November 2015

Tennessee Integrated Assessment of Watershed Health

A Report on the Status and Vulnerability of Watershed Health in Tennessee

Prepared for—

US Environmental Protection Agency Healthy Watersheds Program

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The information presented in this document is intended to support screening-level assessments of watershed protection priorities and is based on modeled and aggregated data that may have been collected or generated for other purposes. Results should be considered in that context and do not supplant site-specific evidence of watershed health.

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Acronyms and Abbreviations

BRT	Boosted Regression Tree
CMIP5	Coupled Model Intercomparison Project 5
COMID	common identifier
CRAN	Comprehensive R Archive Network
EPA	U.S. Environmental Protection Agency
GCN	greatest conservation need
GFDL CM3	NOAA Geophysical Fluid Dynamics Laboratory Coupled Physical Model
GIS	geographical information system
GOF	goodness of fit
HAZ	hydrologically active zone
HUC	USGS hydrologic unit code
HWP	EPA Healthy Watersheds Program
IBI	Index of Biological Integrity
IQR	interquartile range
LCC	Appalachian Landscape Conservation Cooperative
MOU	Memorandum of Understanding
NHDPlus	National Hydrography Dataset Plus
NID	National Inventory of Dams
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
OSI	Open Space Institute
Q1	first quartile
Q3	third quartile
RBP	Rapid Bioassessment Protocol
SC	specific conductance
SE-GAP	Southeast Gap Analysis Program
SFC	streamflow characteristic
SSURGO	Soil Survey Geographic Database
STORET	EPA's Storage and Retrieval Data Warehouse
TDEC	Tennessee Department of Environment & Conservation
THWI	Tennessee Healthy Watershed Initiative
TMI	Tennessee Macroinvertebrate Index
TN	total nitrogen
TN SWAP	Tennessee State Wildlife Action Plan
TNC	The Nature Conservancy

TP	total phosphorus
TVA	Tennessee Valley Authority
TWRA	Tennessee Wildlife Resources Agency
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WQ	water quality

Executive Summary

Tennessee's water resources are rich and varied, from the native brook trout streams of the Blue Ridge Mountains in the east to the wide alluvial plains of the Mississippi River to the west. These resources are a valuable asset to Tennessee and the protection and preservation of healthy waters in the state provide recreational opportunities, clean drinking water, and other ecosystem services. This study was conducted by the U.S. Environmental Protection Agency (EPA) in partnership with the Tennessee Healthy Watershed Initiative (THWI). The THWI is a partnership among the Tennessee Department of Environment and Conservation, the Tennessee Valley Authority, the Tennessee Chapter of The Nature Conservancy, and the West Tennessee River Basin Authority working together to maintain and protect water resources across the state by promoting communication, collaboration, and thoughtful planning. The results from this study will be used to support the efforts of THWI and others working to protect and restore the state's aquatic ecosystems.

The main goal of this *Tennessee Integrated Assessment of Watershed Health* (henceforth referred to as the Assessment) is to identify healthy watersheds and characterize relative watershed health across the state to guide future protection and restoration activities. A healthy watershed has the structure and function in place to support healthy aquatic ecosystems. Key components of a healthy watershed include:

- intact and functioning headwater streams, floodplains, riparian corridors, biotic refugia, instream habitat, and biotic communities;
- a predominance of natural vegetation in the landscape; and
- expected hydrology, sediment transport, fluvial geomorphology, and disturbance regimes for its location.

This report presents the methods and results of the Assessment and outlines proposed uses of the results. The Assessment applied a *system's approach* that views watersheds and their aquatic ecosystems as dynamic and interconnected systems in the landscape connected by surface and ground water and natural vegetative corridors. Watershed health was quantified at the stream catchment scale from existing geospatial datasets and from predictive models derived from data collected as part of existing monitoring programs. This information was synthesized into several sub-indices that measured aquatic ecological health and were combined into a comprehensive index of watershed health. The potential for future degradation of watershed health was reported as a watershed vulnerability index.

An important facet of the Assessment is that it leverages existing efforts to analyze the characteristics of watersheds and the aquatic ecosystems within them. Several agencies and organizations assess various aspects of watershed health at statewide and regional scales. This project has used disparate datasets to provide a more complete picture of watershed health across the state.

