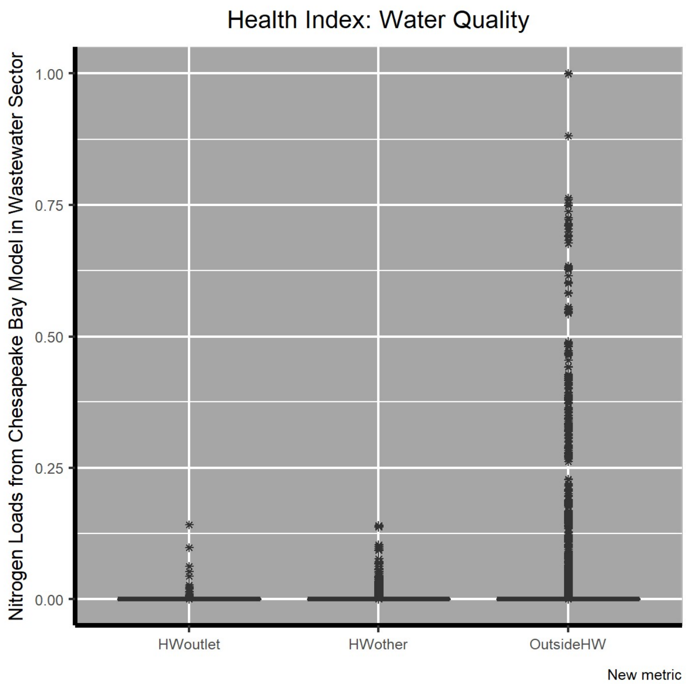


Figure 16: Comparison of distributions for biological condition metric for catchments at outlet of state-identified healthy watersheds (dark green), other catchments within those healthy watersheds (light green), and catchments outside of those healthy watersheds (yellow)

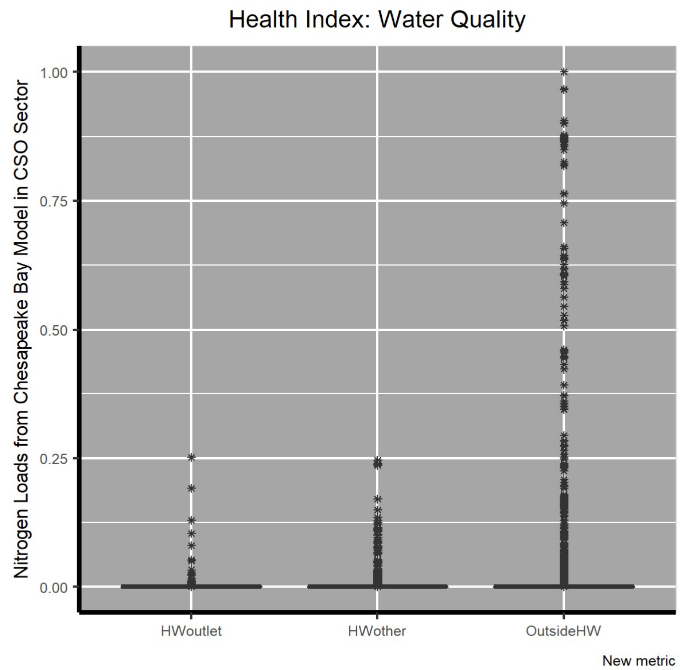


(A)
Health Index: Water Quality
Percent Stream Length Impaired (Catchment)
1.00
0.75
0.50
0.25
0.00
HWoutlet
HWother
OutsideHW
New metric
(B)
Health Index: Water Quality
Estimated Nitrogen Loads from SPARROW Model (Ws)
1.00
0.75
0.50
0.25
0.00
HWoutlet
HWother
OutsideHW
New metric
(C)
Health Index: Water Quality
Nitrogen Loads from Chesapeake Bay Model in Developed Lands
1.00
0.75
0.50
0.25
0.00
HWoutlet
HWother
OutsideHW
New metric
(D)
Health Index: Water Quality
Nitrogen Loads from Chesapeake Bay Model in Agricultural Sector
1.00
0.75
0.50
0.25
0.00
HWoutlet
HWother
OutsideHW
New metric

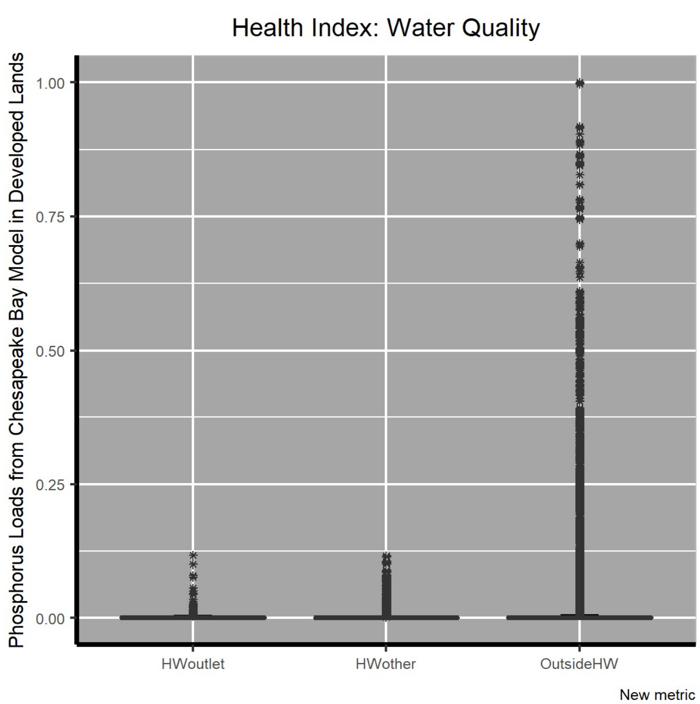
(E)


Health Index: Water Quality
Nitrogen Loads from Chesapeake Bay Model in Wastewater Sector
1.00
0.75
0.50
0.25
0.00
HWoutlet
HWother
OutsideHW
New metric

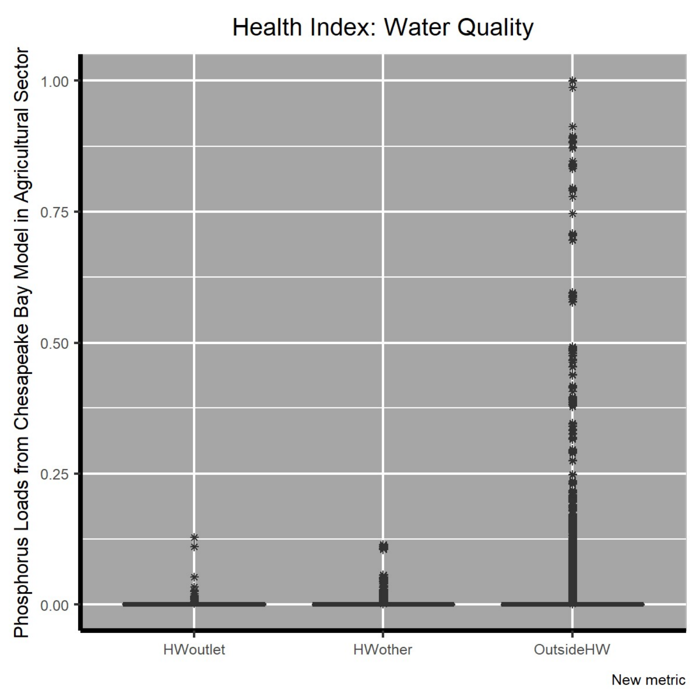
(F)


Health Index: Water Quality
Nitrogen Loads from Chesapeake Bay Model in CSO Sector
1.00
0.75
0.50
0.25
0.00
HWoutlet
HWother
OutsideHW
New metric

(G)


Health Index: Water Quality
Phosphorus Loads from Chesapeake Bay Model in Developed Lands
1.00
0.75
0.50
0.25
0.00
HWoutlet
HWother
OutsideHW
New metric

(H)


Health Index: Water Quality
Phosphorus Loads from Chesapeake Bay Model in Agricultural Sector
1.00
0.75
0.50
0.25
0.00
HWoutlet
HWother
OutsideHW
New metric

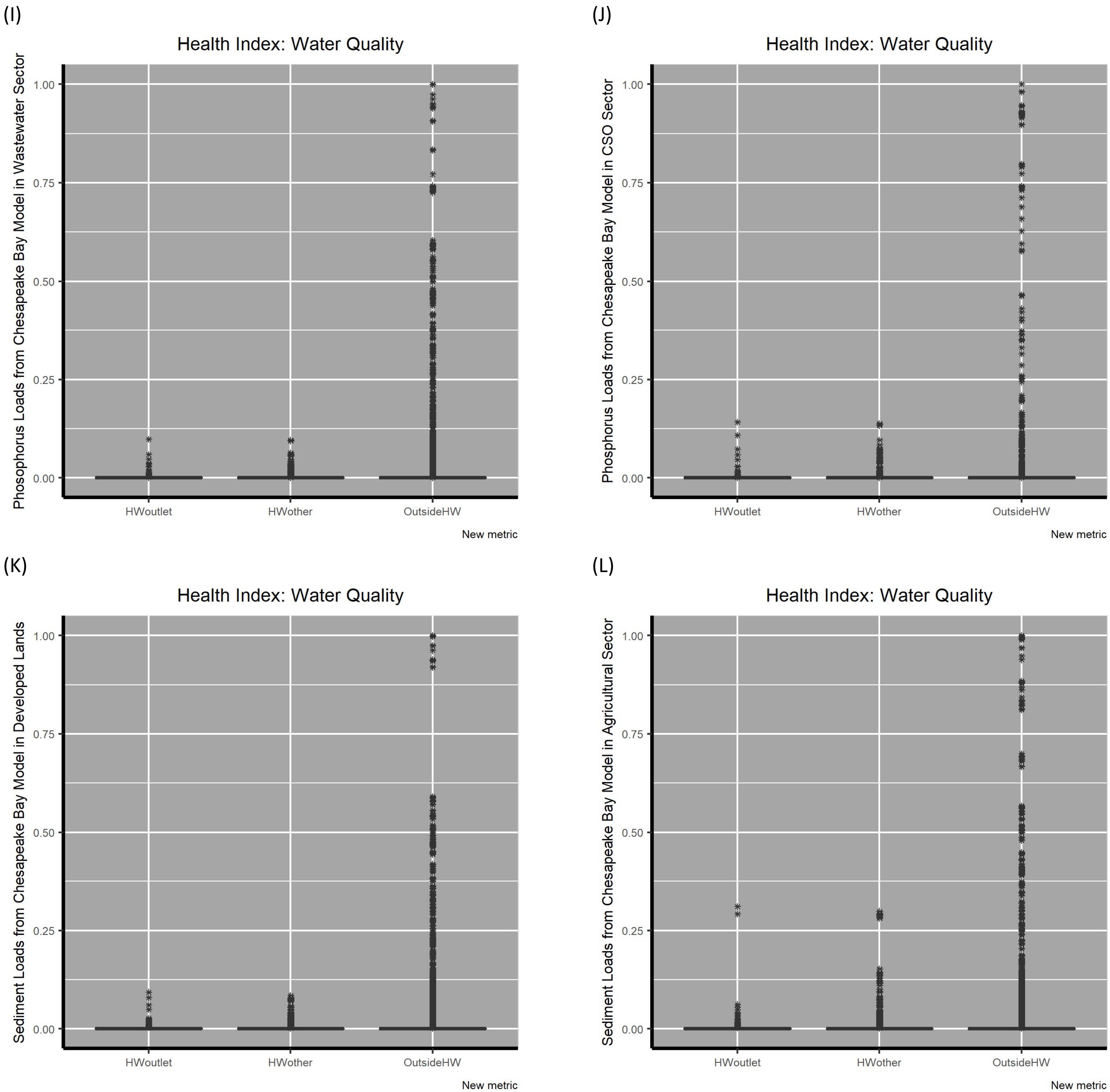


Figure 17: Comparison of distributions for example water quality metrics for catchments at outlet of state-identified healthy watersheds (dark green), other catchments within those healthy watersheds (light green), and catchments outside of those healthy watersheds (yellow) for (A) Percent of Stream Length Impaired, (B) Estimated Nitrogen Load from SPARROW Model, and Chesapeake Bay Watershed Model Load Estimates for (C) Nitrogen from Developed Lands, (D) Nitrogen from Agriculture, (E) Nitrogen from Wastewater, (F) Nitrogen from Combined Sewer Overflows (CSO), (G) Phosphorus from Developed Lands, (H) Phosphorus from Agriculture, (I) Phosphorus from Wastewater, (J) Phosphorus from CSO, (K) Sediment from Developed Lands, and (L) Sediment from Agriculture.

6.2 Correlations Among Metrics

Correlations among all of the proposed suite of metrics were evaluated to identify relationships between individual candidate metrics. Correlations demonstrate how strongly (either positively or negatively) pairs of variables are related. This information was used to assess whether metrics were providing similar or redundant information. The range of Pearson correlations (r values) and a graphic depiction of correlation results are presented in Figure 18. The Pearson correlation coefficient is a test statistic that measures the relationship between two continuous variables. It is widely considered the best method for measuring the association between two variables because it provides insight into the magnitude and directionality of the correlation.

The highest positive correlations ($r > 0.6$) were noted for

- Percent Natural Land Cover in Watershed vs. Percent Forest in Watershed
- Population Density in Watershed vs. Housing Unit Density in Watershed
- Population Density in Watershed vs. Percent Impervious in Watershed
- Housing Unit Density vs. Percent Impervious in Watershed
- Percent Forest Remaining vs. Outlet Aquatic Condition Score
- Estimated Nitrogen Load from SPARROW Model vs. Outlet Aquatic Condition Score
- Nitrogen (N) Load from Agriculture vs. Phosphorus (P) Load from Agriculture and Sediment Load from Agriculture
- P Load from Agriculture vs. Sediment Load from Agriculture
- N Load from CSO vs. P Load from CSO and Sediment Load from CSO
- P Load from CSO vs. Sediment Load from CSO
- N Load from Development vs. P Load from Development and Sediment Load from Development
- P Load from Development vs. Sediment Load from Development
- N Load from Wastewater vs. P Load from Wastewater

The strongest negative correlations were noted for

- Percent Forest Loss vs. Percent Forest Remaining
- Percent Forest Loss vs. Outlet Aquatic Condition Score

Many of the correlation results confirm what would be expected with respect to relationships among metrics and may be useful in future applications of the healthy watersheds data. A strong correlation suggests that either the Population or Housing Unit Density could be used alone. Both are strongly related to Percent Impervious, a landscape characteristic that can be evaluated through remote sensing data, often at a greater frequency than the 10-year census estimates of population. The correlations among nitrogen, phosphorus, and sediment load metrics within source types suggest that they could be combined under categories of Agricultural, CSO, Development, and Wastewater pollution sources.

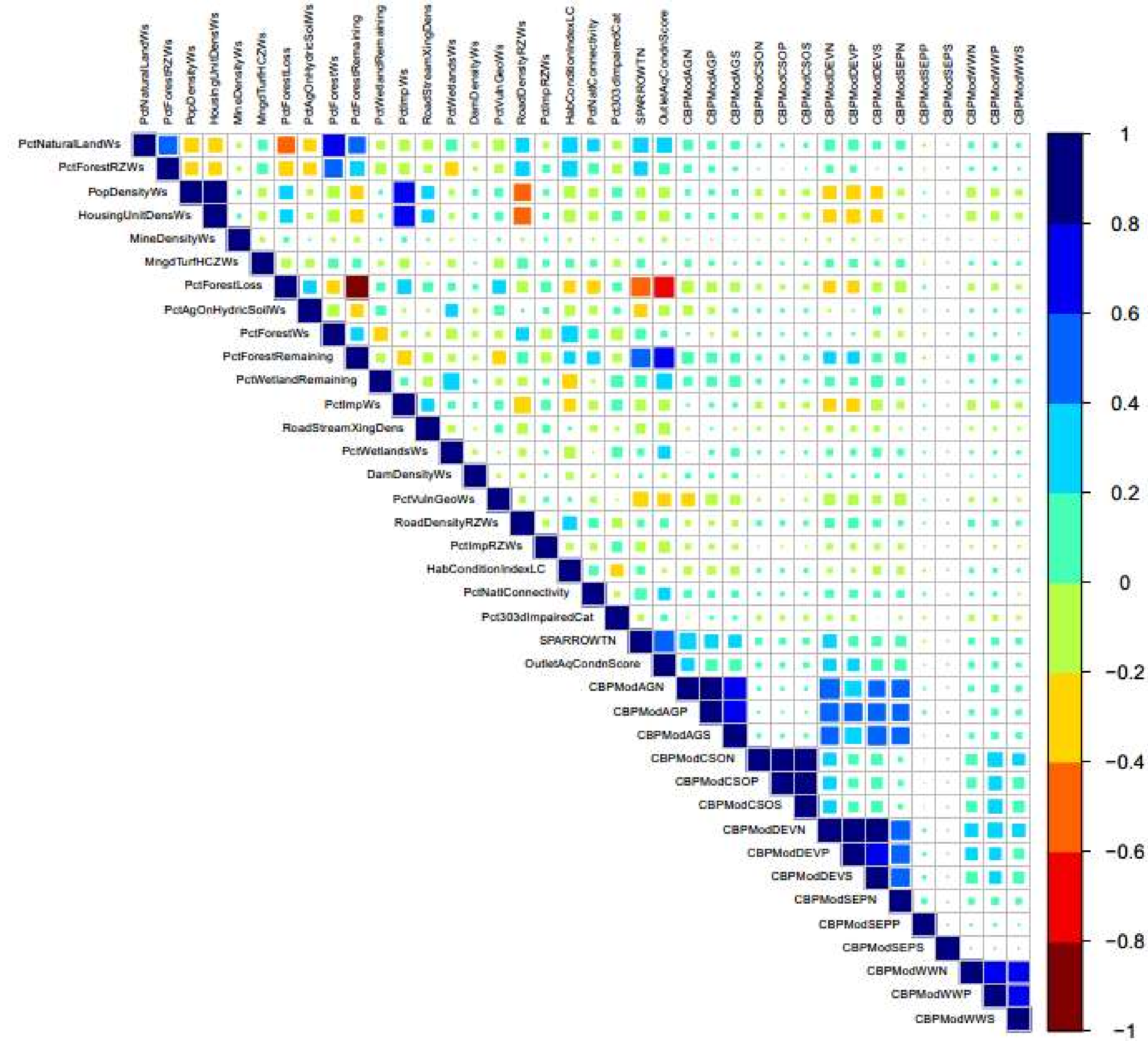


Figure 18: Correlations among candidate watershed condition metrics. The correlation between any two variables is shown as strongly positive (dark blue) to strongly negative (dark red). The colored symbols in each box represent the Pearson correlation coefficients (r values) for each pair of variables, according to the scale shown. Variable names are listed in Appendix C.

6.3 Combining Metrics into Overall Watershed Health Indicator – Sub-Index Method

Although individual metrics provide information about certain aspects of watershed condition, they can also be combined into an overall indicator of watershed health. The national PHWA approach was to calculate six sub-indices as the mean of normalized values for the individual metrics in each of the defined categories: landscape condition, hydrology, geomorphology, habitat, biological condition, and water quality. The mean of these six sub-indices was calculated to yield an overall index of watershed health.

This PHWA method was used to calculate sub-indices and a watershed health indicator for each of the catchments in the Chesapeake Bay Watershed. Before combining into sub-indices, values were converted to a 0 to 1 scale using a unity normal transformation, where 1 = the maximum value and other values were computed as the original value divided by the maximum. Positive metrics (i.e., those such as Percent Forest, with values expected to be higher in healthy watersheds) were not further transformed, but negative metrics (i.e., those such as Percent Impervious Cover, with values expected to be lower in healthy watersheds) were transformed as one minus the metric, to yield an adjusted score that would be positively associated with watershed health. Each sub-index was calculated as the mean of individual metric scores in that category, and an overall index of watershed health was calculated as the mean of the six sub-index values.

Watershed health sub-index values for state-identified healthy watersheds are shown in the maps in Figures 19 to 24. Distributions of the six sub-indices for catchments in three groups (those at the outlet, within, and outside of state-identified healthy watersheds) are shown in Figure 25. Plots of the landscape condition, biological condition, and water quality sub-indices suggest that catchments within state-identified healthy watersheds do not generally score in the lowest part of the range for these sub-indices, in comparison with catchments outside of healthy watersheds.