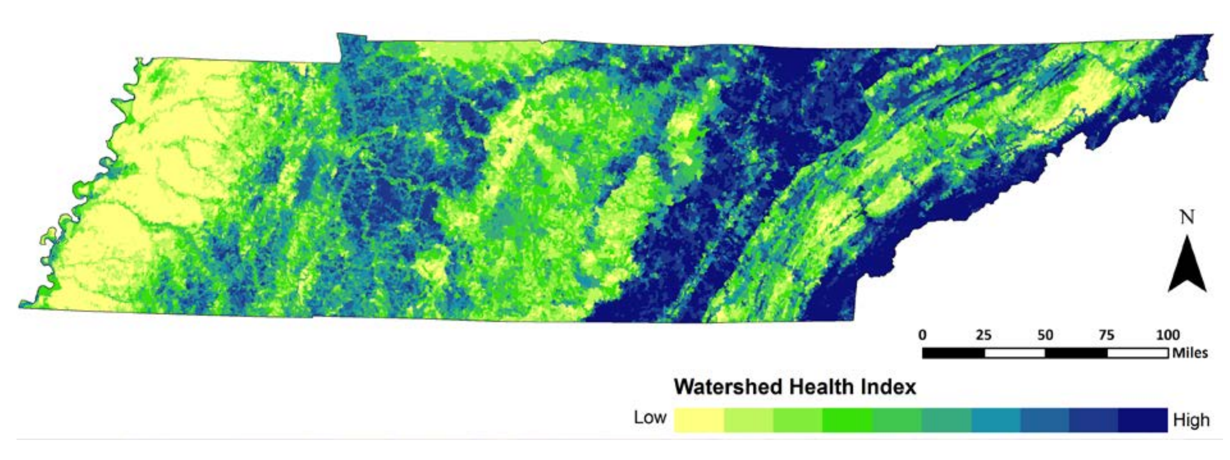
One output of the Assessment is a database of watershed health scoring metrics and catchment-based information that can be used by THWI and other groups involved in watershed protection and restoration planning. The database is intended to help identify healthy watersheds that are priorities for local-scale assessment of protection opportunities. Several immediate uses of the database include outreach and communication and prioritization of restoration and protection areas.

A second output is the integrated assessment framework developed by EPA and the THWI Technical Team. This framework reflects our understanding of the interconnected nature of the physical, chemical, and biological conditions of aquatic ecosystems; the significant effects of landscape- and watershed-scale processes on aquatic ecosystem health; and the need to view water bodies as connected parts within a larger system rather than as isolated units. The framework serves as a common platform for the multistate agencies and organizations tasked with the protection and restoration of Tennessee's water resources to collaborate and apply a unified approach rather than undertake disjointed efforts. Over the long term, the existing framework can be updated as data gaps are filled and improved assessment methodologies are identified.

The Assessment identifies relative health of watersheds across the entire state of Tennessee at the catchment (approximately 1 square mile) level, based on metrics characterizing Landscape Condition, Geomorphic Condition, Hydrologic Condition, Water Quality, Habitat Condition, and Biological Condition. The scores from these six sub-indices were combined to create a Watershed Health Index. The Vulnerability Index calculated from metrics characterizing potential threats to future watershed health including Land Use, Water Use, and Climate.

Results can be presented for each metric, sub-index, or Watershed Health or Vulnerability Index at multiple scales (i.e., catchment level or larger watersheds). **Figure ES-1** illustrates the Watershed Health Index at the catchment level. The highest scoring areas are in the Blue Ridge and Appalachian Mountains in eastern Tennessee and scattered throughout the Interior Plateau in the central part of the state. These areas are influenced by stable geomorphology, low deviation from natural streamflow, and relatively good water quality and habitat conditions able to support diverse biological communities.

Figure ES-1. Watershed Health Index for Tennessee.



1. Introduction

1.1 Purpose and Intended Use

In 1996, the Tennessee Department of Environment and Conservation (TDEC) adopted a watershed-based approach to monitoring and assessing their aquatic resources. This approach includes identifying and prioritizing water quality challenges in the watershed, developing increased public involvement, coordinating activities with other agencies, and measuring success through increased and more efficient monitoring and other data gathering. Traditionally, these watershed efforts have focused on restoring impaired streams, rivers, and lakes. Although some success has been achieved, many miles of stream and acres of lake remain degraded, and new impairments continue to be identified. It is not only costly to restore impaired water bodies, but also these water bodies are not able to provide the same ecological, social, and recreation services as healthy aquatic ecosystems. Together, these issues call for the expanded use of protection of healthy watersheds as a tool to preserve ecosystem services and prevent the need for costly restoration.

The main goal of this *Tennessee Integrated Assessment of Watershed Health* (henceforth referred to as the Assessment) was to characterize the relative health of watersheds in Tennessee to guide future protection and restoration activities in the system. The Assessment synthesizes disparate datasets to depict current landscape and aquatic ecosystem conditions throughout Tennessee. It is framed with the recognition that the biological, chemical, and physical processes are interrelated and fundamentally connected to the health of a water body and the maintenance of natural watershed processes. By integrating information on multiple ecological attributes at several spatial and temporal scales, this study provides a systems perspective on watershed health. This study was funded by the U.S. Environmental Protection Agency's (EPA's) Healthy Watersheds Program and was performed in conjunction with the Tennessee Healthy Watershed Initiative (THWI).

This report presents the methods, results, and intended applications of the Assessment. Readers are asked to consider the following points regarding the scope of the Assessment as they review methods and interpret results:

- The Assessment characterizes *relative* watershed health throughout Tennessee using a collection of metrics that focus on the natural attributes of a watershed and its freshwater ecosystems. No statement on the absolute condition of any watershed or water body is made (e.g., attainment of designated uses), and results do not reflect the influence of factors not considered for analysis.