The overall combined Watershed Health index is mapped for catchments in state-identified healthy watersheds in Figure 26. Figure 27 shows the distributions of Watershed Health index values for catchments throughout Chesapeake Bay Watershed, by catchment group. The median Watershed Health index for catchments within state-identified healthy watersheds (either at outlets or otherwise within) is slightly higher than for catchments outside; however, there is substantial overlap in the distributions.

In future refinement of the CHWA, additional options should be explored regarding the method of constructing an overall index of watershed health. First, transforming of metrics via simple normalization could reduce the skewness currently observed with some metrics. Simple normalization reduces the influence of a single or few outlier values that may bias results. Second, the method currently used to calculate sub-indices and watershed health indicator is a simple equal-weighted average. There are many other options that could be employed, such as trans-distance weighting (which accounts for correlation between each variable). Finally, predictive models of watershed health, as discussed in Section 6.4, offer additional options to represent overall watershed health.

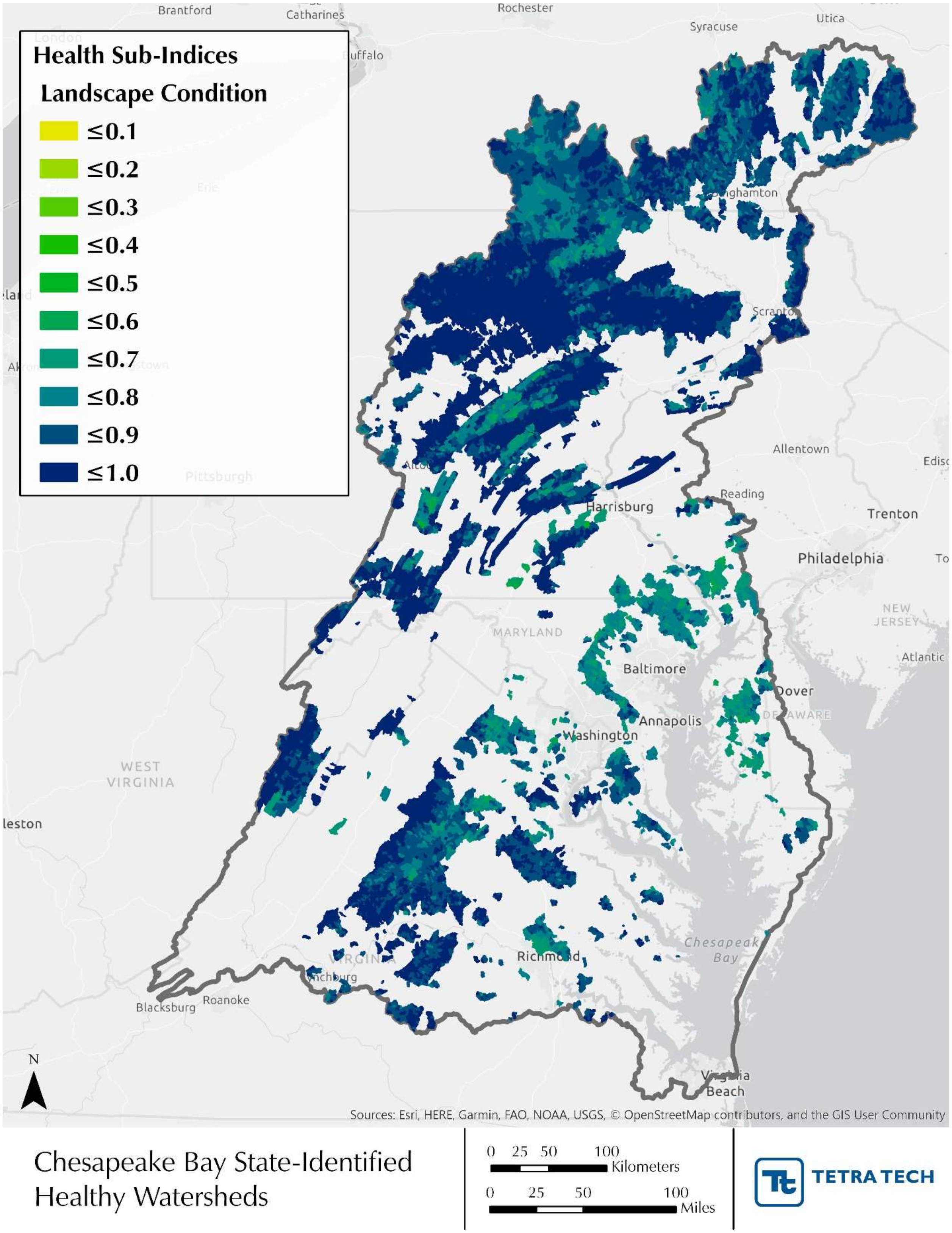


Figure 19: Characterizing watershed health: Landscape Condition sub-index scores for catchments in state-identified healthy watersheds

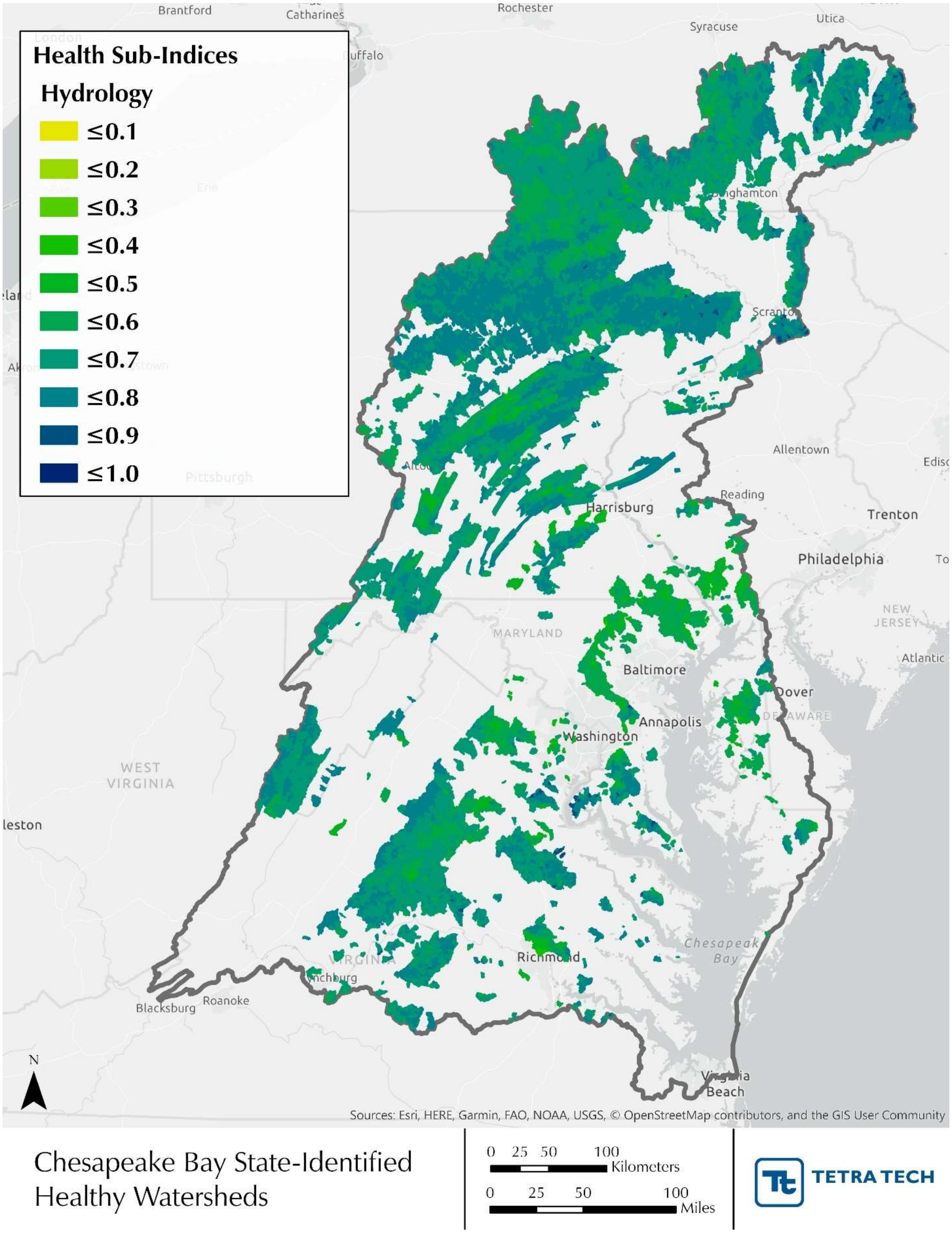


Figure 20: Characterizing watershed health: Hydrology sub-index scores for catchments in state-identified healthy watersheds

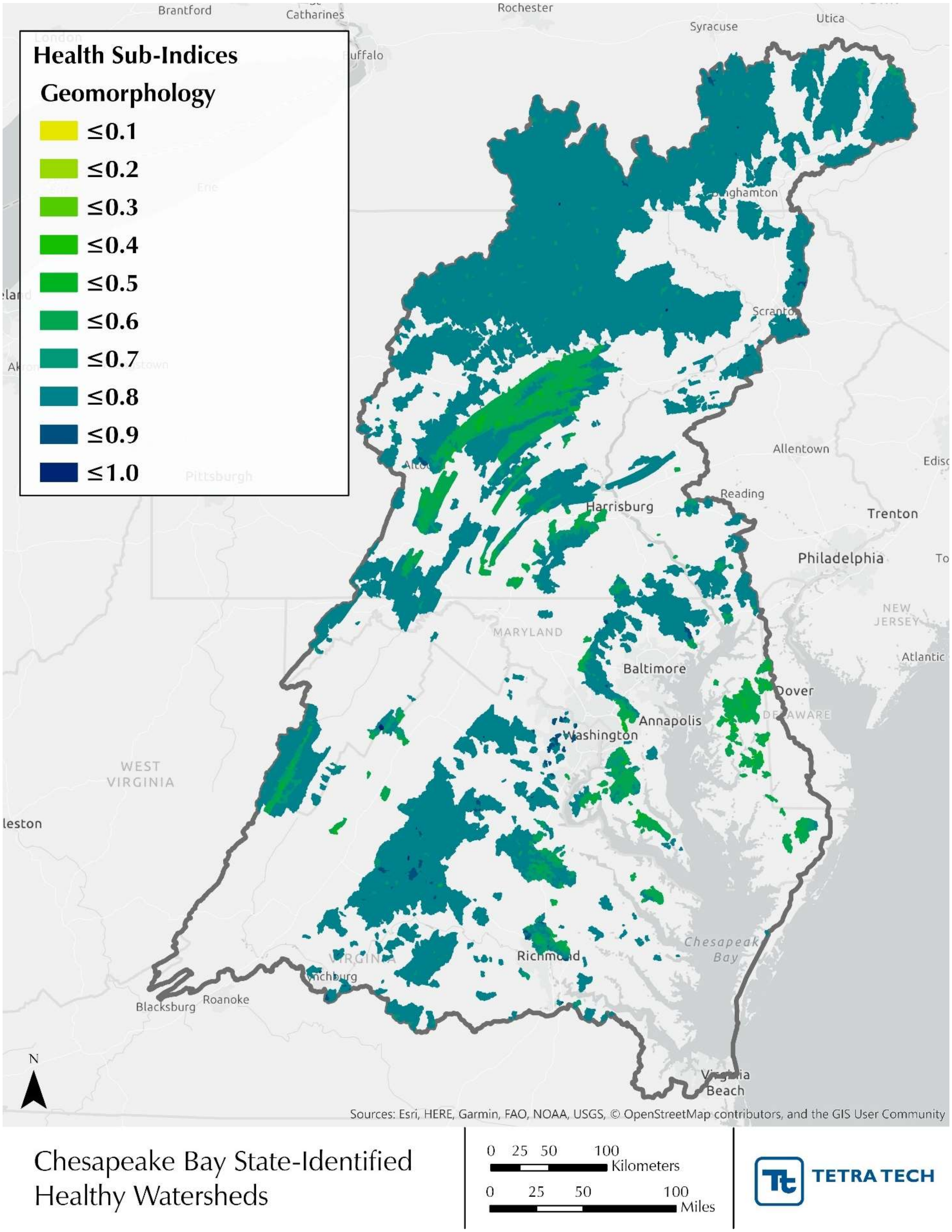


Figure 21: Characterizing watershed health: Geomorphology sub-index scores for catchments in state-identified healthy watersheds

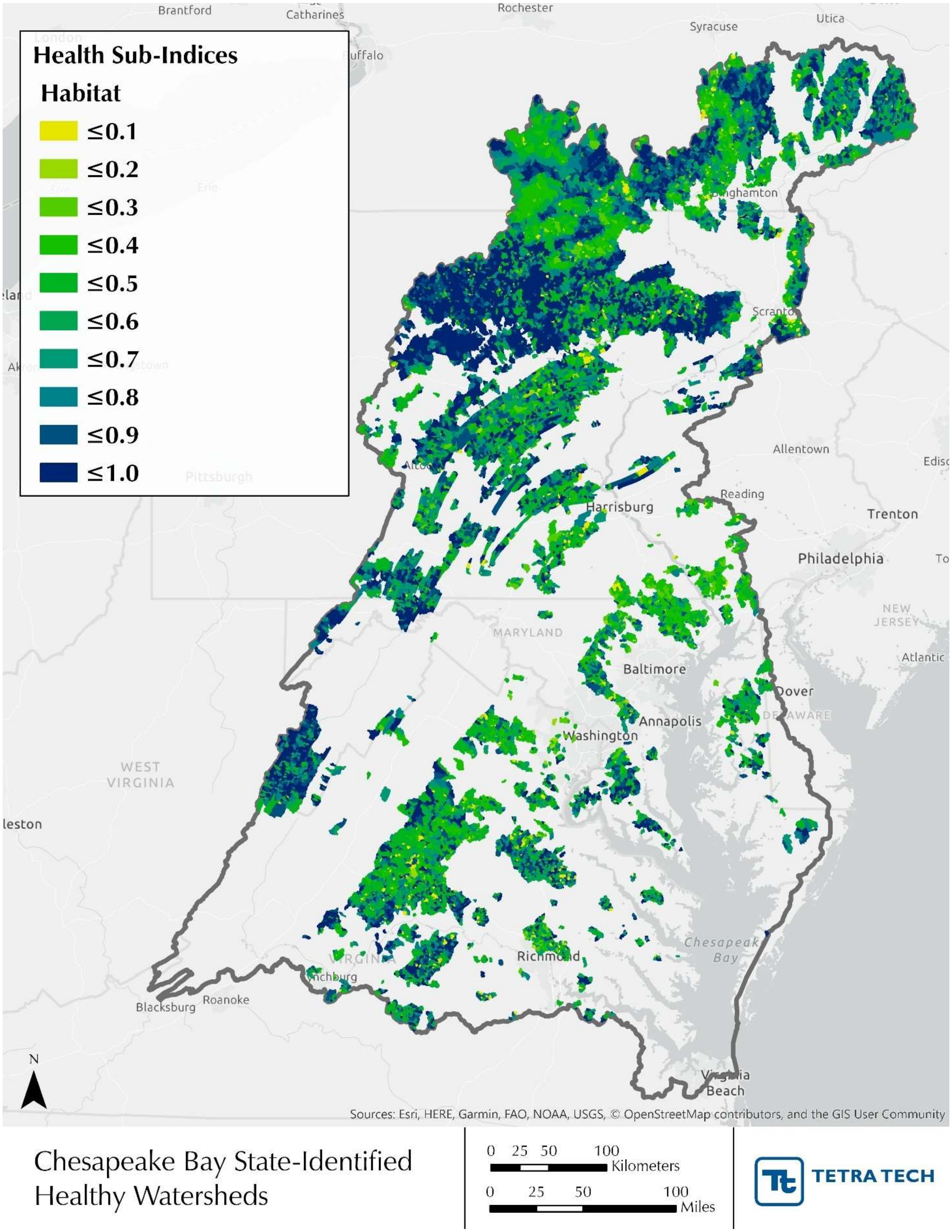


Figure 22: Characterizing watershed health: Habitat sub-index scores for catchments in state-identified healthy watersheds

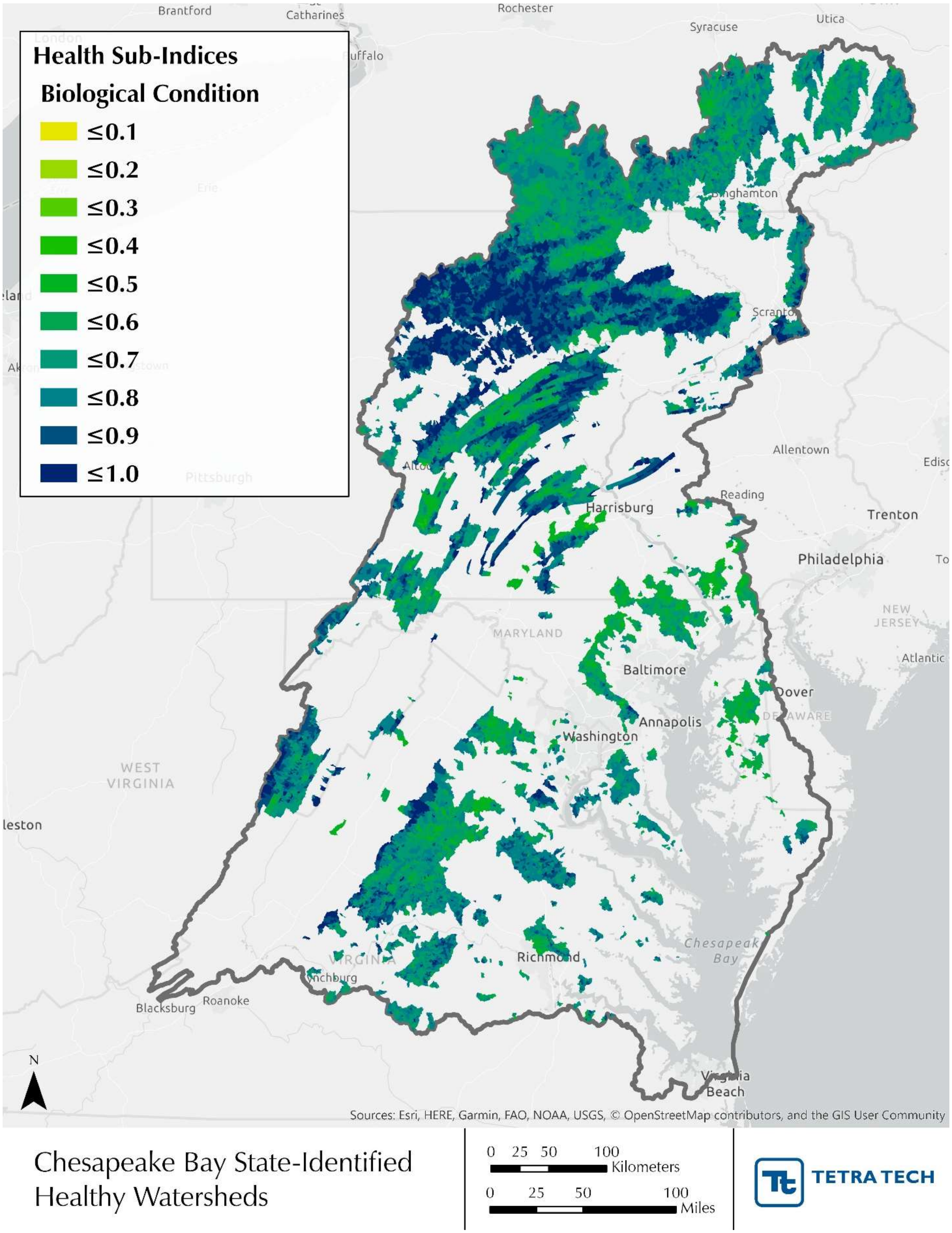


Figure 23: Characterizing watershed health: Biological Condition sub-index scores for catchments in state-identified healthy watersheds

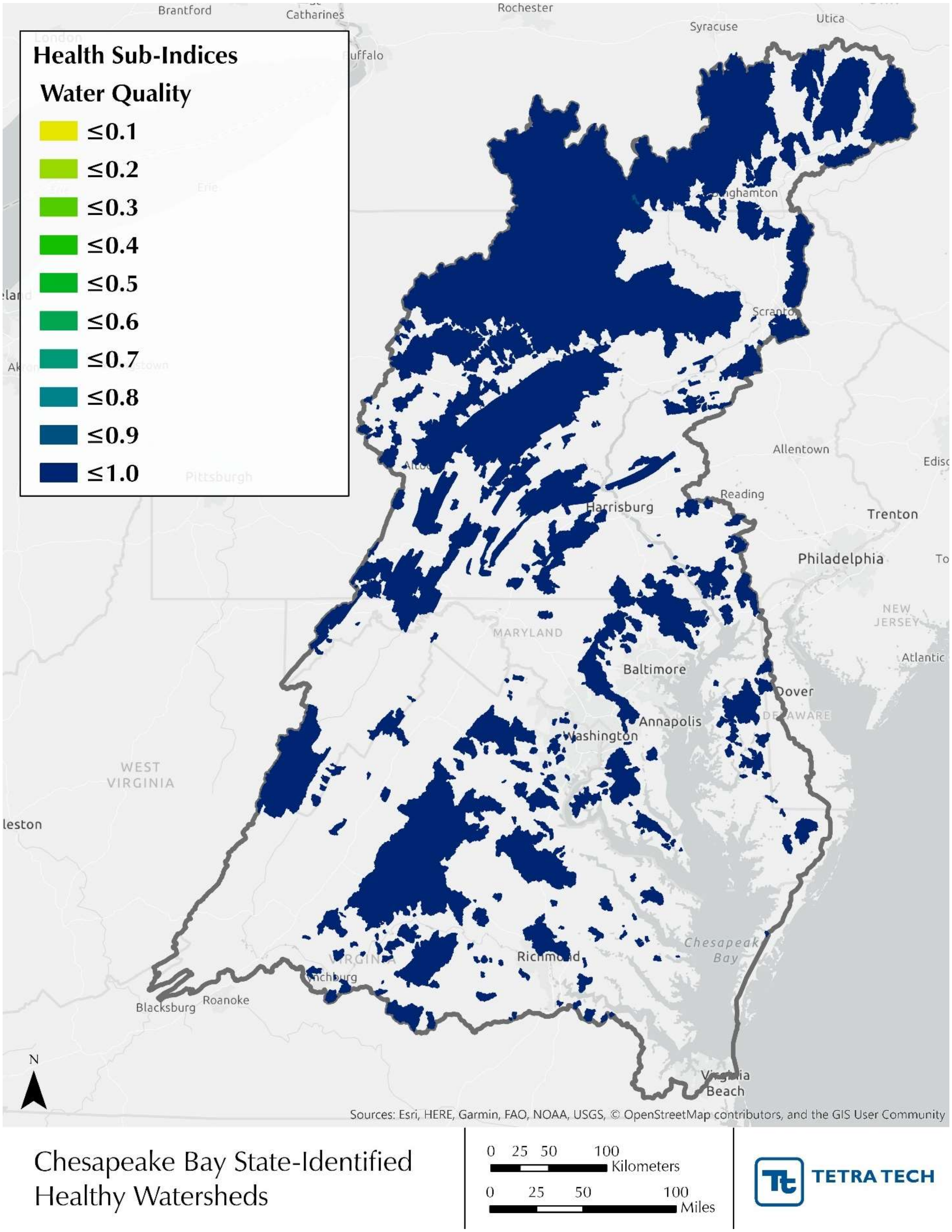
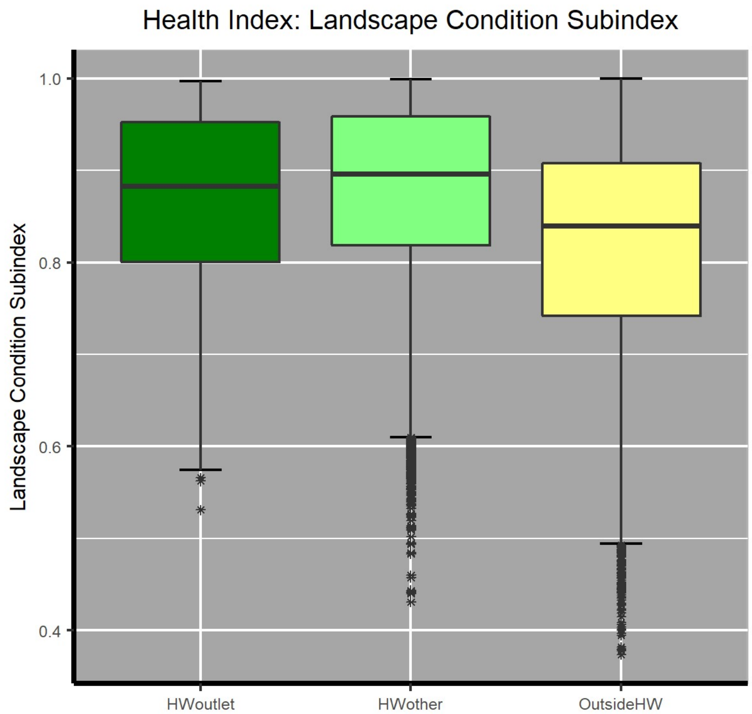


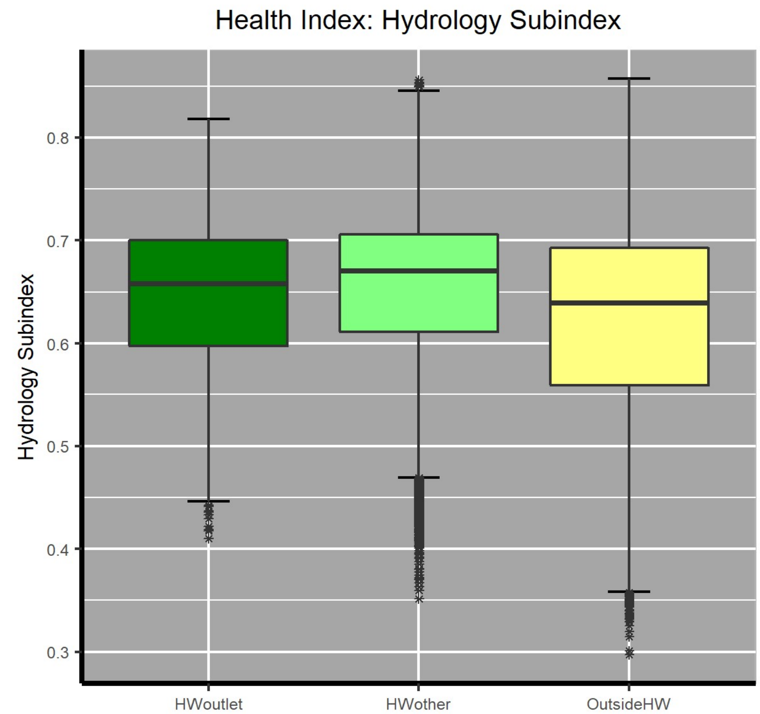
Figure 24: Characterizing watershed health: Water Quality sub-index scores for catchments in state-identified healthy watersheds

(A)



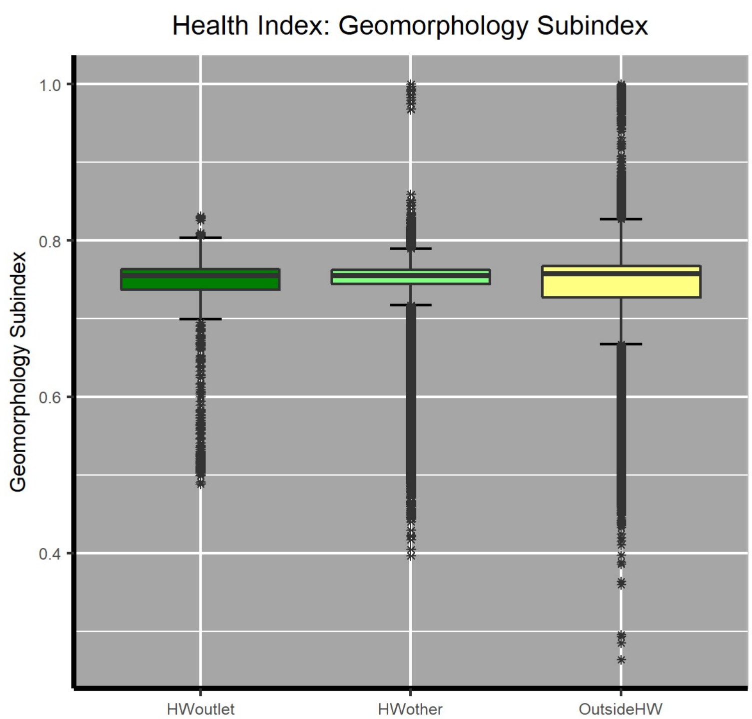
Health Index: Landscape Condition Subindex
Landscape Condition Subindex
1.0
0.8
0.6
0.4
HWoutlet
HWother
OutsideHW

(B)



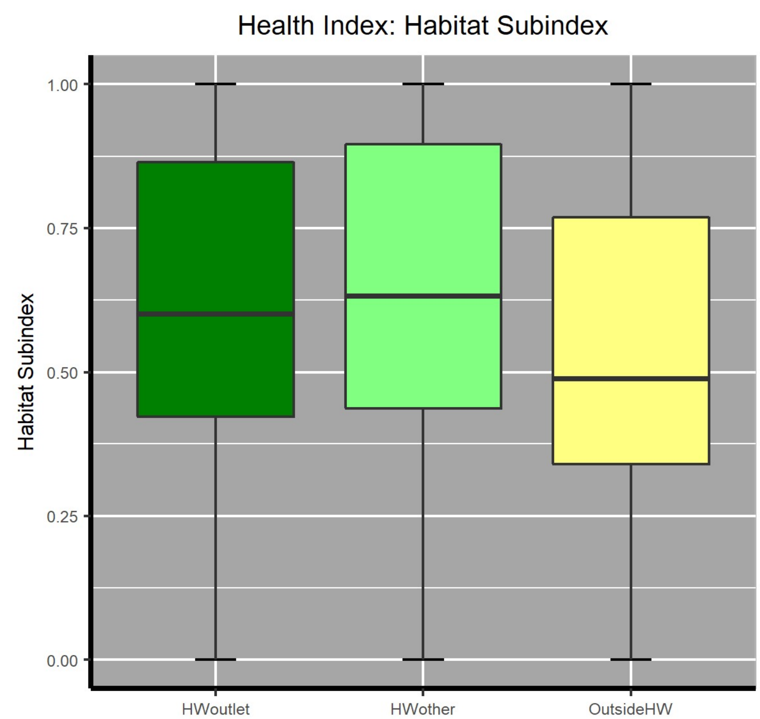
Health Index: Hydrology Subindex
Hydrology Subindex
0.8
0.7
0.6
0.5
0.4
0.3
HWoutlet
HWother
OutsideHW

(C)



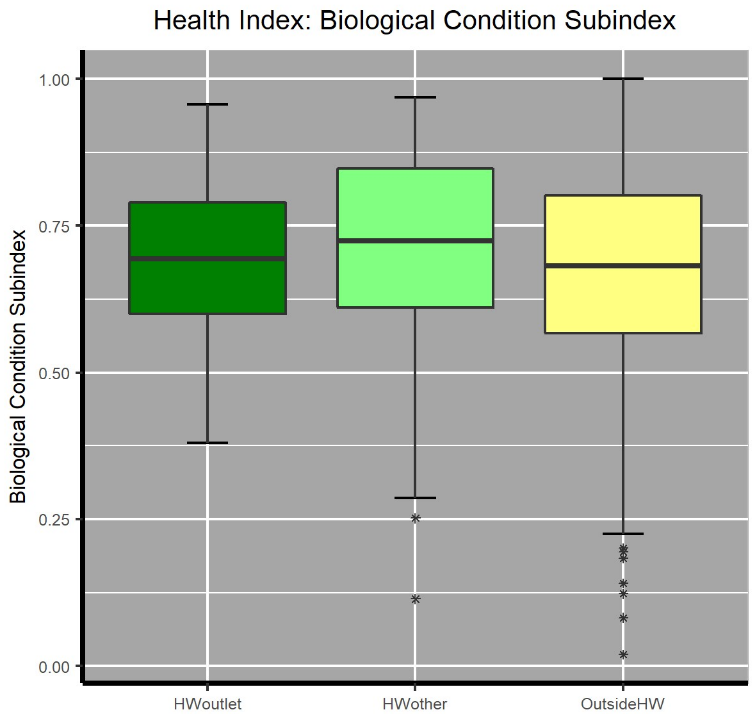
Health Index: Geomorphology Subindex
Geomorphology Subindex
1.0
0.8
0.6
0.4
HWoutlet
HWother
OutsideHW

(D)



Health Index: Habitat Subindex
Habitat Subindex
1.00
0.75
0.50
0.25
0.00
HWoutlet
HWother
OutsideHW

(E)



(F)

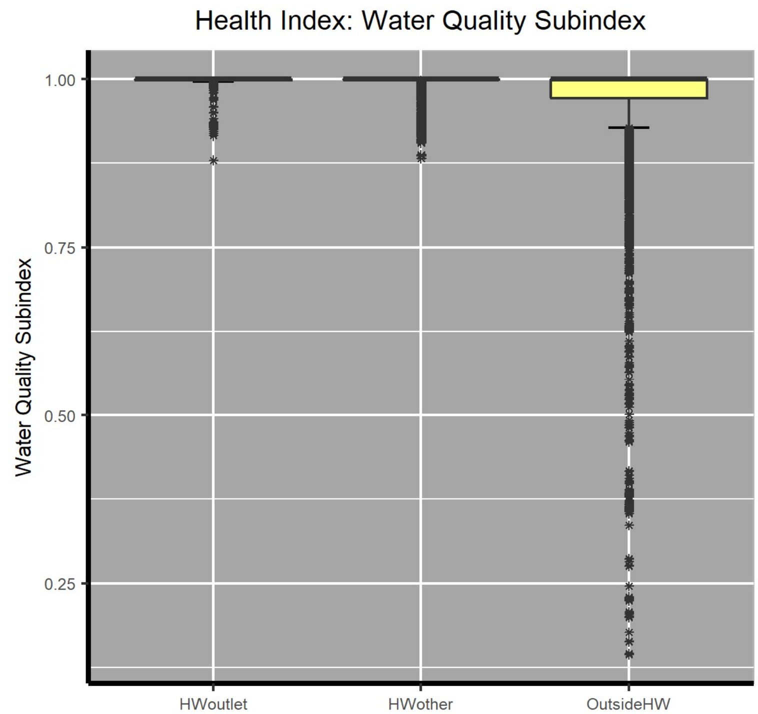


Figure 25: Comparison of distributions of six watershed health sub-indices for catchments at outlet of state-identified healthy watersheds (dark green), other catchments within those healthy watersheds (light green), and catchments outside of those healthy watersheds (yellow) for (A) Landscape Condition, (B) Hydrology, (C) Geomorphology, (D) Habitat, (E) Biological Condition, and (F) Water Quality.

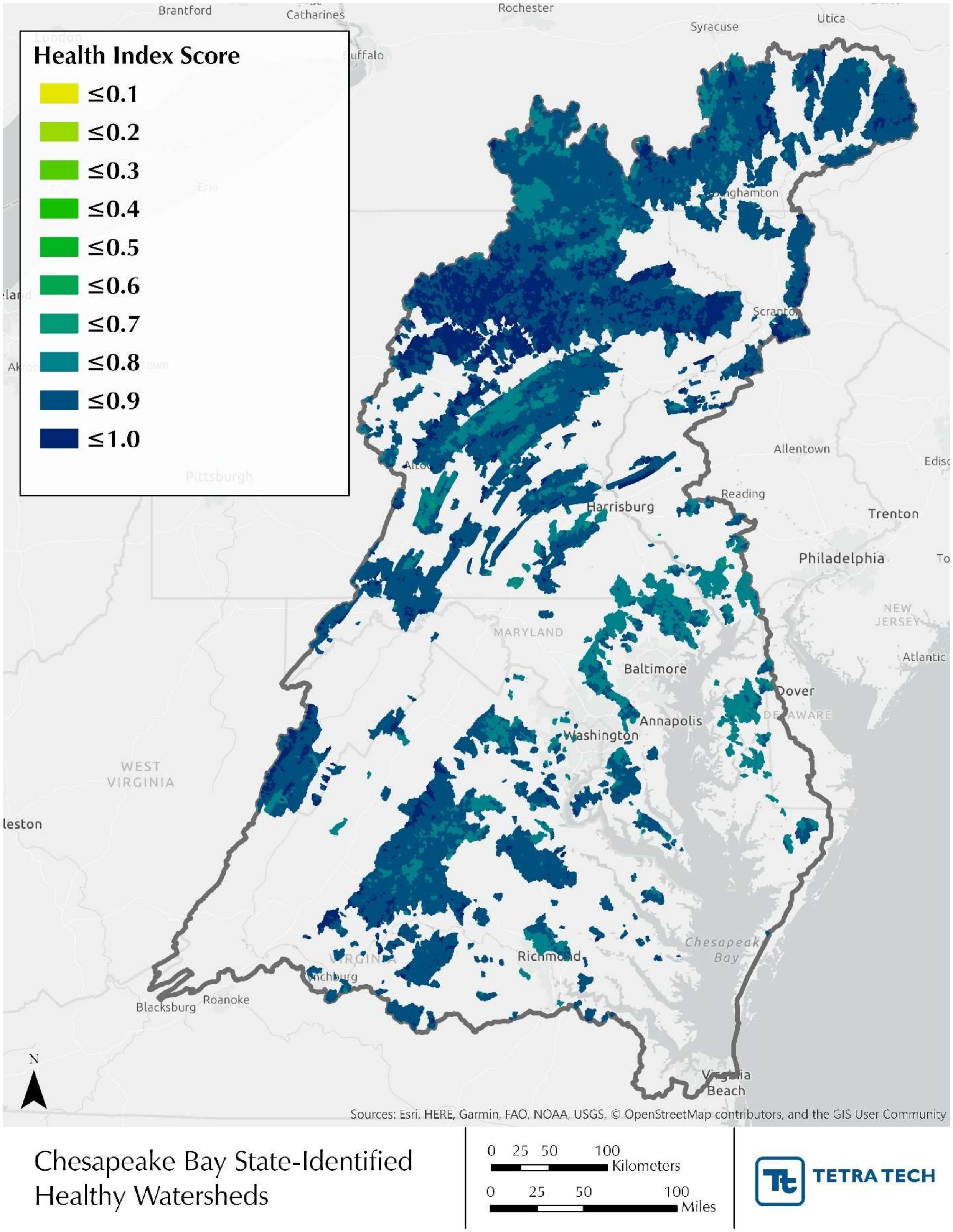


Figure 26: Characterizing watershed health: overall Watershed Health index scores for catchments in state-identified healthy watersheds

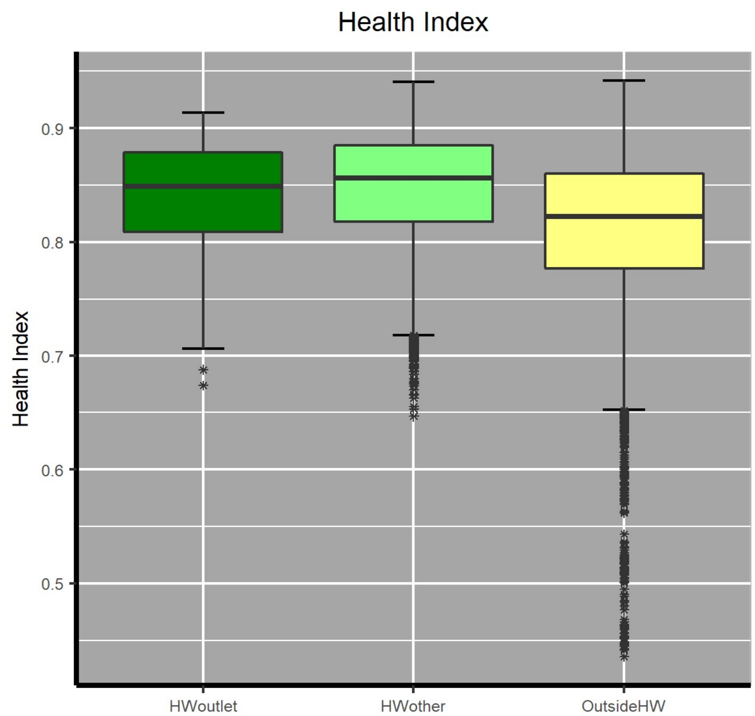


Figure 27: Comparison of distributions of the overall Watershed Health index for catchments at outlet of state-identified healthy watersheds (dark green), other catchments within those healthy watersheds (light green), and catchments outside of those healthy watersheds (yellow)

6.4 Evaluating Predictive Ability of Metrics – Stepwise Regression Model

Another approach explored for the Chesapeake Healthy Watersheds Assessment was to examine the predictive ability of all candidate metrics using a stepwise regression model, with individual metrics as predictors and classification of a catchment as healthy or non-healthy (based on state-identified designations of watershed health) as the response variable. The correlation assessment described above provides both a visual and numeric estimation of how related variables are to one another. Here, stepwise regression tests multiple combinations of variables while systematically removing those that are not important. It does this in a "stepwise" manner, where after each regression test the model removes the weakest correlated variable. At the end, the model retains only the variables that explain the distribution of data the best.