- Data and information on relative watershed health are intended to support a screening-level assessment of protection priorities across broad geographic areas (e.g., statewide or within regional planning units). Assessment data should not supplant in-depth, site-specific evidence of protection priorities, and conclusions drawn for smaller-sized areas should be validated with site-specific information.

1.2 The Healthy Watersheds Program

EPA launched the Healthy Watersheds Program to support active protection of our nation's remaining healthy watersheds (USEPA, 2012). A healthy watershed is 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. Natural vegetative cover in the landscape, including the riparian zone, helps maintain the natural flow regime and fluctuations in water levels in lakes and wetlands. This, in turn, helps maintain natural geomorphic processes, such as sediment storage and deposition that form the basis of aquatic habitats. Connectivity of aquatic and riparian habitats in the longitudinal, lateral, vertical, and temporal dimensions helps ensure the flow of chemical and physical materials and movement of biota among habitats.

Learn More Online:

Visit the EPA Healthy Watersheds Program Web site to view background material and project reports: www2.epa.gov/hwp

EPA recommends using integrated assessments of watershed health to help states and others identify healthy waters and prioritize candidate waters for protection and restoration. Integrated assessments combine information on landscape condition, geomorphology, hydrology, habitat, water chemistry, and biological communities. The Assessment synthesizes disparate datasets to depict current landscape and aquatic ecosystem conditions throughout Tennessee. By combining multidisciplinary data from multiple spatial scales, integrated assessments reflect our understanding of the:

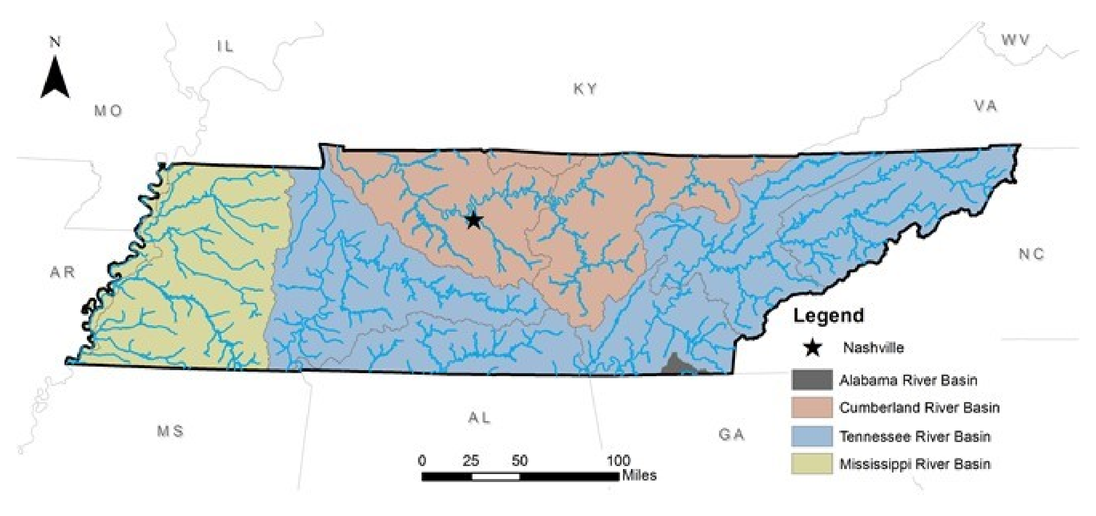
- interconnected nature of the physical, chemical, and biological conditions of aquatic ecosystems (lakes, rivers, streams, and wetlands);
- significance of landscape- and watershed-scale processes; and
- need to view water bodies as connected parts within a larger system rather than as isolated units unaffected by their surrounding landscapes.

1.3 Overview of Ecoregions in Tennessee

Tennessee's water resources are rich and varied, from the native brook trout streams of the Blue Ridge Mountains in the east to the wide alluvial plains of the Mississippi River to the west (**Figure 1**). Locally high precipitation and diverse types of wetlands found especially in the eastern region of the state provide habitat for many rare species of plants and animals. One small, shallow shoal within the Clinch River is home to at least 35 mussel species, more than any other place on Earth. The Upper and Lower sections of the Tennessee River sweep back and forth across the state for 360 miles before eventually emptying into the Ohio River in neighboring Kentucky. The Cumberland River, located in north-central Tennessee, flows into the state from the mountains of Kentucky through Nashville and back north into