Results of exploratory analyses showed that about 10 metrics were consistently selected in model iterations as significant predictors of catchment health (see examples, Figure 28). If these metrics alone were combined into a watershed health index, its performance would be stronger than the index that employs all metrics. Among these 10 metrics, high correlations were noted for Percent Forest vs. Percent Forest in Riparian Zone, and Percent Forest vs. Percent Natural Land.

Further investigations can be employed to explore the benefits of this approach in developing an overall indicator of watershed health. Ideally, metric performance would be tested against independent, diagnostic measures of stream and watershed health (Claggett et al. 2019), to ascertain which metrics are the best predictors. Further testing of the CHWA metrics should employ independent data quantifying aspects of stream health, such as hydrologic measures (e.g., flow variability or other indicators derived from flow data), aquatic community condition (e.g., indicators such as the fish or benthic Index of Biotic Integrity), temperature indicators, or water chemistry. Predictive models can then be used to select the most effective watershed health metrics for assessing and tracking conditions, individually or within a combined watershed health index.

Similar multi-factor predictive models have been employed to predict stream quality from landscape, physical, and water chemistry data in other investigations. The healthy watersheds assessment for Wisconsin (Cadmus Group 2014b) used boosted regression tree models to predict stream nutrient and sediment concentrations, habitat ratings, and biological integrity ratings for fish and benthic macroinvertebrates, to provide values for catchments where direct data were lacking. A similar modeling approach could predict scores and compare them with known data. Hill et al. (2017) employed a random forest model with geospatial indicators of land use, land cover, climate, and other landscape features from StreamCat to correctly predict the biological condition class of 75% of sites in national stream survey data. In the Chesapeake region, Maloney et al. (2018) developed random forest models to predict stream macroinvertebrate ratings for the Chesapeake Bay Basin-wide Index of Biotic Integrity (Chessie BIBI) from landscape, physical, and atmospheric deposition data to provide biological assessments for unsampled watersheds. In earlier work within Maryland, Vølstad et al. (2003) integrated landscape and habitat assessments with Maryland Biological Stream Survey data to predict benthic condition class under varying degrees of urbanization. These or additional, related types of statistical analyses can be customized for use with the CHWA metrics.

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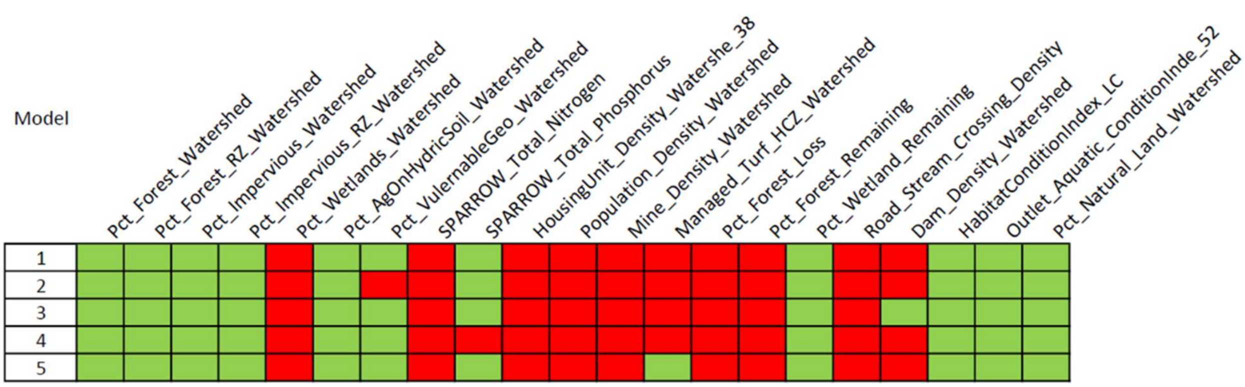


Figure 28: Exploratory analyses: best five model runs showing metrics selected by stepwise linear model. Green box indicates metric provided significant contribution when added to model; red indicates not significant

7. Developing an Assessment of Watershed Vulnerability

In addition to providing information about current conditions, one of the main objectives of the Chesapeake Healthy Watersheds Assessment was to provide information about the vulnerability of healthy watersheds to future degradation. A series of candidate metrics of watershed vulnerability were considered and evaluated as indicators of the susceptibility of watersheds to key stressors. Data were compiled and vulnerability metrics were developed for each of the 83,623 catchments within the Chesapeake Bay Watershed. A final recommended set of metrics available for assessing watershed vulnerability is presented in Figure 29. A summary of these metrics and data sources is provided in Table 4. Further details regarding data sources will be found in metadata within the accompanying geodatabase.

Nearly all data supported derivation of data at the catchment scale. While the three water use metrics were assigned to catchments, their values were downscaled from USGS HUC-12 data provided by EnviroAtlas because finer-scale data were not available.

Prior to analysis, project partners had emphasized an interest in handling watershed vulnerability indicators separately to best support watershed managers in evaluating individual vulnerability factors, rather than compiling these metrics into a combined indicator. Therefore, results are presented here for individual vulnerability metrics and sub-indices, but not as a combined index.

Individual vulnerability metrics may be used to examine factors of interest. For example, climate change may bring warmer temperatures that result in less-favorable habitat for cold-water species like Eastern brook trout. Examining spatial patterns of predicted brook trout occurrence under current v. warmer conditions can point to areas that may be most vulnerable. The climate change metric related to predicted change in occurrence of brook trout is illustrated in Figure 30.

Descriptive statistics for vulnerability metrics in the state-identified healthy watersheds are shown in Appendix D, Table D-1. The values presented in Table D-1 are for catchments at the outlet of each state-identified healthy watershed; therefore, for metrics designated as watershed-wide, these data reflect conditions throughout the area draining to each healthy watershed.

Vulnerability results can be used to quantify factors that may affect future watershed health. For example, according to modeled land use change by 2050, the mean percent of additional developed land upstream of state-identified healthy watersheds is estimated at 1.5% (ranging from 0 to 48%). The mean percentage of protected land upstream of state-identified healthy watersheds is 30% (range 0 to 100%). Further breakdowns by state or for various catchment types can also be produced from the data set. Results can be used to drill down to watersheds (or catchments) most vulnerable to future stress, for example those where future development is expected to be high or the current percentage of protected land is low. Alternatively, areas that forecast sustained future brook trout populations in the face of increasing temperature and increased impervious cover may indicate resilience to certain climatic factors due to more protected lands coverage or greater proportions of riparian forest buffers.

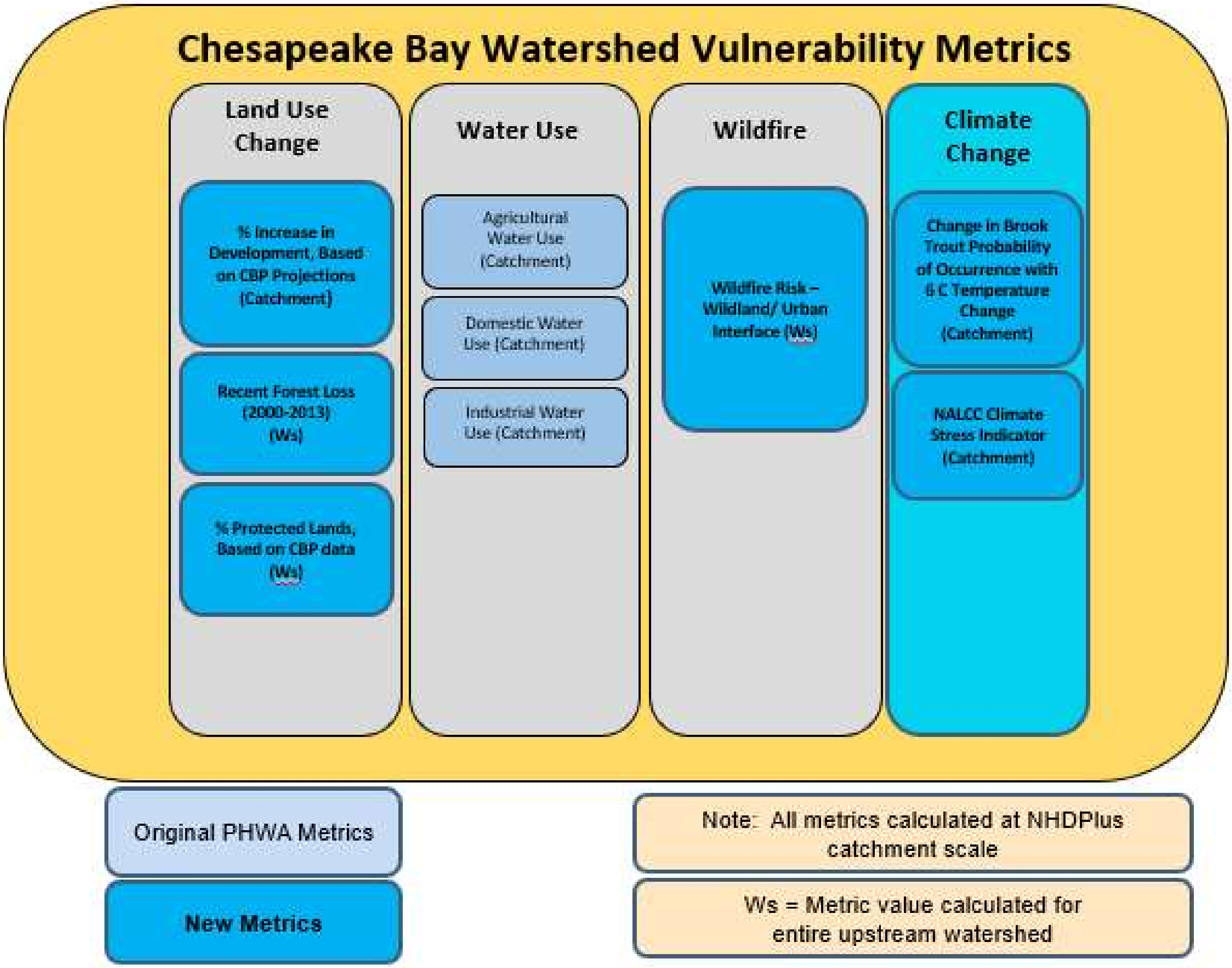
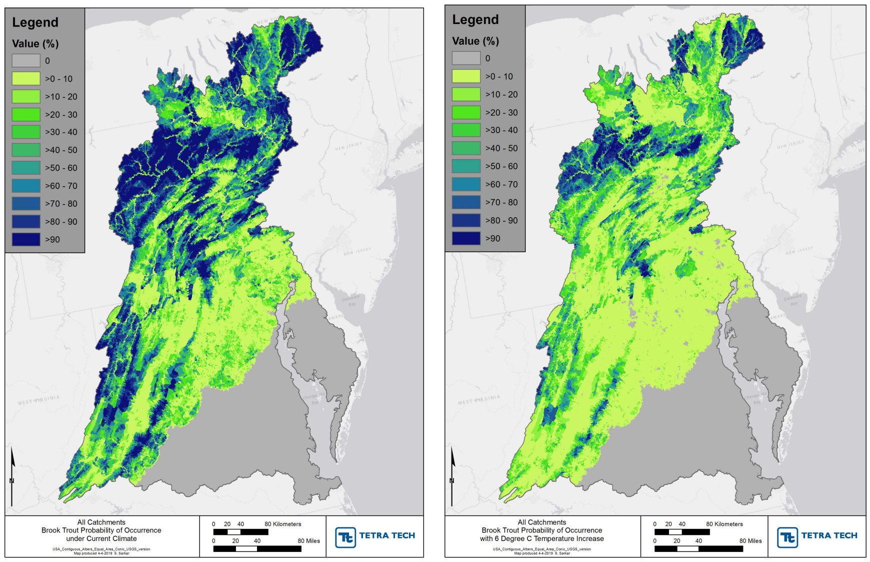


Figure 29: Recommended metrics indicative of watershed vulnerability for catchments in Chesapeake Bay Watershed. Light blue boxes are metrics from the original, national PHWA, but developed here at the catchment scale. Bright blue boxes indicate new metrics.

Table 4: Recommended watershed vulnerability metrics for catchments in Chesapeake Bay watershed

Sub-Index	Metrics	Notes: Data Source
Land Use Change	% Increase in Development in Catchment	CBLCM v4, 2050 projection, 2018 data set
	Recent Forest Loss in Watershed	StreamCat, Forest Loss 2000-2013 / Global Forest Change
	% Protected Lands in Watershed	CBP Protected Lands data, Dec. 2018
Water Use	Agricultural Water Use in Catchment	Downscaled from HUC12 data, EPA EnviroAtlas, 2015
	Domestic Water Use in Catchment	Downscaled from HUC12 data, EPA EnviroAtlas, 2015
	Industrial Water Use in Catchment	Downscaled from HUC12 data, EPA EnviroAtlas, 2015
Wildfire Risk	% Wildland Urban Interface in Watershed	University of Wisconsin - Madison SILVIS lab. Wildland Urban Interface, 2010 data, published 2017.
Climate Change	Change in Probability of Brook Trout Occurrence, Current Conditions v. Future Conditions (plus 6 degrees C) in Catchment	North Atlantic Landscape Conservation Cooperative (NALCC), Nature's Network, USGS Conte Lab, 2017
	Climate Stress indicator in Catchment	North Atlantic Landscape Conservation Cooperative (NALCC), Nature's Network, 2017

Nature's Network / USGS Conte Lab has developed a model of predicted brook trout occurrence, which can be used to project future conditions under various climate change scenarios. The model incorporates influences of landscape, land-use, and climate variables on the probability of brook trout occupancy in stream reaches. Predictions are available for current condition and with increased stream temperature of 2 to 6 degrees; the 6-degree scenario was chosen to provide the most sensitive signal of potential change across the region. For Chesapeake Bay catchments, results show the Brook Trout Probability of Occurrence under current climate condition (left) decreasing across much of the region with a 6 degree C increase in stream temperature (right).



Expressed as the difference between current and future probability of occurrence, the Change in Brook Trout Probability of Occurrence can be a useful vulnerability metric, providing an early warning for areas most susceptible to loss of suitable habitat for brook trout with increasing temperature. Results (as illustrated below) can be obtained for all catchments (left) or in those associated with state-identified healthy watersheds (right). Areas with the greatest anticipated decline in brook trout occurrence are in New York and Pennsylvania, which currently support the greatest percent occurrence. Healthy watersheds in the states farther south also appear to be susceptible to declines in brook trout occurrence, such that the species may be highly threatened in some watersheds currently providing suitable coldwater habitat.

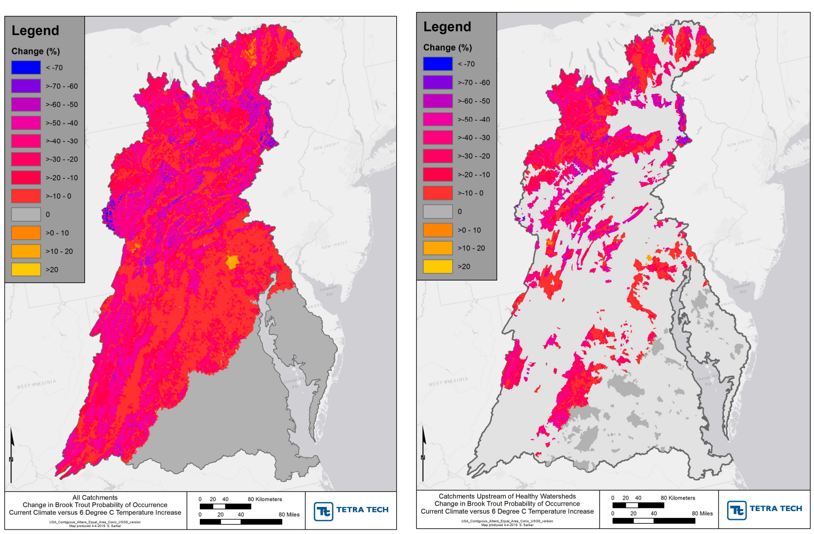


Figure 30: Example watershed vulnerability metric: Change in Brook Trout Probability of Occurrence with Increasing Temperature

7.1 Distributions of Watershed Vulnerability Metric Scores by Catchment

To examine the range of metric values for healthy watersheds, as well as other watersheds, box-and-whisker plots were prepared to illustrate the distribution of metric values in different types of catchments, i.e., those at the outlet, within, and outside of state-identified healthy watersheds. Distributions of individual watershed vulnerability metrics for catchments in three groups (those at the outlet, within, and outside of state-identified healthy watersheds) are shown in Figures 31-34. Note that these figures illustrate individual vulnerability metric scores, not transformed for directionality. For example, low values for the Future Development metric mean less development is projected.

These plots illustrate how vulnerability metrics for catchment within the healthy watersheds compare to values across the broader population of catchments not designated as healthy. Although there is substantial overlap for many metrics, it is interesting to note some patterns. For example, projections of future development for catchments at the outlet of state-identified healthy watersheds are at the lower end of the scale (all less than 49%), while some catchments outside of healthy watersheds are projected to have much more development (Figure 31A). State-identified healthy watersheds appear to be as vulnerable as other watersheds to water use demands (Figure 32). Wildfire risk in the state-identified healthy watersheds appears fairly low in comparison with other watersheds, but there is substantial overlap in values (Figure 33). Change in brook trout probability of occurrence in comparison with current conditions varies broadly (Figure 34A), likely associated with the diversity of stream condition, elevation, and groundwater contributions to streamflow. Median value for the climate stress metric in state-identified healthy watersheds is lower than elsewhere, but distributions overlap greatly (Figure 34B).

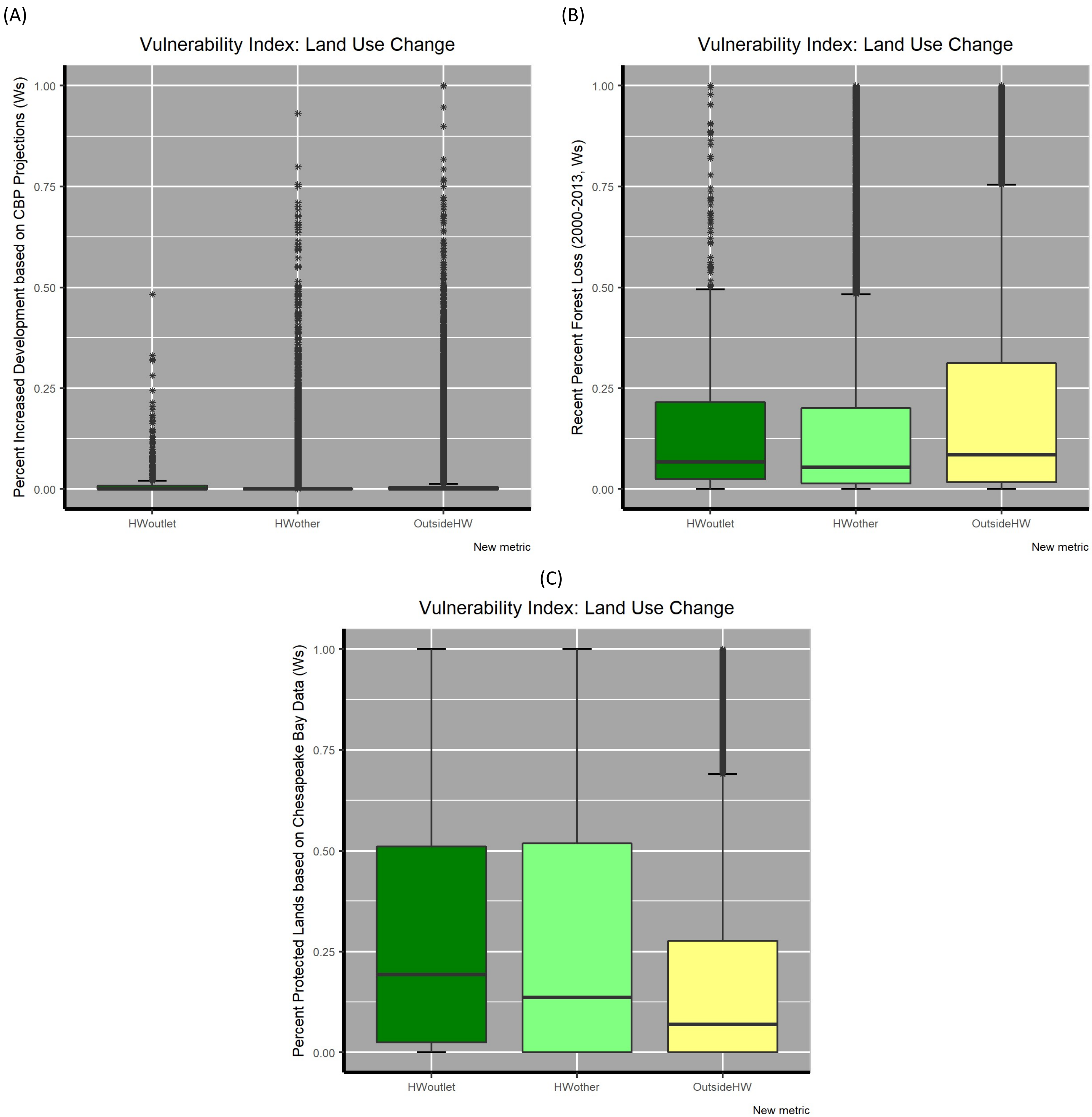


Figure 31: Comparison of distributions for land use change vulnerability metrics for catchments at outlet of state-identified healthy watersheds (dark green), other catchments within those healthy watersheds (light green), and catchments outside of those healthy watersheds (yellow) for (A) Percent Increase in Development, (B) Recent Forest Loss, and (C) Percent Protected Lands

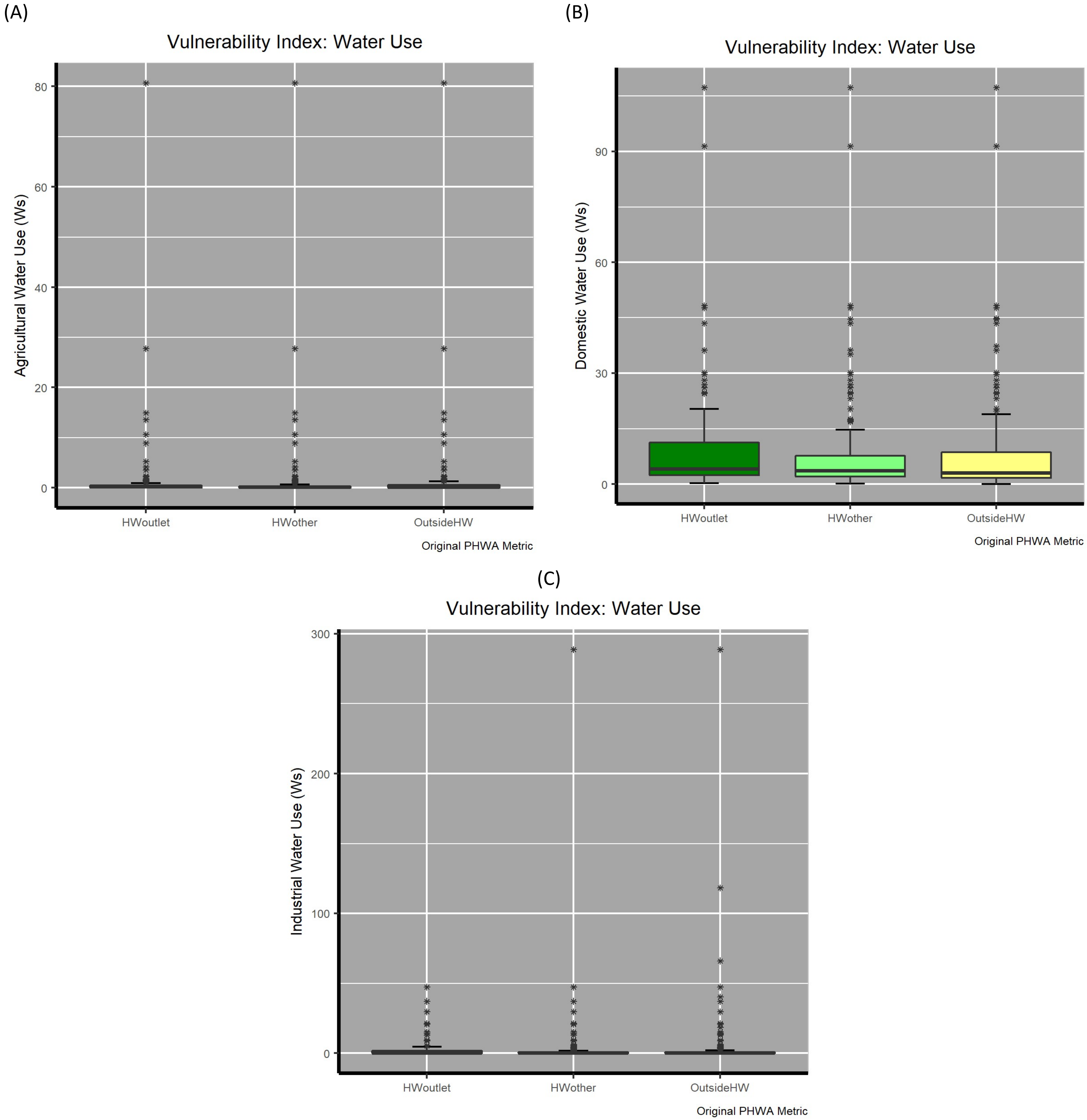


Figure 32: Comparison of distributions for water use vulnerability metrics for catchments at outlet of state-identified healthy watersheds (dark green), other catchments within those healthy watersheds (light green), and catchments outside of those healthy watersheds (yellow) for (A) Agricultural, (B) Domestic, and (C) Industrial Water Use

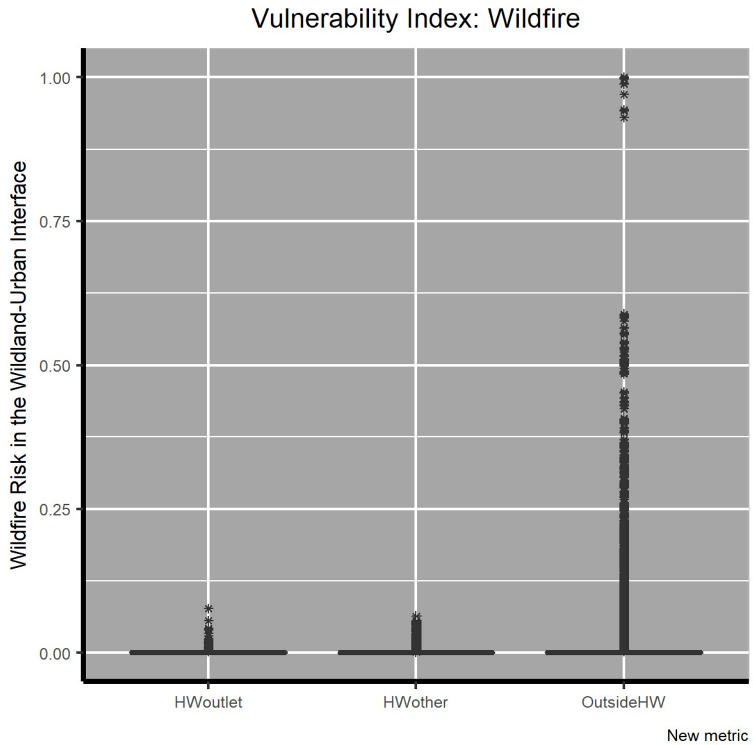


Figure 33: Comparison of distributions for wildfire risk vulnerability metric for catchments at outlet of state-identified healthy watersheds (dark green), other catchments within those healthy watersheds (light green), and catchments outside of those healthy watersheds (yellow)

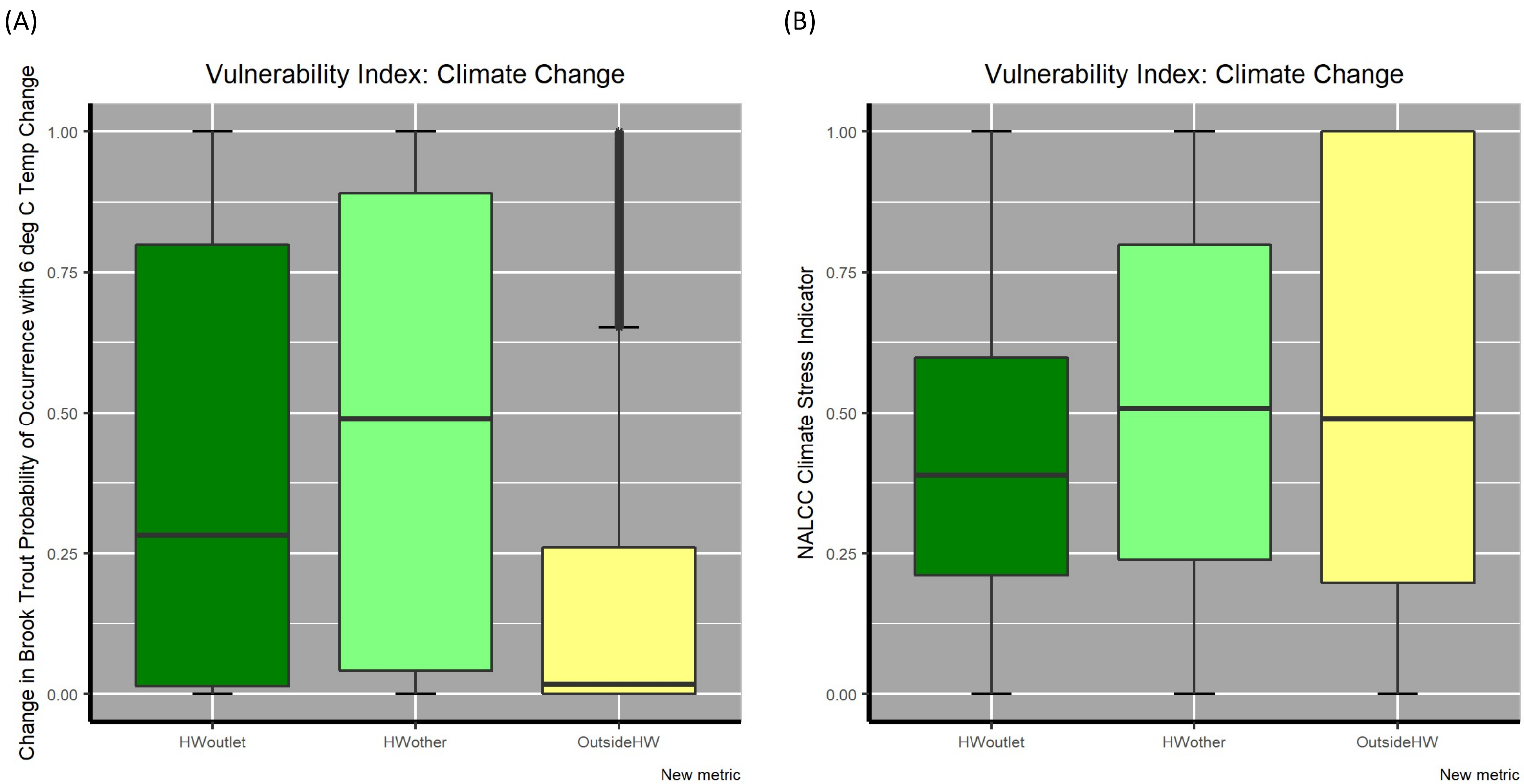


Figure 34: Comparison of distributions for climate change vulnerability metrics for catchments at outlet of state-identified healthy watersheds (dark green), other catchments within those healthy watersheds (light green), and catchments outside of those healthy watersheds (yellow) for (A) Change in Brook Trout Probability of Occurrence with 6 Degree Temperature Change and (B) NALCC Climate Stress Indicator

7.2 Combining Metrics into Watershed Vulnerability Sub-Indices

The individual vulnerability metrics were combined into four sub-indices of vulnerability: land use change, water use, wildfire risk, and climate change. The approach for combining metrics followed the same method used in combining watershed health metrics, as described in Section 6.3. The directionality of metrics was adjusted in the computation of combined sub-indices. Positive metrics (i.e., Percent Protected Lands and projected change in brook trout occurrence) were not transformed for directionality. Each of the remaining metrics (e.g., Future Development) was treated as a negative metric and was transformed as one minus the metric, to yield an adjusted score. These scores were combined into sub-index values. Therefore, a high vulnerability sub-index value is associated with conditions favorable to watershed health (low stress) while a low sub-index value is associated with less favorable conditions (high stress). To explore data, maps were prepared for each of these four sub-indices, as shown in Figures 35 to 38. Distributions of scores for the four sub-indices for catchments in three groups (those at the outlet, within, and outside of state-identified healthy watersheds) are shown in Figure 39.

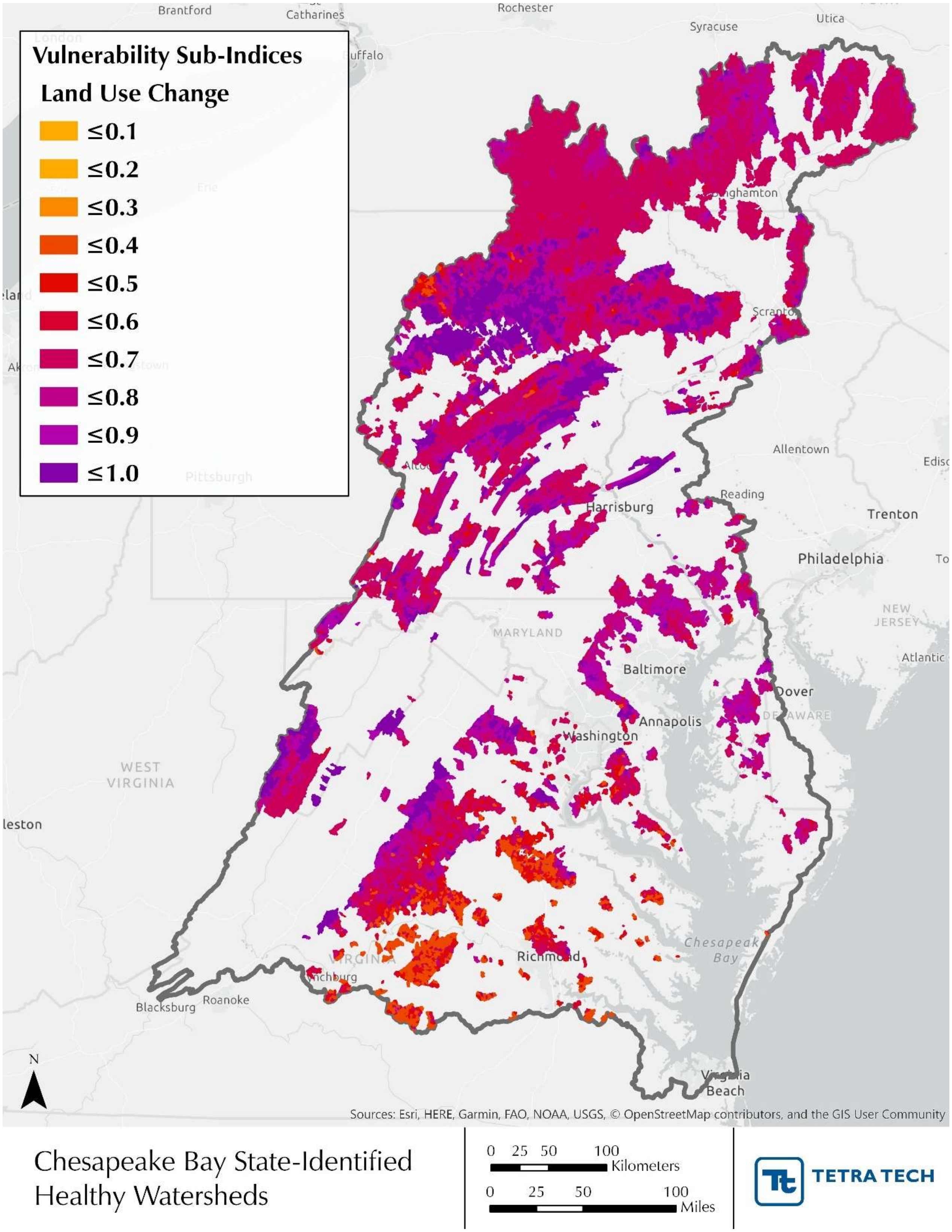


Figure 35: Characterizing watershed vulnerability: Land Use Change sub-index scores for catchments in state-identified healthy watersheds

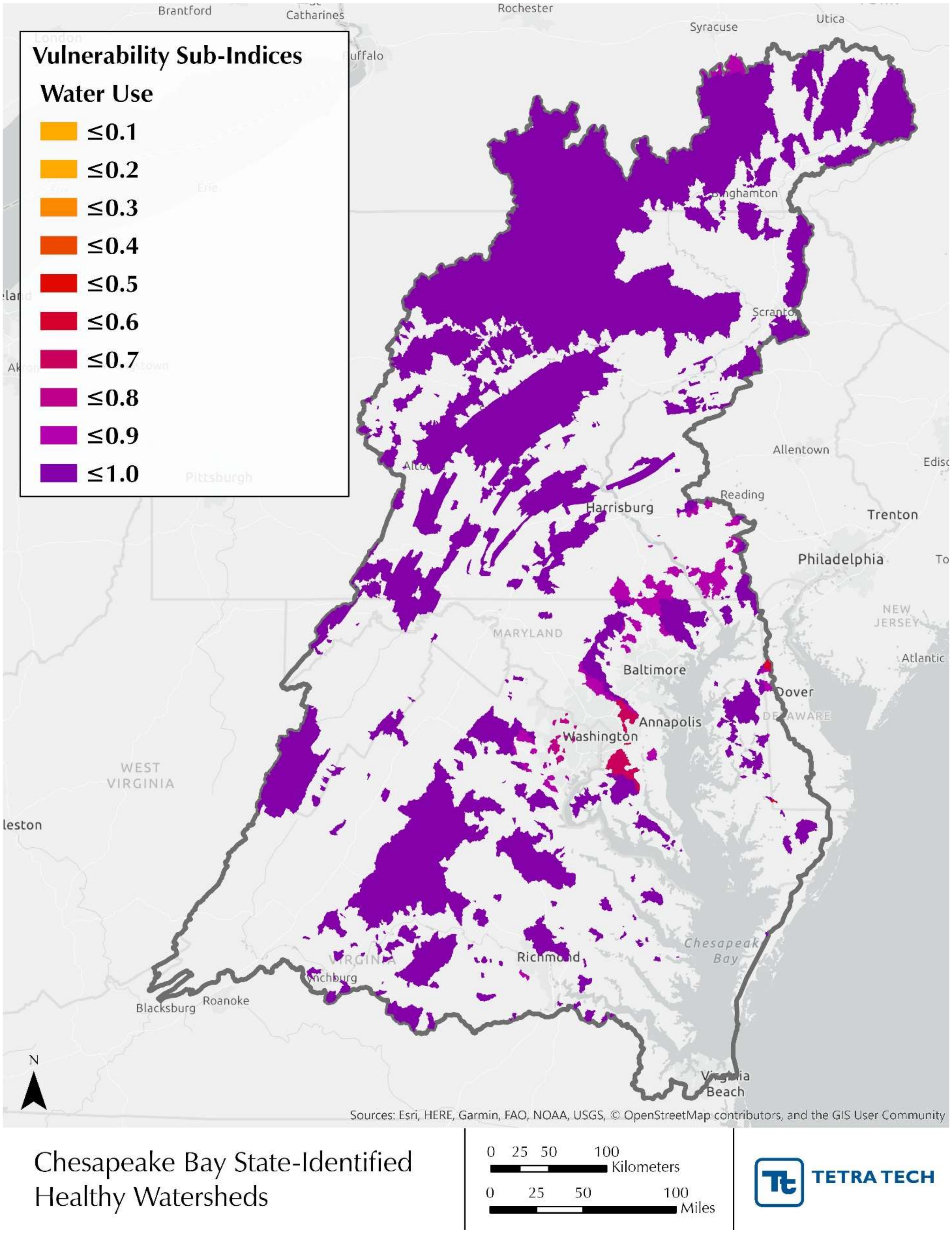


Figure 36: Characterizing watershed vulnerability: Water Use sub-index scores for catchments in state-identified healthy watersheds