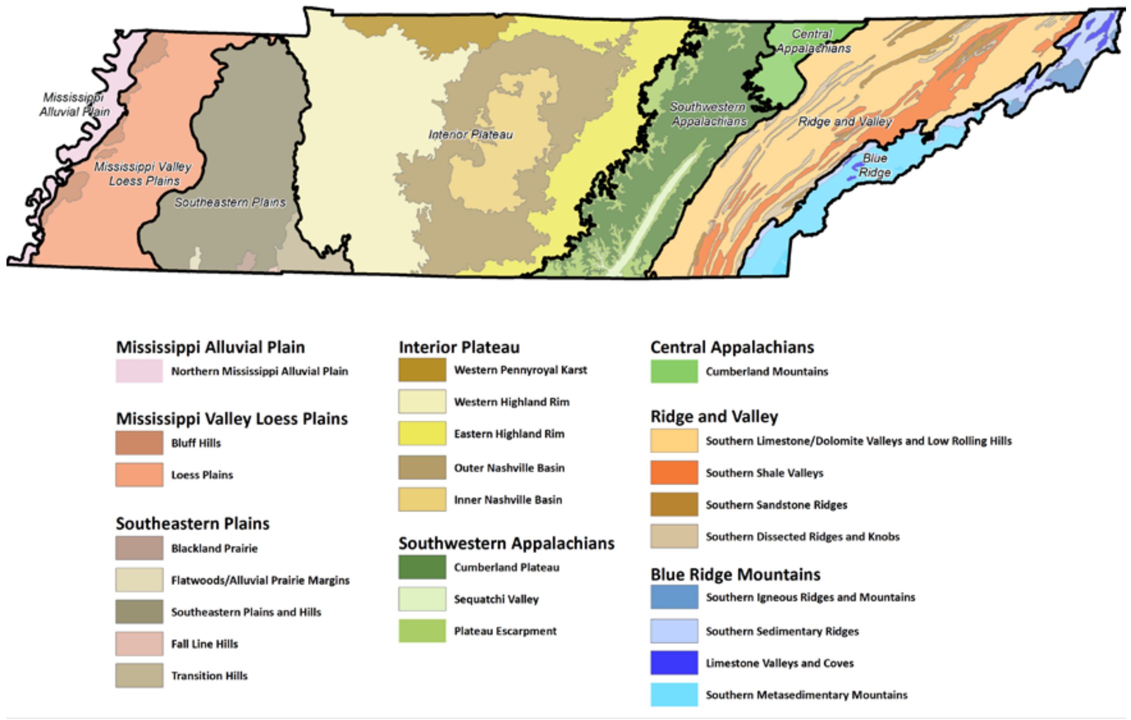
Kentucky to join the Ohio River. The Mississippi River Basin dominates the western edge of the state. Reelfoot Lake, in the northwestern corner of Tennessee, was created in the early 1800s by a series of violent earthquakes and is now an important habitat for a large diversity of wintering and breeding populations of waterfowl, including a significant population of wintering bald eagles.

Figure 1. Main river basins in Tennessee.



Eight Level III ecoregions made up of 25 smaller Level IV ecoregions have been delineated within Tennessee (**Figure 2**). Below is a brief description of the Level III ecoregions and the subsequent Level IV ecoregions with information adapted from Griffith and others (1997) and Omernik and Griffith (2009).

Figure 2. Level III and IV ecoregions of Tennessee.



- **Mississippi Alluvial Plain**: This riverine ecoregion along the Mississippi River is a flat, broad floodplain dotted with river terraces and levees. The soils tend to be poorly drained, and bottomland deciduous forest covered the region before most of the area was cleared for agriculture. Within Tennessee, it comprises the Level IV Northern Mississippi Alluvial Plain ecoregion entirely, which is bounded on the east by the Bluff Hills and on the west by the Mississippi River. Most of this low-elevation region is cultivated, with natural vegetation consisting of southern floodplain forest. Areas with poor drainage may contain wooded swampland and oxbow lakes that serve as habitat for waterfowl, raptors, and migratory songbirds, which are relatively abundant here.

- **Mississippi Valley Loess Plains**: This ecoregion in Tennessee abuts the Mississippi Alluvial Plain and consists primarily of irregular plains with oak-hickory and oak-hickory-pine natural vegetation. The primarily low-gradient streams in this region tend to have silty substrates. The Bluff Hills and the Loess Plains are the two Level IV ecoregions within this zone in Tennessee. Within the Bluff Hills ecoregion along the alluvial plain boundary, smaller streams have areas of increased gradient and gravel substrate that create aquatic habitats where unique, isolated fish assemblages more typical of upland habitats can be found. The Loess Plains ecoregion is characterized by gently rolling, irregular plains where most land has been cleared for agriculture, but some areas of bottomland forest and cypress-gum swamp habitats remain. The region is crossed by several large river systems with wide floodplains, where streams are murky with silt and sand bottoms, and most have been channelized.

- **Southeastern Plains**: These irregular plains are located in the western half of the state, just east of the Mississippi Valley Loess Plains, and are characterized by their higher elevations and rolling topography. Streams in this area are relatively slow moving and sandy bottomed. The majority of this ecoregion within Tennessee is delineated as the Level IV Southeastern Plains and Hills ecoregion, where the natural vegetation type is oak-hickory forest, grading into oak-hickory-pine to the south. The other four Level IV ecoregions within the Southeastern Plains are located along the southern Tennessee border and are very small in area within the state: Blackland Prairie, Flatwoods/Alluvial Prairie Margins, Fall Line Hills, and Transition Hills. The Transition Hills exhibit the highest elevations in the Southeastern Plains, and the streams resemble the sandy clear streams of the Interior Plateau ecoregion directly to the east.