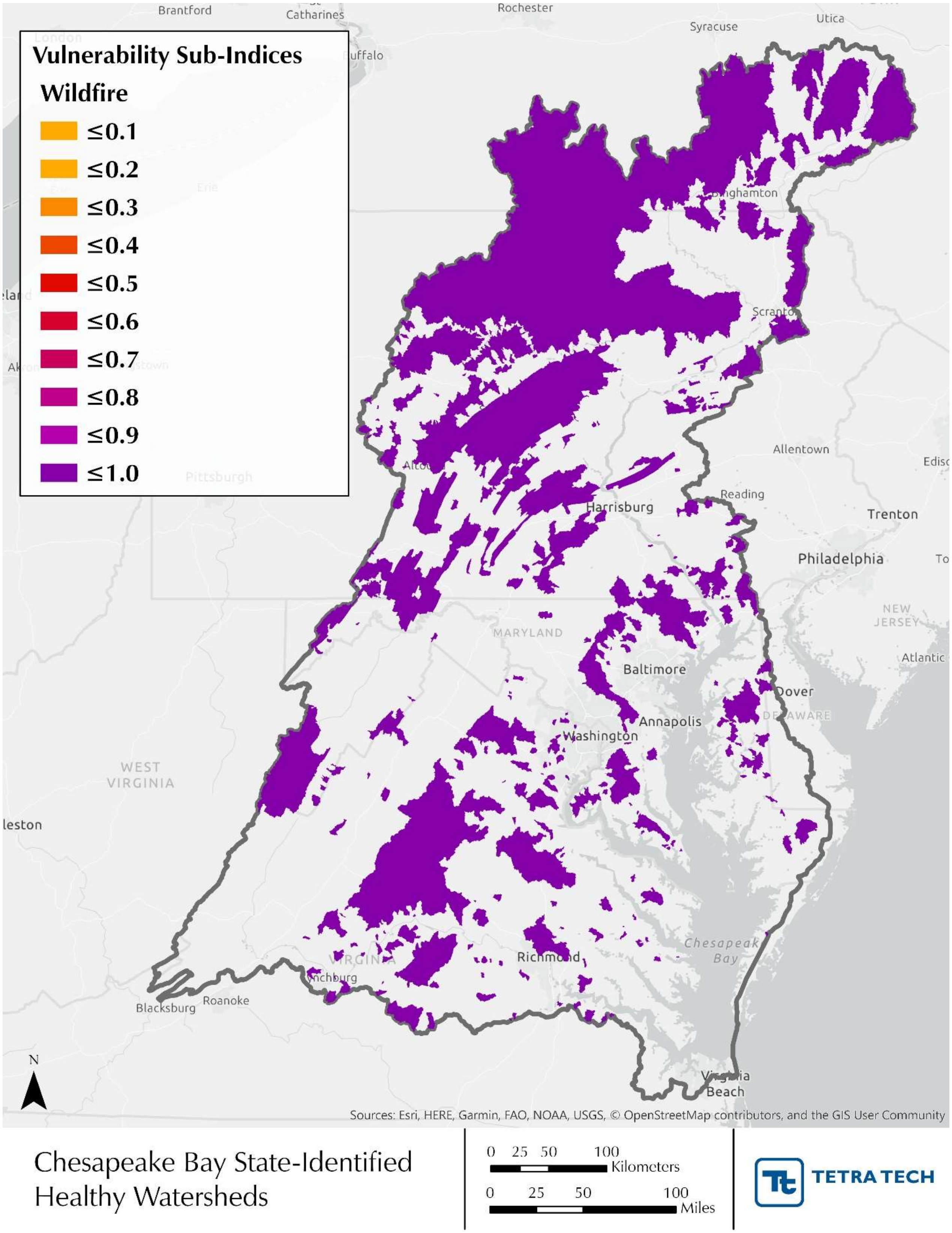


Figure 37: Characterizing watershed vulnerability: Wildfire Risk sub-index scores for catchments in state-identified healthy watersheds

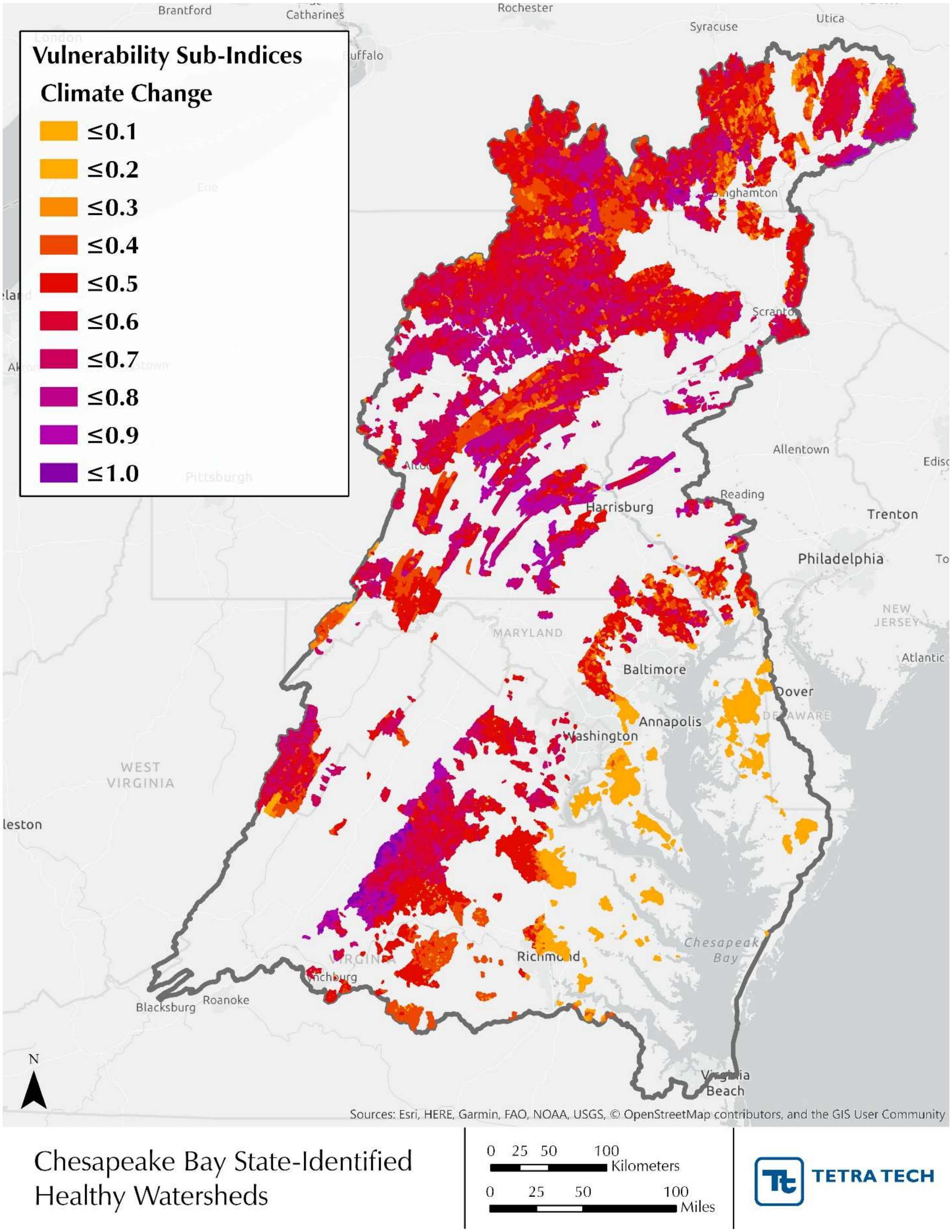


Figure 38 : Characterizing watershed vulnerability: Climate Change sub-index scores for catchments in state-identified healthy watersheds

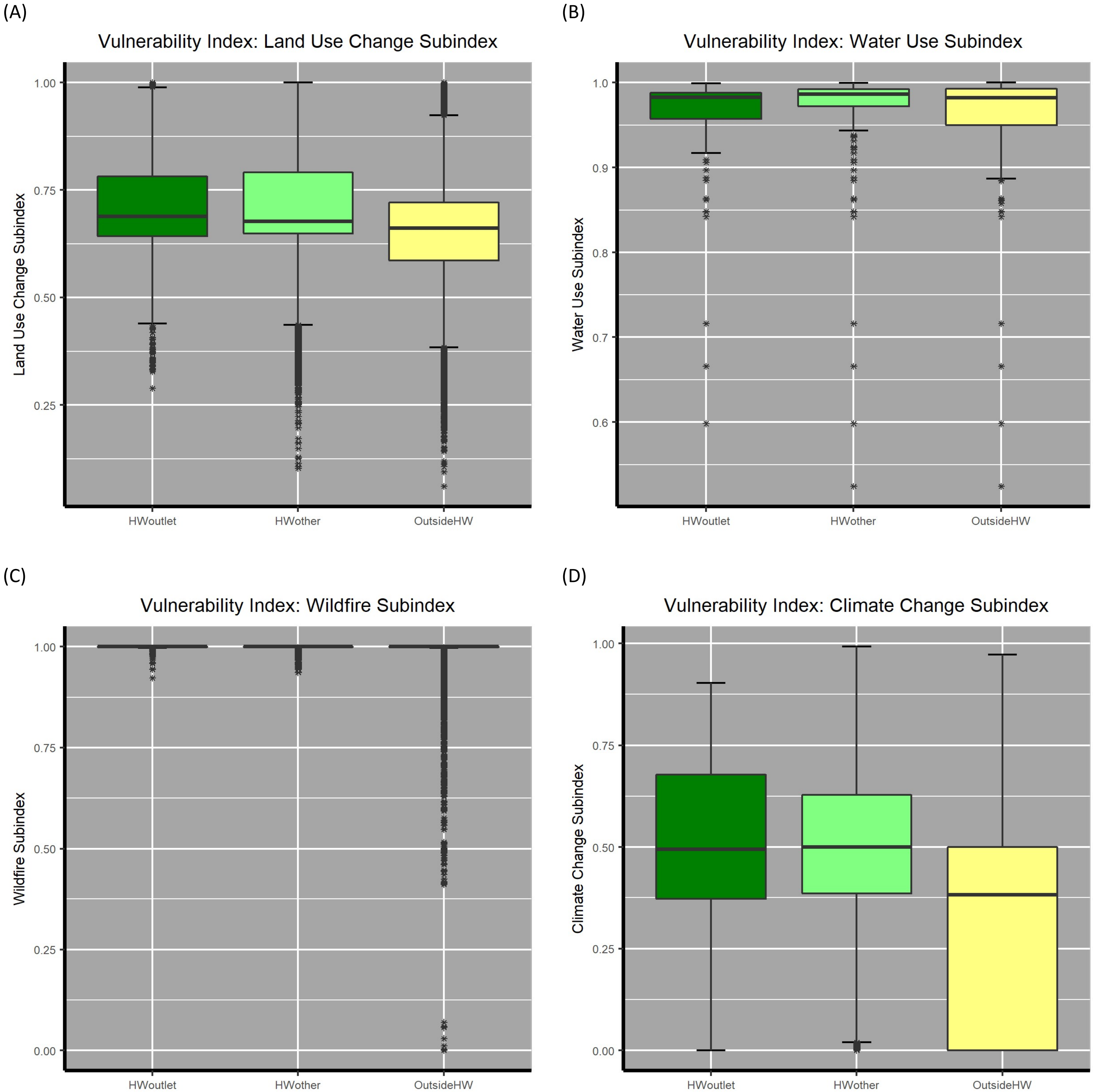


Figure 39: Comparison of distributions of four watershed vulnerability sub-indices for catchments at outlet of state-identified healthy watersheds (dark green), other catchments within those healthy watersheds (light green), and catchments outside of those healthy watersheds (yellow) for (A) Land Use Change, (B) Water Use, (C) Wildfire Risk, and (D) Climate Change

8. Recommendations for Tracking Watershed Health and Vulnerability

Using CHWA metrics, watershed health and vulnerability can be tracked, offering information on the degree to which watershed health is being sustained or providing a warning sign that health may be declining or about to decline. These signals of change would be useful for management purposes, potentially helping to identify and address current or future stressors that threaten watershed health. While on-the-ground monitoring may be ideal for documenting and tracking conditions in healthy watersheds, resources for collecting field data are often limited. The CHWA offers another way to characterize conditions, detect change, and target future monitoring if needed.

The Chesapeake Bay metrics for watershed health and vulnerability compiled here represent a first step towards assessing and tracking conditions in the state-identified healthy watersheds, as well as other areas within the Bay watershed. As new data become available, this framework can be adapted to include new or updated data to provide a refined assessment of overall watershed condition or aspects of condition, as well as tracking changes in condition. Data will allow assessments of vulnerability using the currently available data or new data that can be incorporated at the catchment scale. The geodatabase is intended to provide a flexible framework for integrating additional data, whether available throughout the Bay watershed or within a subarea.

Some metrics lend themselves to being updated with new versions of datasets that are scheduled or likely to be updated. Table 5 summarizes future data updates that are expected. For example, metrics based on Chesapeake Bay high-resolution land use/land cover data can be updated at regular intervals as those data are slated to be refined frequently based on newly acquired imagery. LANDFIRE data for the Northeast are scheduled for next release in 2020 through the LANDFIRE Remap effort (LandFire 2019). Metrics that are derived from national sources such as EPA's StreamCat and EnviroAtlas can be updated when periodic updates of those datasets become available, although a schedule of updates has not been established.

Long-term tracking of stream and watershed conditions in healthy watersheds may ideally make use of two types of data, both from actual or direct monitoring and also from indicators derived from landscape and other metrics available at a broad spatial scale. Given that monitoring data are not likely to be available at all locations or perhaps not at a frequency that would be desired, metrics such as those provided by the CHWA can be useful predictors of condition. The relationships between metrics and diagnostic measures of stream and watershed condition can be assessed at locations where data are available, to build models for predicting stream and watershed health applicable elsewhere. In addition to CHWA's regional data, available state-specific data should be integrated into further diagnostic investigations. As discussed in Section 6.4, further statistical evaluations of the watershed health and vulnerability metrics and their relationships with independent measures will be an important next step to establish a framework for evaluating when a statistically significant change is occurring (or about to occur) and to provide signals of change to understand when conditions are likely to fall short of expectations for healthy watersheds. Predictive models can inform the selection of watershed health metrics for assessing and tracking conditions, individually or within a combined watershed health index.

Table 5: Future availability of data for watershed condition and vulnerability metrics

Watershed Condition Metrics		
Sub-Index	**Metrics**	**Notes: Future Data Availability**
Landscape Condition	% Natural Land Cover in Watershed	CBP high-resolution land use/land cover data - future iterations (e.g., 2017, 2019, 2021, 2023 updates)
	% Forest in Riparian Zone in Watershed	CBP high-resolution land use/land cover data - future iterations (e.g., 2017, 2019, 2021, 2023 updates)
	Population Density in Watershed	StreamCat - future census data (2020 and beyond)
	Housing Unit Density in Watershed	StreamCat updates
	Mining Density in Watershed	StreamCat updates
	% Managed Turf Grass in Hydrologically Connected Zone (HCZ) in Watershed	CBP high-resolution land use/land cover data - future iterations (e.g., 2017, 2019, 2021, 2023 updates)
	Historic Forest Loss in Watershed	LANDFIRE Remap for Northeastern US, scheduled for release January - June 2020
Hydrology	% Agriculture on Hydric Soil in Watershed	EPA EnviroAtlas - future updates
	% Forest in Watershed	CBP high-resolution land use/land cover data - future iterations (e.g., 2017, 2019, 2021, 2023 updates)
	% Forest Remaining in Watershed	LANDFIRE Remap for Northeastern US, scheduled for release January - June 2020
	% Wetlands Remaining in Watershed	LANDFIRE Remap for Northeastern US, scheduled for release January - June 2020
	% Imperviousness in Watershed	CBP high-resolution land use/land cover data - future iterations (e.g., 2017, 2019, 2021, 2023 updates)
	Density Road-Stream Crossings in Watershed	StreamCat updates
	% Wetlands in Watershed	CBP high-resolution land use/land cover data - future iterations (e.g., 2017, 2019, 2021, 2023 updates)
Geomorphology	Dam Density in Watershed	StreamCat updates
	Vulnerable Geology in Watershed	Geologic data, unlikely to change
	Road Density in Riparian Zone, in Watershed	StreamCat updates

Table 5: Future availability of data for watershed condition and vulnerability metrics

	% Impervious in Riparian Zone in Watershed	CBP high-resolution land use/land cover data - future iterations (e.g., 2017, 2019, 2021, 2023 updates)
Habitat	National Fish Habitat Partnership (NFHP) Habitat Condition Index in Catchment	Updates to national fish habitat indicator and new regional fish habitat assessment under development for CBP
	Chesapeake Bay Conservation Habitats in Catchment	Updates to Landscope / Nature's Network Conservation Design for the Northeast
Biological Condition	Outlet Aquatic Condition Score in Catchment	CBP / ICPRB Chessie BIBI
Water Quality	% of Stream Length Impaired in Catchment	EPA ATTAINS or State-specific data
	Estimated Nitrogen Load from SPARROW Model (lbs/acre/yr), in Watershed	
	Nitrogen, Phosphorus, and Sediment Load from Chesapeake Bay Watershed Model, by Sector (Developed Land, Agriculture, Wastewater, Septic, and CSO), in Watershed (13 separate metrics)	Future CBP Model Estimates
Watershed Vulnerability Metrics		
Land Use Change	% Increase in Development in Catchment	Future updates to CBP model
	Recent Forest Loss in Watershed	Updates to StreamCat, Global Forest Watch
	% Protected Lands in Watershed	CBP and partner updates to protected lands data
Water Use	Agricultural Water Use in Catchment	Updates to USGS water use data
	Domestic Water Use in Catchment	Updates to USGS water use data
	Industrial Water Use in Catchment	Updates to USGS water use data
Wildfire Risk	% Wildland Urban Interface in Watershed	Updates to Wildland Urban Interface data, University of Wisconsin - Madison SILVIS lab. A 2020 version of the WUI data is planned using 2020 census data, expected to be ready by 2021. Future versions are likely using decadal census data. Also, SILVIS currently in the process of generating future decadal WUI projection datasets for 2020-2070 using econometric models that predict where housing growth will

Table 5: Future availability of data for watershed condition and vulnerability metrics

		occur across the U.S. over that time frame. Projection data may be ready by end of 2019.
Climate Change	Change in Probability of Brook Trout Occurrence, Current Conditions v. Future Conditions (plus 6 degrees C) in Catchment	New/updated research on brook trout vulnerability
	Climate Stress indicator in Catchment	New/updated research on climate stress

In addition, new indicators based on analyses currently under development will provide information for integration into future versions of the healthy watershed assessment for Chesapeake Bay.

- ***Stream biological condition.*** The Interstate Commission on the Potomac River Basin (ICPRB) has led the development and refinement of an index for assessing stream biological integrity based on benthic macroinvertebrates, the Chesapeake Basin-wide Index of Biotic Integrity (Chessie BIBI, Smith et al. 2017). Using the Chessie BIBI, ICPRB and its partners have developed a preliminary baseline condition assessment for stream health throughout the Bay watershed (Buchanan et al. 2018), applying a combination of monitoring data and modeling predictions. Their results are provided by HUC-12 subwatershed but incorporate random forest model analysis conducted at the catchment scale (Maloney et al. 2018).

- ***Fish habitat.*** updates to the NFHP assessments are made every five years. In addition, the Chesapeake Bay Program is undertaking development of a fish habitat assessment for the Bay's tidal and non-tidal systems, beginning with development of an assessment framework and inventory and evaluation of extensive data sets to support a regional assessment (Hunt et al. 2018).

- ***Climate change.*** Ongoing CBP work to develop indicators related to climate change trends and impacts may provide new information at a scale applicable to assessing the vulnerability of healthy watersheds.

As new environmental issues gain importance, the healthy watersheds framework can be a useful tool for organizing regional data. For example, data on water use for hydraulic fracturing (fracking) could be included. The tool will enable statistical analyses to be conducted and updated as new metrics are incorporated.

9. Management Applications and Availability of Chesapeake Healthy Watersheds Assessment Data

The assessment framework, metrics, and geodatabase created for the Chesapeake Healthy Watersheds Assessment (CHWA) are intended to be useful for a variety of management applications. Primarily, the assessment will support the Chesapeake Bay Program and its jurisdiction partners in detecting signals of change in the state-identified healthy watersheds, providing information useful to support strategies to protect and maintain watershed health. In particular, indicators of vulnerability may help to provide an "early warning" to identify factors that could cause future degradation, allowing for steps to be taken related to communication and management actions to head off these potential negative effects.

The CHWA will be integrated with other Bay Program efforts in support of ecosystem health. For one, the CBP Stewardship, Habitat, Healthy Watersheds, and Water Quality Goal Implementation Teams (GITs) want to better understand key stressors or "risk factors" impacting stream health and aquatic habitats beyond nutrient and sediment impairments. Online tools can be utilized to better communicate watershed and aquatic habitat health, vulnerability, and resilience to decisionmakers and other stakeholders. For example, The Planning for Change Module of the Watershed Data Dashboard and Chesapeake Open Data Portal can be further developed to better visualize and communicate:

- Which streams, watersheds, and vital lands are most vulnerable and resilient to future impacts from land use and climate change?
- How do landscape patterns and hydrologic connectivity affect the impact of historic and future land use change on stream and aquatic health?

The CHWA will support a number of strategies and actions outlined in the Chesapeake Bay Program's recently updated Management Strategy for the Healthy Watersheds Outcome (CBP 2020a) and 2020-2021 Logic and Action Plan (CBP 2020b). The CHWA will provide information in support of federal and state efforts in assessing watershed status and characterizing watershed vulnerability to future risks. The geospatial data provided by the CHWA will be useful in conveying information to local governments and other decision makers for the protection of healthy watersheds. In addition, the CHWA will assist in understanding and addressing specific healthy watershed vulnerabilities.

CHWA data can help managers prioritize healthy watersheds in terms of risk and the need for additional protective measures, using available information on their current condition, existing protections and relative vulnerability. The landscape metrics in the CHWA, along with other, direct measures of stream and watershed health, can provide "signals of change" to identify locations where ecological health is threatened and where appropriate steps can be taken to help prevent further degradation.

The CHWA can contribute to watershed assessment and protection efforts within an overall management framework (CBP 2020a) that includes:

1) maps of state-identified healthy watersheds,
2) the best available assessments of the vulnerability of those watersheds,
3) the most current information on protections that are in place to ensure the long-term sustainability of watershed health, and
4) analyses on land use change or other landscape characteristics to track the health and viability of the watersheds over time.

As outlined in the Management Strategy (CBP 2020a), the CHWA can support the Healthy Watersheds GIT in its interactions with other Bay Program efforts, including the following:

- Coordination with the Scientific and Technical Assessment and Reporting Team in developing approaches for identifying, assessing, and monitoring the condition of existing healthy watersheds.
- Collaborate with the Sustainable Fisheries Goal Implementation Team and Fish Habitat Action Team in integrating CHWA findings with the regional Fish Habitat Assessments being developed for non-tidal and tidal waters that will inform habitat restoration and conservation efforts. The groups should investigate opportunities to integrate online visualization of the CHWA and the ongoing work related to the Fish Habitat Assessment to better understand landscape and instream stressors to both healthy watersheds and fish habitat.
- Coordination with the Habitat Goal Implementation Team and the Stream Health Workgroup, as those groups apply Bay-wide stream assessment tools (such as the Chesapeake basin-wide index of biotic integrity, Chessie BIBI) to track stream health and compile additional research findings about stressors affecting stream and watershed health in the Bay watershed.
- Work with the Enhancing Partnering, Leadership and Management Goal Implementation Team and Local Leadership Workgroup to engage with local organizations on conservation measures that support and maintain watershed health.
- Integrating with the Climate Resiliency workgroup to better understand the vulnerability and resilience of healthy watersheds to the impacts of climate change.
- Help with communication efforts to convey information about healthy watersheds to local stakeholders.

State-level healthy watershed program managers and state agencies can use the information from the CHWA and other sources pro-actively to implement improvements to policies, incentives, plans and tools that will reduce losses of natural lands and other stressors that threaten watershed health. For example, Maryland Department of Environment can use CHWA data to track conditions in its Tier II waters to identify and evaluate potential threats to watershed health and to adapt management strategies to best protect and maintain these high-quality waters. Similarly, local agencies, land trusts, and other conservation organizations can use data to guide watershed protection. The CHWA provides a flexible framework that can be updated periodically and can be augmented with new or more specific local data.

Because the CHWA provides data on all catchments, not just those within areas currently designated as healthy watersheds, it can also potentially be used to screen watersheds to identify healthy ecosystems not currently protected as healthy watersheds. CHWA data can help to better understand watershed health, vulnerability, and resilience of catchments across the Bay watershed and could potentially be used to identify watersheds that are stressed.

Other potential management applications of the CHWA include:

- Examining/quantifying stressors affecting stream health (not just in healthy watersheds)
- Assessing landscape factors affecting fish habitat in non-tidal and tidal watersheds, in coordination with CBP's Fish Habitat Assessments
- Identifying areas of brook trout populations susceptible to climate shifts
- Engagement with local governments to inform land use decisions
- Supporting land trusts and other organizations managing protected lands
- Source water protection (drinking water)

- Examining spatial patterns of population density and land use change in association with watershed health

The geodatabase produced for this assessment provides a framework for data management and additional analyses, with data for the various metrics organized by NHDPlus Catchment (with identifier "COMID"). The structure is simple, presenting the CHWA watershed health metrics organized within the six topic areas, vulnerability metrics within the four topic areas, values for sub-indices, and the watershed health index. In addition, the geodatabase includes attributes for each catchment such as state, HUC, and whether within state-identified healthy watersheds to assist the user in sorting data for display and analysis. The geodatabase provides a straightforward display of catchment data, readily integrated with other user data, and the ability to conduct queries by location, score, or other factors defined by the geodatabase user.

Data will be made available through the CBP online platform for a variety of users including state and local governments and watershed groups. Further development of data analysis and visualization components through a user-friendly interface would help users in exploring and accessing data to address new management questions at a variety of scales, from regional to statewide to local. Statistics such as rankings and percentiles (either Baywide or by state) or comparisons of local catchment scores to regional distributions can be developed and displayed. Data visualization functions can be built into a web-based mapping application, allowing users online access to view maps, graphs, and other data summaries. It is recommended that the Healthy Watersheds GIT work with others at CBP to share information and develop on online platform that meets multiple end user needs.

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Appendix A

Members of the Maintain Healthy Watersheds Goal Implementation Team and Chesapeake Bay Healthy Watersheds Assessment Core Group

Maintain Healthy Watersheds Goal Implementation Team (July 2019)

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Appendix B

Meeting Notes and Presentations

Appendix C

List of Metrics and Source Data

Sub-Index	Watershed Condition Metrics					
Sub-Index	**Metrics (NHD+ Catchments)**	**Notes / Data Source**	**Notes / Future Data Availability**	**Field Name**	**Metric Description**	**Data Source Details**
Landscape Condition	% Natural Land Cover in Watershed	CBP high-resolution land use/land cover data, 2013	CBP high-resolution land use/land cover data - future iterations (e.g., 2017, 2019, 2021, 2023 updates)	PctNaturalLandWs	Percent Forest + Percent Wetland = Percent Natural land in watershed. From Chesapeake Bay Program High Resolution Land Use / Land Cover data, 2013.	Chesapeake Bay Program LULC 10m grids (combining WLF, WLO, WLT, and FOR). Data provided by Peter Claggett, USGS Chesapeake Bay Program. Calculated zonal statistics by catchment and integrated across the entire upstream watershed.
	% Forest in Riparian Zone in Watershed	CBP high-resolution land use/land cover data, 2013	CBP high-resolution land use/land cover data - future iterations (e.g., 2017, 2019, 2021, 2023 updates)	PctForestRZWs	Percent Forest in riparian zone within watershed	Chesapeake Bay Program LULC 10m grids; data provided by Peter Claggett, USGS Chesapeake Bay Program. Applied 100-m riparian buffer. Calculated statistics by catchment and integrated across entire upstream riparian area.
	Population Density in Watershed	StreamCat, 2010 census data	StreamCat - future census data (2020 and beyond)	PopDensityWs	Mean population density (people/square km) within watershed	Mean of all popden2010 values within the upstream watershed (Ws). Raster of population density derived from an ESRI shapefile of block group-level 2010 US Census data. Density was calculated as block group population / block group area. This shapefile was then converted to 90m x 90m resolution raster. 2014
	Housing Unit Density in Watershed	StreamCat, 2010 data	StreamCat updates	HousingUnitDensWs	Mean housing unit density (housing units/square km) within watershed	Mean of all huden values within the upstream watershed. Raster of population density derived from an ESRI shapefile of block group-level 2010 US Census data. Density was calculated as block group population / block group area. This shapefile was then converted to 90m x 90m resolution raster. 2014
	Mining Density in Watershed	StreamCat	StreamCat updates	MineDensityWs	Density of mine sites within watershed (mines/square km)	Density of georeferenced mine sites (mines.shp) within the upstream watershed (Ws). Shapefile of georeferenced locations (points) of mines and mineral plants in the USA that were considered active in 2003.
	% Managed Turf Grass in Hydrologically Connected Zone (HCZ) in Watershed	CBP high-resolution land use/land cover data, 2013	CBP high-resolution land use/land cover data - future iterations (e.g., 2017, 2019, 2021, 2023 updates)	MngdTurfHCZWs	Percent Managed Vegetation in hydrologically connected zone in watershed	Chesapeake Bay Program LULC 10m grids; data provided by Peter Claggett, USGS Chesapeake Bay Program. Applied HCZ mask proved by U.S. EPA; calculated statistics by catchment and integrated across entire upstream riparian area.
	Historic Forest Loss in Watershed	LANDFIRE. Reflects forest loss from European colonization to 2010. 2014 data.	LANDFIRE Remap for Northeastern US, scheduled for release January - June 2020	PctForestLoss	Percent of forest cover loss relative to pre-development forest cover.	Source data were from the Landscape Fire and Resource Management Planning Tools (LANDFIRE) program (http://www.landfire.gov/viewer/). LANDFIRE classifies vegetative cover across the US at 30-meter resolution. Used LANDFIRE Environment Site Potential (ESP) and Existing Vegetation Type (EVT) to get delta (change in forest cover) and then calculated zonal stats for NHDPlus v2.1 catchments. 2014
Hydrology	% Agriculture on Hydric Soil in Watershed	EPA EnviroAtlas	EPA EnviroAtlas - future updates	PctAgOnHydricSoilWs	Percent Agriculture on Hydric soils in watershed	Percentage of land managed for agriculture that has hydric soils within each subwatershed (12-digit HUC) for 2006-2010. This includes all land dedicated to the production of crops, but excludes land managed for pasture.

Sub-Index	Watershed Condition Metrics					
Sub-Index	Metrics (NHD+ Catchments)	Notes / Data Source	Notes / Future Data Availability	Field Name	Metric Description	Data Source Details
	% Forest in Watershed	CBP high-resolution land use/land cover data, 2013	CBP high-resolution land use/land cover data - future iterations (e.g., 2017, 2019, 2021, 2023 updates)	PctForestWs	Percent forest in watershed	Used data provided by Peter Claggett, USGS Chesapeake Bay Program. CBP high-resolution land use/land cover data, 2013%. Calculated zonal stats.
	% Forest Remaining in Watershed	LANDFIRE, 2014 data.	LANDFIRE Remap for Northeastern US, scheduled for release January - June 2020	PctForestLoss, PctForestRemaining	Percent of forest cover remaining relative to pre-development forest cover	Source data were from the Landscape Fire and Resource Management Planning Tools (LANDFIRE) program (http://www.landfire.gov/viewer/). LANDFIRE classifies vegetative cover across the US at 30-meter resolution. Used LANDFIRE Environment Site Potential (ESP) and Existing Vegetation Type (EVT) to get delta (change in forest cover) and then calculated zonal stats for NHDPlus v2.1 catchments. 2014
	% Wetlands Remaining in Watershed	LANDFIRE, 2014 data.	LANDFIRE Remap for Northeastern US, scheduled for release January - June 2020	PctWetlandLoss, PctWetlandRemaining	Percent of wetland cover remaining relative to pre-development forest cover	Source data were from the Landscape Fire and Resource Management Planning Tools (LANDFIRE) program (http://www.landfire.gov/viewer/). LANDFIRE classifies vegetative cover across the US at 30-meter resolution. Used LANDFIRE Environment Site Potential (ESP) and Existing Vegetation Type (EVT) to get delta (change in forest cover) and then calculated zonal stats for NHDPlus v2.1 catchments. 2014
	% Imperviousness in Watershed	CBP high-resolution land use/land cover data, 2013	CBP high-resolution land use/land cover data - future iterations (e.g., 2017, 2019, 2021, 2023 updates)	PctImpWs	Percent impervious cover in watershed	Used data provided by Peter Claggett, USGS Chesapeake Bay Program. CBP high-resolution land use/land cover data, 2013. Calculated zonal stats.
	Density Road-Stream Crossings in Watershed	StreamCat, 2010 data	StreamCat updates	RoadStreamXingDens	Density of roads-stream intersections (2010 Census Tiger Lines-NHD stream lines) within watershed (crossings/square km)	Sum of all rdstrcrs values within the upstream watershed (Ws) divided by the area of the Ws. A binary raster of road and stream intersections, where 1 = intersection and 0 = no intersection. This raster was provided by James Falcone of the USGS.
	% Wetlands in Watershed	CBP high-resolution land use/land cover data, 2013	CBP high-resolution land use/land cover data - future iterations (e.g., 2017, 2019, 2021, 2023 updates)	PctWetlandsWs	Percent wetland in watershed	Used data provided by Peter Claggett, USGS Chesapeake Bay Program. CBP high-resolution land use/land cover data, 2013. Calculated zonal stats.
Geomorphology	Dam Density in Watershed	StreamCat, 2013 data	StreamCat updates	DamDensityWs	Density of georeferenced dams within watershed (dams/ square km)	Density of georeferenced dams within the upstream watershed (Ws). Shapefile of georeferenced dam locations (points) and associated dam and reservoir characteristics (where available), such as dam height, reservoir volume, and year constructed from the National Inventory of Dams.
	Road Density in Riparian Zone, in Watershed	StreamCat	StreamCat updates	RoadDensityRZWs	Density of roads (2010 Census Tiger Lines) within watershed and within a 100-m buffer of NHD stream lines (km/square km)	Mean of all rddens values within the upstream watershed (Ws). Raster of road density calculated using 2010 Census Tiger Line files and the ArcGIS Line Density tool.

Sub-Index	Watershed Condition Metrics					
Sub-Index	Metrics (NHD+ Catchments)	Notes / Data Source	Notes / Future Data Availability	Field Name	Metric Description	Data Source Details
	% Impervious in Riparian Zone in Watershed	CBP high-resolution land use/land cover data, 2013	CBP high-resolution land use/land cover data - future iterations (e.g., 2017, 2019, 2021, 2023 updates)	PctImpRZWs	Percent impervious in riparian zone within watershed	Used data provided by Peter Claggett, USGS Chesapeake Bay Program. CBP high-resolution land use/land cover data, 2013. Calculated zonal stats.
	Vulnerable Geology in Watershed	CBP	Geologic data, unlikely to change	PctVulnGeoWs	Percent Vulnerable Geology in watershed. Geology makes groundwater (and therefore streams) in some areas especially vulnerable to high nitrogen inputs. These include carbonate and coarse coastal plain geology.	Data provided by Emily Trentacoste, EPA Chesapeake Bay Program. Geology shapefile from USGS called "Gen_Lithology"with GENGEOL attribute; values of "carbonate" and "coarse coastal plain" are considered the vulnerable areas. 2018
Habitat	National Fish Habitat Partnership (NFHP) Habitat Condition Index in Catchment	USGS, 2015 data	Updates to national fish habitat indicator and new regional fish habitat assessment under development for CBP	HabConditionIndexLC	Local catchment Habitat Condition Index (HCI) score. From National Fish Habitat Partnership, national assessment.	Mean Habitat Condition Index (HCI) score for the catchment from the National Fish Habitat Partnership (NFHP) 2015 National Assessment. Scores range from 1 (high likelihood of aquatic habitat degradation) to 5 (low likelihood of aquatic habitat degradation) based on land use, population density, roads, dams, mines, and point-source pollution sites. Source data were NFHP 2015 National Assessment Local Catchment HCI scores. See http://ecosystems.usgs.gov/fishhabitat/nfhap_download.jsp and http://assessment.fishhabitat.org/ for more information on the NFHP National Assessment.
	Chesapeake Bay Conservation Habitats in Catchment	Landscope / Nature's Network Conservation Design for the Northeast	Updates to Landscope / Nature's Network Conservation Design for the Northeast	PctNatlConnectivity	Nature's Network Conservation Design depicts an interconnected network of lands and waters that, if protected, will support a diversity of fish, wildlife, and natural resources that the people of the Northeast and Mid-Atlantic region depend upon. Includes Core Habitat for Imperiled Species, Terrestrial Core-Connector Network, Grassland Bird Core Areas, Lotic Core Areas, and Lentic Core Areas.	From Nature's Network Conservation Design for the Northeast, available at http://naturesnetwork.org/data-tools/download-tables/. Conservation Design data are a simplified composite layer, available along with its components including Core Habitat for Imperiled Species, Terrestrial Core-Connector Network, Grassland Bird Core Areas, Lotic Core Areas, and Lentic Core Areas. Further information is available at the North American Landscape Conservation Cooperative: https://nalcc.databasin.org/datasets/3d670fad4c924e7ba2ae02f04a128256. 2018
Biological Condition	Outlet Aquatic Condition Score in Catchment	EPA Office of Research and Development, StreamCat-based model of NRSA biological condition, 2016	CBP / ICPRB Chessie BIBI	OutletAqCondnScore	Index of catchment integrity	StreamCat. EPA Office of Research and Development StreamCat-based model of NRSA biological condition; NHDPlus2 hydrography.