- **Interior Plateau:** The Interior Plateau is a diverse ecoregion consisting of five Level IV ecoregions that stretch across a wide section of middle Tennessee. This ecoregion contains the most diverse fish fauna in the state. The Level IV Western Highland Rim ecoregion is characterized by rolling hills and streams with gravel and sand substrates and relatively clear water. To the north, small sinkholes and depressions are common in the Western Pennyroyal Karst ecoregion. The Inner and Outer Nashville Basin ecoregions are in the center of the Interior Plateau and have distinctive fish fauna and occasionally high densities of fish because of productive, nutrient-rich streams. The limestone cedar glades of the Inner Nashville Basin, a unique mixed grassland/forest vegetation type with many endemic species, result in a distinct distribution of amphibian and reptile species in this area. To the east, bordering the Cumberland Plateau escarpment, the Eastern Highland Rim ecoregion contains numerous springs and spring-associated fish fauna. Sinkholes and depressions are also common here because of areas of karst terrain.

- **Southwestern Appalachians**: This ecoregion within Tennessee is characterized primarily by the tablelands of the Level IV Cumberland Plateau ecoregion. These low mountain areas receive slightly more precipitation with cooler annual temperatures than the surrounding lower elevations. The eastern boundary of the ecoregion is relatively smooth and notched by small stream drainages that flow eastward into the Great Valley of East Tennessee (Ridge and Valley ecoregion). At the western boundary of the Cumberland Plateau, the Plateau Escarpment Level IV ecoregion is characterized by steep, forested slopes and fast-moving streams and waterfalls that have cut into the limestone. The resulting ravines and gorges provide wet and cool environments that can harbor distinct plant communities, such as hemlock stands along rocky streamsides and river birch along floodplain terraces. A third Level IV ecoregion, the Sequatchie Valley, outlines the Sequatchie River where erosion of broken rock to the south of the Crab Orchard Mountains scooped out the long, narrow valley.

- **Central Appalachians**: This ecoregion in northern Tennessee is made up entirely of the Cumberland Mountains Level IV ecoregion. The Cumberland Mountains are characterized by rugged terrain, cool climate, and infertile soils that limit agriculture, resulting in a mostly forested land cover. Steep slopes and narrow, winding valleys separate mountain ridges. The natural vegetation is a mixed mesophytic forest, although species diversity and abundance depend largely on microclimate. Coal mining activities, including strip mining in the Cumberland Mountains, have caused siltation and acidification of streams in this ecoregion.

- **Ridge and Valley:** Also known as the Great Valley of East Tennessee, this low-lying region between the Blue Ridge Mountains to the east and the Cumberland Plateau on the west is characterized by high aquatic habitat diversity and a diverse fish fauna. Springs and caves are relatively numerous in this ecoregion. This region has four Level IV ecoregions; the predominant are the Southern Limestone/Dolomite Valleys and the Low Rolling Hills where landforms are mostly low rolling ridges and valleys. White oak forests, bottomland oak forests, and sycamore-ash-elm riparian forests are the common forest types. The Level IV Southern Shale Valleys ecoregion consists of lowlands and rolling valleys, with well-drained soils that are often slightly acidic. Sandstone ridges and valleys with sandy, poor soils typify the other two Level IV ecoregions (Southern Sandstone Ridges and Southern Dissected Ridges and Knobs).

- **Blue Ridge Mountains**: The Blue Ridge Mountains of eastern Tennessee are characterized by forested slopes and cool, fast-moving streams. Annual precipitation of nearly 80 inches can occur on the well-exposed high peaks of the Great Smoky Mountains that reach over 6,000 feet. The southern Blue Ridge is one of the richest centers of biodiversity in the eastern United States. Blue Ridge streams have a distinct fish fauna, with some containing brook trout, the only salmonid native to Tennessee. Wetlands such as bogs, fens, and upland pools provide varying habitats among the otherwise steep topography. These wetland communities, despite their very small acreage, serve as important habitats for rare plant and animal species. Level IV ecoregions within the Blue Ridge Mountains are the Southern Igneous Ridges and Mountains, Southern Sedimentary Ridges, Limestone Valleys and Coves, and Southern Metasedimentary Mountains.

2. Methods Overview

2.1 Description of the Assessment Process

This Assessment was conducted by EPA's Healthy Watersheds Program and in partnership with the THWI. The THWI is a collaboration of federal, state, and nonprofit organizations committed to maintaining and improving water resources in Tennessee watersheds. The THWI was launched under a Memorandum of Understanding (MOU) executed by the Tennessee Department of Environment and Conservation (TDEC), the Tennessee Valley Authority (TVA), the Tennessee Chapter of The Nature Conservancy (TNC), and West Tennessee River Basin Authority in August 2011. The MOU signatories recognize that many other governmental agencies and nongovernmental organizations have an interest and a role in the health of Tennessee watersheds. The MOU and THWI Charter provide a structure that others can participate in to the extent of their interest and ability, whether that is focused on a single watershed, a region of the state, or the entire state (THWI, 2015).

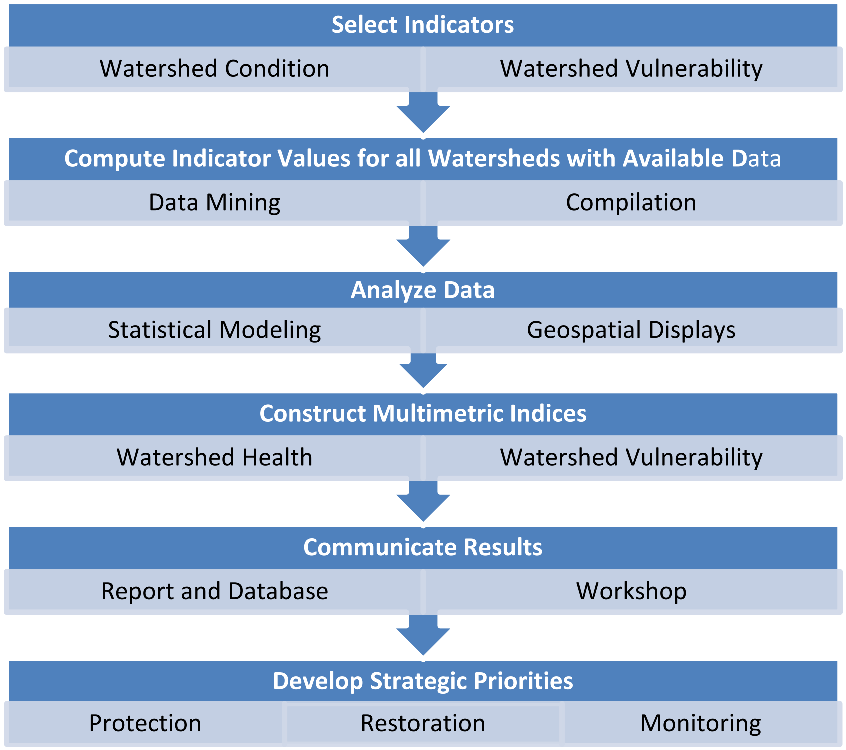
Learn More Online:

Visit the Tennessee Healthy Watershed Initiative Web site to review more information about this collaborative effort: https://www.tn.gov/environment/article/wr-ws-tennessee-healthy-watershed-initiative

For this Assessment, TNC was the lead THWI member organization, and they assembled representatives from federal and state agencies (e.g., TVA, TDEC, U.S. Geological Survey [USGS], U.S. Army Corps of Engineers – Nashville District, Tennessee Wildlife Resources Agency [TWRA]) to serve on the Technical Team. The Technical Team participated throughout the Assessment process by providing data and information for the Assessment, reviewing the technical approach, and providing comments on the preliminary analyses and draft report. **Figure 3** illustrates the roadmap for the Assessment.

The first step of the Assessment was to create an inventory of available field monitoring and geospatial data to assess current landscape, geomorphologic, hydrologic, habitat, water quality, and biologic conditions throughout Tennessee. Data were gathered directly from the Technical Team and other publically available sources such as EPA's Storage and Retrieval Data Warehouse (STORET) and USGS's National Water Information System. Based on the available data, the technical approach for the Assessment was prepared and reviewed by the Technical Team during an in-person meeting. The meeting included a review of available data, discussion of the geospatial and statistical methodologies, and discussion of the candidate watershed health and vulnerability metrics. Consensus on the key technical aspects of the approach was achieved before implementing the technical approach. The preliminary results were presented through a series of webinars to the Technical Team where the technical approach was further refined.

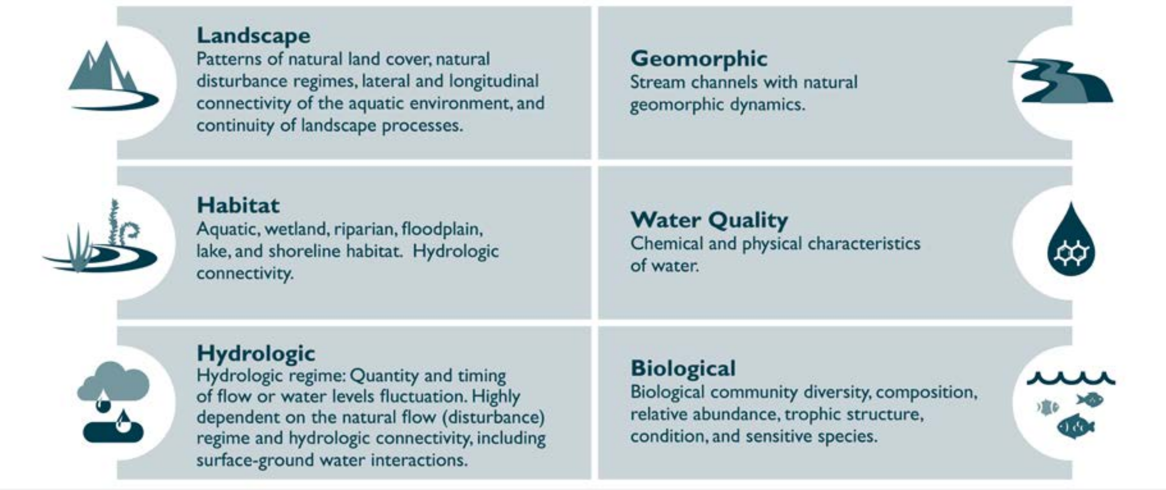
Figure 3. Roadmap for this Assessment.