Sub-Index	Watershed Condition Metrics					
Sub-Index	Metrics (NHD+ Catchments)	Notes / Data Source	Notes / Future Data Availability	Field Name	Metric Description	Data Source Details
Water Quality	% of Stream Length Impaired in Catchment	EPA ATTAINS	Future versions of EPA ATTAINS and State data	Pct303dImpairedCat	Percent Impaired Streams in Local Catchment	Under Section 303(d) of the CWA, states, territories, and authorized tribes (referred to here as states) are required to develop lists of impaired waters. These are waters that are too polluted or otherwise degraded to meet the state water quality standards. The law requires that these jurisdictions establish priority rankings for waters on the lists and develop TMDLs for these waters. Note: the CWA Section 303(d) list of impaired waters does not contain impaired waters with an established TMDL, impaired waters for which other pollution control mechanisms are in place and expected to attain water quality standards, or waters impaired as a result of pollution. For more information, please see EPA's Integrated Reporting Guidance at: http://www.epa.gov/tmdl/integrated-reporting-guidance. 2015
	Estimated Nitrogen Load from SPARROW Model (lbs/acre/yr), in Watershed	CBP SPARROW model		SPARROWTN	-	Data provided by EPA Chesapeake Bay Program.
	Nitrogen, Phosphorus, and Sediment Load from Chesapeake Bay Model, by Sector (Developed Land, Agriculture, Wastewater, Septic, and CSO), in Watershed (13 separate metrics)	CBP Model (Phase 6)	Future CBP Model Estimates	CBPModAGN, CBPModAGP, CBPModAGS, CBPModCSON, CBPModCSOP, CBPModCSOS, CBPModDEVN, CBPModDEVP, CBPModDEVS, CBPModSEPN, CBPModWWN, CBPModWWP, CBPModWWS	Nitrogen, phosphorus, and sediment loads by sector. Only nitrogen load for septic.	Data provided by Peter Claggett, USGS Chesapeake Bay Program. From the Chesapeake Bay Program Phase 6 Watershed Model. 2019

Sub-Index	Watershed Vulnerability Metrics					
Sub-Index	**Metrics (NHD+ Catchments)**	**Notes / Data Source**	**Notes / Future Data Availability**	**Field Name**	**Metric Description**	**Data Source Details**
Land Use Change	% Increase in Development in Catchment	CBP model (Phase 6), 2050 projection, 2018 data set	Future updates to CBP model (e.g., 2017, 2019, 2021, 2023 updates)	FutureDev	Percent of catchment land projected to undergo development by 2050, according to CBP projections.	Data provided by Peter Claggett, USGS Chesapeake Bay Program. Year 2050 forecast data were provided by NHD catchment for the Current Zoning (cz2) baseline scenario. Data were provided as simplified table showing just the COMID and mean amount of forecasted development (acres) across 101 simulations for the scenario. Acres of forecasted development were used along with catchment (COMID) area to calculate percent of land projected to undergo future development.
	Recent Forest Loss in Watershed	StreamCat, Forest Loss 2000-2013 / Global Forest Change	Updates to StreamCat, Global Forest Change (e.g., 2017, 2019, 2021, 2023 updates)	AvgPctForestLossWs	Percent tree canopy cover loss between years 2000-2013, within the watershed (Ws).	StreamCat tree canopy data were derived from Global Forest Change project, University of Maryland - Department of Geographical Sciences. Hansen, M. C., P. V. Potapov, R. Moore, M. Hancher, S. A. Turubanova, A. Tyukavina, D. Thau, S. V. Stehman, S. J. Goetz, T. R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C. O. Justice, and J. R. G. Townshend. 2013. "High-Resolution Global Maps of 21st-Century Forest Cover Change." Science 342 (15 November): 850–53. Data available online from: http://earthenginepartners.appspot.com/science-2013-global-forest
	% Protected Lands in Watershed	CBP Protected Lands data, Dec. 2018	CBP and partner updates to protected lands data	PctProtLandsWs	Percent of catchment land protected	Protected Lands data provided December 2018 by Renee Thompson, USGS Chesapeake Bay Program. Includes compilation of protected lands data from: US Geological Survey, Gap Analysis Program (GAP), May 2016, Protected Areas Database of the United States (PADUS), version 1.4 Combined Feature Class (Fee and Easement); Maryland Department of Natural Resources; Maryland Department of Planning; Delaware Department of Natural Resources and Environmental Control (Division of Fish and Wildlife); Freshwater Institute (WV Protected Lands); PA Bureau of Farmland Preservation; PA Department of Conservation & Natural Resources; and VA Department of Conservation and Recreation.
Water Use	Agricultural Water Use in Catchment	EPA EnviroAtlas, 2015	Updates to USGS water use data	AgWaterUse	Daily agricultural water use in the HUC12 (million gallons per day). Agricultural water use includes surface and groundwater that is self-supplied by agricultural producers or supplied by water providers (governments, private companies, or other organizations). Catchments were assigned values from surrounding HUC12.	Water used in a HUC12 may originate from within or outside the HUC12. Calculated by downscaling county water use estimates for 2005 reported by US Geological Survey ("Estimated Use of Water in the United States County-Level Data for 2005") using the 2006 National Land Cover Database (2006 NLCD) Land Cover dataset, the 2010 Cropland Data Layer, and a custom geospatial dataset of irrigated area locations. Counties with zero reported water use were assigned a state-level average value to address issues with water use reporting. This indicator was calculated for EPA EnviroAtlas. Detailed information on source data and calculation methods can be found at: https://edg.epa.gov/metadata/catalog/search/resource/details.page?uuid=%7BD5113083-CFCD-48EC-BC24-0ADA5B9BDDB7%7D

Sub-Index	Watershed Vulnerability Metrics					
Sub-Index	Metrics (NHD+ Catchments)	Notes / Data Source	Notes / Future Data Availability	Field Name	Metric Description	Data Source Details
	Domestic Water Use in Catchment	EPA EnviroAtlas, 2015	Updates to USGS water use data	DomesticWaterUse	Daily domestic water use in the HUC12 (million gallons per day). Domestic water use includes indoor and outdoor household uses, such as drinking, bathing, cleaning, landscaping, and pools. Domestic water can include surface or groundwater that is self-supplied by households or publicly-supplied.	EPA EnviroAtlas "Domestic Water Demand by 12-Digit HUC for the Conterminous United States" dataset. December 15, 2015 version. Water used in a HUC12 may originate from within or outside the HUC12. Calculated by downscaling county water use estimates for 2005 reported by US Geological Survey ("Estimated Use of Water in the United States County-Level Data for 2005") using the 2006 National Land Cover Database (2006 NLCD) Land Cover dataset and 2010 US Census population estimates from the US Census Bureau. This indicator was calculated for EPA EnviroAtlas. Additional information on source data and calculation methods can be found at: https://edg.epa.gov/metadata/catalog/search/resource/details.page?uuid=%7BC6DBEBAB-03EF-43C8-8DCA-8D2845E06A96%7D
	Industrial Water Use in Catchment	EPA EnviroAtlas, 2015	Updates to USGS water use data	IndustrialWaterUse	Daily industrial water use in the HUC12 (million gallons per day). Industrial water use includes water used for chemical, food, paper, wood, and metal production. Only includes self-supplied surface water or groundwater by private wells or reservoirs. Industrial water supplied by public water utilities is not counted.	EPA EnviroAtlas "Industrial Water Use by 12-Digit HUC for the Conterminous United States" dataset. May 7, 2015 version. Water used in a HUC12 may originate from within or outside the HUC12. Calculated by downscaling county water use estimates for 2005 reported by US Geological Survey ("Estimated Use of Water in the United States County-Level Data for 2005") using a geospatial dataset on the location of industrial facilities as of 2009/10. Water use by industrial facilities in counties that were reported to have zero industrial water use in the USGS dataset was estimated from values for nearby facilities. This indicator was calculated for EPA EnviroAtlas. Additional information on source data and calculation methods can be found at: https://edg.epa.gov/metadata/catalog/search/resource/details.page?uuid=%7B4E58C04B-8A17-4B07-9EE4-1D9365D5B0D9%7D
Wildfire Risk	% Wildland Urban Interface in Watershed	University of Wisconsin - Madison SILVIS lab. Wildland Urban Interface, 2010 data, published 2017.	Updates to Wildland Urban Interface data, University of Wisconsin - Madison SILVIS lab. A 2020 version of the WUI data is planned using 2020 census data, expected to be ready by 2021. Future versions are likely using decadal census data. Also, SILVIS currently in the process of generating future decadal WUI projection datasets for	WildfireRiskUrbInterface	The wildland-urban interface (WUI) is the area where houses meet or intermingle with undeveloped wildland vegetation, making the WUI a focal area for human-environment conflicts such as wildland fires, habitat fragmentation, invasive species, and biodiversity decline. WUI 2010 data were used, including interface and intermix categories.	Wildland Urban Interface data from Univ. of Wisconsin - Madison SILVIS lab, http://silvis.forest.wisc.edu/data/wui-change/ Data developers integrated U.S. Census and USGS National Land Cover Data to map the Federal Register definition of WUI (Federal Register 66:751, 2001) for the conterminous United States from 1990-2010. Reference: Radeloff, Volker C.; Helmers, David P.; Kramer, H. Anu; Mockrin, Miranda H.; Alexandre, Patricia M.; Bar Massada, Avi; Butsic, Van; Hawbaker, Todd J.; Martinuzzi, Sebastián; Syphard, Alexandra D.; Stewart, Susan I. 2017. The 1990-2010 wildland-urban interface of the conterminous United States - geospatial data. 2nd Edition. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2015-0012-2. Credit to the USDA Forest Service Northern Research Station.

Sub-Index	Watershed Vulnerability Metrics					
Sub-Index	**Metrics (NHD+ Catchments)**	**Notes / Data Source**	**Notes / Future Data Availability**	**Field Name**	**Metric Description**	**Data Source Details**
			2020-2070 using econometric models that predict where housing growth will occur across the U.S. over that time frame. Projection data may be ready by end of 2019.			
Climate Change	Change in Probability of Brook Trout Occurrence, Current Conditions v. Future Conditions (plus 6 degrees C) in Catchment	North Atlantic Landscape Conservation Cooperative (NALCC), Nature's Network, USGS Conte Lab, 2017	New/updated research on brook trout vulnerability	Brook_Trout_Occur_6CTempChang, Brook_Trout_Occur_Current	Brook Trout probability of occurrence is intended to provide predictions of occupancy (probability of presence) under current environmental conditions and for future increases in stream temperature. Change in brook trout probability of occurrence was calculated as the difference between probability under current condition vs. the plus 6 degrees C scenario.	Brook Trout probability of occurrence was developed by the Conte Lab for the Northeast and Mid-Atlantic region from Virginia to Maine. The dataset provides predictions under current environmental conditions and for future increases in stream temperature. Data are available for four scenarios: current condition, plus 2 degrees C, plus 4 degrees C, and plus 6 degrees C. Data and information are available through the North Atlantic Landscape Conservation Cooperative at: https://nalcc.databasin.org/datasets/7f3aaf6f9c59423391eb5a1526f28beb For further information see http://conte-ecology.github.io/Northeast_Bkt_Occupancy/ Reference: Benjamin Letcher (Principal Investigator), North Atlantic Landscape Conservation Cooperative (administrator), 2017-06-22 (creation), 2017-10-20 (lastUpdate), 2017-05 (Publication), Brook Trout Probability of Occurrence, Northeast U.S. https://www.sciencebase.gov/arcgis/rest/services/Catalog/594be372e4b062508e385070/MapServer/
	Climate Stress indicator in Catchment	North Atlantic Landscape Conservation Cooperative (NALCC), Nature's Network, 2017	New/updated research on climate stress	ClimateStress	The Climate Stress Metric is one of a suite of products from the Nature's Network project (naturesnetwork.org). Nature's Network is a collaborative effort to identify shared priorities for conservation in the Northeast, considering the value of fish and wildlife species and the natural areas they inhabit. This dataset represents a measure of the estimated magnitude of climate stress that may be exerted on habitats (ecosystem types) in 2080, on a scale of 30 m^2 cells. Cells where 2080 climate conditions depart substantially from conditions where the underlying ecosystem type currently occurs (the ecosystem's	Data available from https://nalcc.databasin.org/datasets/d207f70858fa403397c631433c2ad57d North Atlantic Landscape Conservation Cooperative (funder), Kevin McGarigal (Principal Investigator), 2017-06-22 (creation), 2017-10-20 (lastUpdate), 2017-03-17 (Publication), Climate Stress Metric, Version 3.0, Northeast U.S. https://www.sciencebase.gov/arcgis/rest/services/Catalog/594c1cc0e4b062508e3854c8/MapServer/

Sub-Index	Watershed Vulnerability Metrics					
Sub-Index	**Metrics (NHD+ Catchments)**	**Notes / Data Source**	**Notes / Future Data Availability**	**Field Name**	**Metric Description**	**Data Source Details**
					"climate niche") are considered to be stressed. Cells where the projected 2080 climate conditions are not substantially different from the current climate niche in the Northeast region are considered to be under low climate stress. Areas with low or zero climate stress may be candidates to function as climate refugia; these are places where ecosystems and associated species can persist relatively longer, compared to typical locations where the ecosystems currently occur.	

Appendix D

Example Descriptive Statistics for Catchments at the Outlet of State-Identified Healthy Watersheds

*Table D-1. Example descriptive statistics for catchments at the outlet of state-identified healthy watersheds. Values include minimum (Min), mean, maximum (Max), standard deviation (SD), and percentiles (5th to 95th percentile). * indicates values normalized.*

Sub-Index	Metric	Min	Mean	Max	SD	Percentile						
						q05	q15	q25	q50	q75	q85	q95
Watershed Health Metrics												
Landscape Condition	% Natural Land Cover in Watershed	0.0122	0.666	1	0.239	0.225	0.377	0.506	0.703	0.871	0.925	0.969
	% Forest in Riparian Zone in Watershed	0.22	0.88	0.988	0.0717	0.746	0.818	0.848	0.891	0.929	0.948	0.969
	Population Density in Watershed (people/km2)	0.85	66.9	2190	181	2.85	7.01	10.6	20.7	46.7	82.6	225
	Housing Unit Density in Watershed (housing units/km2)	0.096	26.4	962	68.1	2.63	3.87	5.32	9.54	18.5	31.4	91.7
	Mining Density in Watershed (sites/km2)	0	0.00115	0.168	0.0083	0	0	0	0	0	0	0.00372
	% Managed Turf Grass in Hydrologically Connected Zone (HCZ) in Watershed	0	0.183	0.888	0.199	0	0.00138	0.0177	0.113	0.285	0.412	0.593
	Historic Forest Loss in Watershed (%)	0	0.295	0.98	0.263	0	0	0.0484	0.248	0.458	0.615	0.797
Hydrology	% Agriculture on Hydric Soil in Watershed	0	0.0141	0.342	0.0357	0	0	0	0.00223	0.0118	0.0197	0.0627
	% Forest in Watershed	0.0122	0.636	0.995	0.248	0.161	0.326	0.465	0.679	0.841	0.899	0.955
	% Forest Remaining in Watershed	0.02	0.705	1	0.263	0.203	0.385	0.542	0.752	0.952	1	1
	% Wetlands Remaining in Watershed	0	0.16	1	0.237	0	0	0	0.0417	0.229	0.363	0.69
	% Impervious in Watershed	0	0.0332	0.498	0.0503	0.0024	0.0064	0.0104	0.0188	0.0347	0.0523	0.109
	Density Road-Stream Crossings in Watershed (crossing/km2)	0	0.517	3.5	0.409	0	0.169	0.247	0.45	0.671	0.825	1.22
	% Wetlands in Watershed	0	0.0304	0.401	0.0486	0.0000349	0.00196	0.00537	0.0144	0.0339	0.0524	0.119
Geomorphology	Dam Density in Watershed (dams/km2)	0	0.0106	0.755	0.0396	0	0	0	0	0	0.0185	0.0497

*Table D-1. Example descriptive statistics for catchments at the outlet of state-identified healthy watersheds. Values include minimum (Min), mean, maximum (Max), standard deviation (SD), and percentiles (5th to 95th percentile). * indicates values normalized.*

Sub-Index	Metric	Min	Mean	Max	SD	Percentile						
						q05	q15	q25	q50	q75	q85	q95
	% Vulnerable Geology in Watershed	0	0.159	1	0.326	0	0	0	0	0.0274	0.518	1
	Road Density in Riparian Zone, in Watershed (km/km2) *	0.652	0.923	1	0.0481	0.839	0.889	0.908	0.932	0.95	0.962	0.98
	% Impervious in Riparian Zone in Watershed	0	0.0313	0.476	0.0371	0	0.00468	0.0119	0.026	0.0389	0.0483	0.0855
Habitat	National Fish Habitat Partnership (NFHP) Habitat Condition Index in Catchment (Index Score)	0	3.91	5	1.16	0	3.4	3.6	4.2	4.6	4.8	5
Habitat	Chesapeake Bay Conservation Habitats in Catchment (%)	0	0.47	1	0.402	0	0.00173	0.0291	0.455	0.907	0.984	1
Biological Condition	Outlet Aquatic Condition Score in Catchment	0.379	0.694	0.957	0.131	0.474	0.552	0.6	0.693	0.79	0.844	0.918
Water Quality	% of Stream Length Impaired in Catchment	0	0.0862	1	0.277	0	0	0	0	0	0	0.997
Water Quality	Estimated Nitrogen Load from SPARROW Model (lbs/acre/yr), in Watershed *	0	0.0014	0.0609	0.00404	0.0000249	0.0000503	0.0000701	0.000214	0.00089	0.00186	0.00765
Water Quality	N Load from Chesapeake Bay Watershed Model, CSO (millions lbs/yr) *	0	0.00146	0.252	0.0132	0	0	0	0	0	0	0.00181
Water Quality	P Load from Chesapeake Bay Watershed Model, CSO (millions lbs/yr) *	0	0.000858	0.142	0.00745	0	0	0	0	0	0	0.00113
Water Quality	Sediment Load from Chesapeake Bay Watershed Model, CSO (millions lbs/yr) *	0	0.00141	0.24	0.0126	0	0	0	0	0	0.000000138	0.00173

*Table D-1. Example descriptive statistics for catchments at the outlet of state-identified healthy watersheds. Values include minimum (Min), mean, maximum (Max), standard deviation (SD), and percentiles (5th to 95th percentile). * indicates values normalized.*

Sub-Index	Metric	Min	Mean	Max	SD	Percentile						
						q05	q15	q25	q50	q75	q85	q95
	N Load from Chesapeake Bay Watershed Model, Developed Land (millions lbs/yr) *	8.02E-08	0.00175	0.0701	0.00515	0.0000382	0.0000872	0.000141	0.000443	0.00128	0.00228	0.00618
	P Load from Chesapeake Bay Watershed Model, Developed Land (millions lbs/yr) *	0.000000126	0.00241	0.117	0.00811	0.0000391	0.0000961	0.000169	0.000554	0.00165	0.0031	0.008
	Sediment Load from Chesapeake Bay Watershed Model, Developed Land (millions lbs/yr) *	0.000000127	0.00175	0.0932	0.00588	0.0000325	0.0000689	0.000114	0.000341	0.00132	0.00232	0.00692
	N Load from Chesapeake Bay Watershed Model, Agriculture (millions lbs/yr) *	5.09E-11	0.00142	0.0796	0.00489	0.00000794	0.0000293	0.000054	0.000244	0.00107	0.00193	0.00567
	P Load from Chesapeake Bay Watershed Model, Agriculture (millions lbs/yr) *	4.05E-10	0.00167	0.128	0.00685	0.0000104	0.0000325	0.0000691	0.000282	0.00113	0.00218	0.00616
	Sediment Load from Chesapeake Bay Watershed Model, Agriculture (millions lbs/yr) *	2.24E-10	0.00265	0.31	0.0156	0.0000128	0.0000452	0.0000842	0.000301	0.00117	0.00263	0.00948
	N Load from Chesapeake Bay Watershed Model, Septic (millions lbs/yr) *	7.17E-08	0.00255	0.108	0.00856	0.0000173	0.0000581	0.000133	0.000539	0.00164	0.0028	0.00926
	N Load from Chesapeake Bay Watershed Model, Wastewater (millions lbs/yr) *	0	0.00109	0.141	0.0071	0	0.000000211	0.00000351	0.0000432	0.000275	0.000664	0.00329
	P Load from Chesapeake Bay Watershed Model, Wastewater (millions lbs/yr) *	0	0.00104	0.0979	0.00529	0	0	0.00000425	0.0000774	0.00039	0.000764	0.00348

*Table D-1. Example descriptive statistics for catchments at the outlet of state-identified healthy watersheds. Values include minimum (Min), mean, maximum (Max), standard deviation (SD), and percentiles (5th to 95th percentile). * indicates values normalized.*

Sub-Index	Metric	Min	Mean	Max	SD	Percentile						
						q05	q15	q25	q50	q75	q85	q95
	Sediment Load from Chesapeake Bay Watershed Model, Wastewater (millions lbs/yr) *	0	0.000795	0.0643	0.00418	0	0.000000438	0.00000215	0.000036	0.000199	0.000478	0.00262
Vulnerability Metrics												
Land Use Change	% Increase in Development in Catchment *	0	0.015	0.483	0.0419	0	0	0	0	0.00801	0.0235	0.0816
	Recent Forest Loss in Watershed (%) *	0	0.201	1	0.29	0.00251	0.0134	0.0254	0.0666	0.215	0.437	1
	% Protected Lands in Watershed	0	0.302	1	0.314	0	0.000141	0.0253	0.193	0.511	0.728	0.952
Water Use	Agricultural Water Use in Catchment (million gallons/day)	0	0.982	80.6	3.93	0	0.02	0.04	0.17	0.44	0.67	3.55
	Domestic Water Use in Catchment (million gallons/day)	0.27	10.8	107	17.4	0.911	2.25	2.43	4.06	11.2	17.2	36.1
	Industrial Water Use in Catchment (million gallons/day)	0	2.01	47.2	5.46	0	0	0	0.14	1.83	3.72	5.12
Wildfire Risk	% Wildland Urban Interface in Watershed	0	0.00177	0.0774	0.00551	0	0.000088	0.000117	0.00032	0.00118	0.00234	0.00738
Climate Change	Change in Probability of Brook Trout Occurrence, Current Conditions v. Future Conditions (plus 6 degrees C) (Index)* in Catchment	0	0.394	1	0.376	0	0	0.0134	0.282	0.799	0.9	0.965
	Climate Stress indicator (Index) in Catchment	0	0.443	1	0.3	0.0506	0.136	0.211	0.388	0.598	0.925	1