2.2 Conceptual Framework

EPA conceptualizes watershed health using six distinct but interrelated attributes: 1) Landscape Condition, 2) Geomorphic Condition, 3) Hydrologic Condition, 4) Water Quality, 5) Habitat Condition, and 6) Biological Condition (**Figure 4**; USEPA, 2012). An integrated watershed health assessment should assess the condition of all six of these attributes using a variety of *watershed health metrics*.

Figure 4. EPA's six attributes of watershed health.



Landscape
Patterns of natural land cover, natural disturbance regimes, lateral and longitudinal connectivity of the aquatic environment, and continuity of landscape processes.

Geomorphic
Stream channels with natural geomorphic dynamics.

Habitat
Aquatic, wetland, riparian, floodplain, lake, and shoreline habitat. Hydrologic connectivity.

Water Quality
Chemical and physical characteristics of water.

Hydrologic
Hydrologic regime: Quantity and timing of flow or water levels fluctuation. Highly dependent on the natural flow (disturbance) regime and hydrologic connectivity, including surface-ground water interactions.

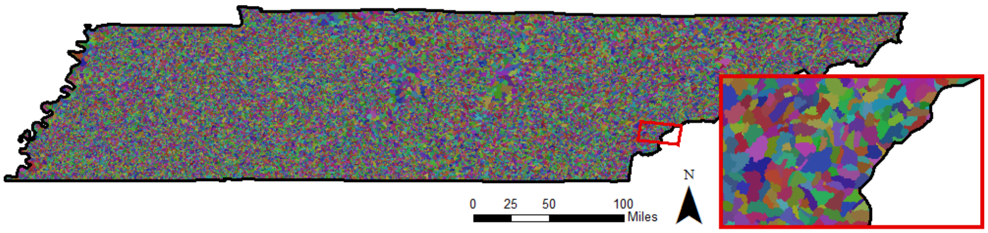
Biological
Biological community diversity, composition, relative abundance, trophic structure, condition, and sensitive species.

Data used to quantify watershed health metrics are selected to represent current conditions. Because watershed health is a dynamic property that can vary with future changes in climate and human activity, the Assessment also evaluates the vulnerability of watershed health to future conditions. Vulnerability is quantified from a collection of *watershed vulnerability metrics* that characterize potential changes in future land use, climate, and water use.

2.3 Spatial Framework

The spatial framework for conducting the Assessment was a network of small catchments represented in the National Hydrography Dataset Plus (NHDPlus) Version 2. 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 (median size of 0.6 square miles) 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 a complete picture of the hydrologic relationships between every catchment in the stream network at the 1:100,000 scale. Tennessee has 61,859 individual NHDPlus catchments (**Figure 5**).

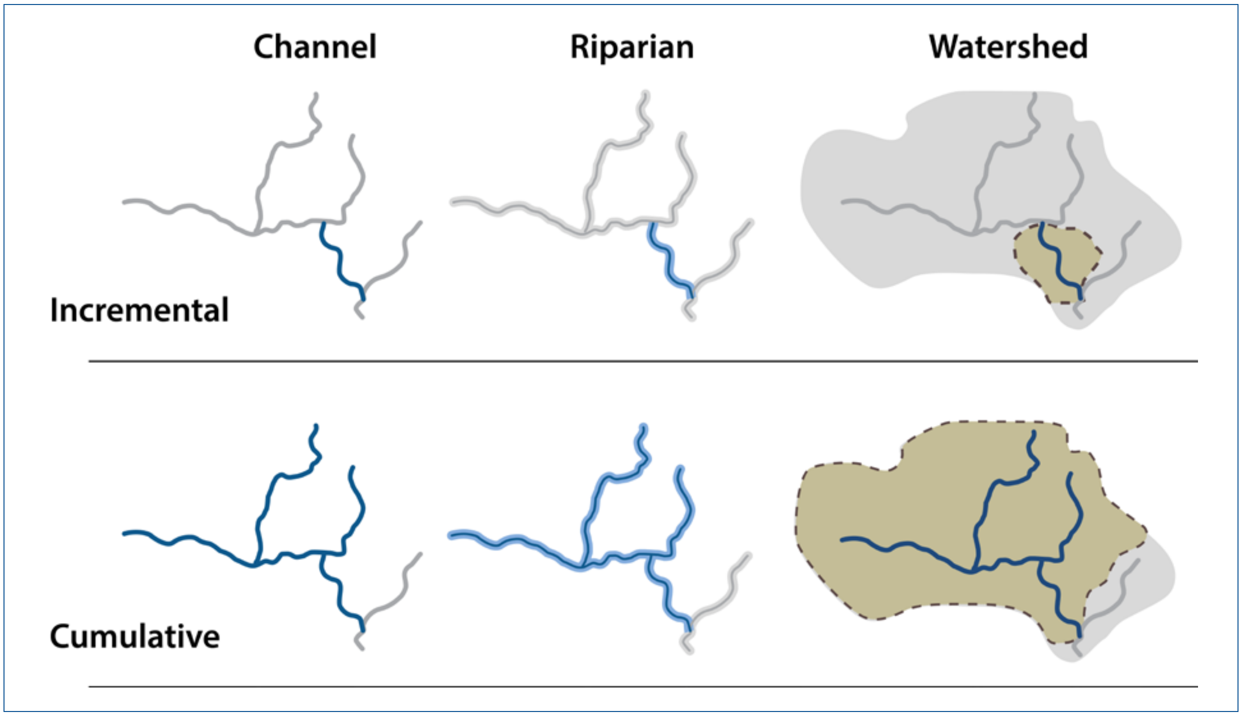
Figure 5. Spatial framework for the Assessment.



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 in Tennessee (**Figure 6**). 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. Calculating some metrics involved summarizing existing geospatial datasets to catchment-specific values. Other metrics were quantified from modeled relationships between stream condition and landscape variables. 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.

Figure 6. Difference between incremental and cumulative scales for quantifying landscape variables for the same example catchment (dashed boundary).



Note: Variables quantified at the incremental scale summarize conditions within catchment boundaries only. Variables quantified at the cumulative scale also summarize conditions throughout all upstream catchments, expressed as a value of the downstream catchment.

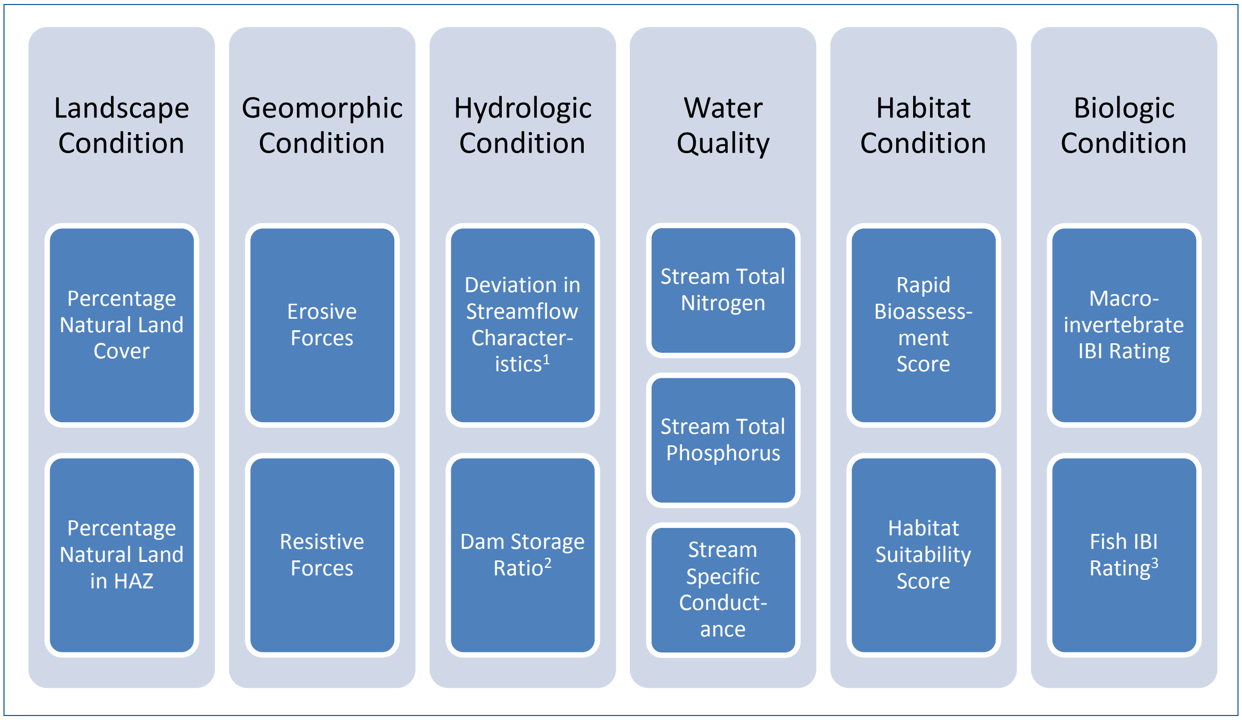
A final note on the spatial framework of the Assessment relates to differences between the scale of analysis and the intended scale of interpretation. Although NHDPlus catchments serve as analysis units, results are not intended to be used to assess the condition of a single catchment. Rather, results should be viewed over broad geographic areas to identify patterns and prioritize watersheds for in-depth, site-specific assessments of protection needs. See Section 5 for more information on the potential uses of the Assessment.

2.4 Watershed Health Metrics

Watershed health metrics were quantified on a catchment-by-catchment basis. Many metrics were explored, but the selection of final metrics to use in the Assessment was determined by the robustness of the dataset, the goodness of the model fit, the availability of data across the entire state, and input from the THWI Technical Team.

A series of webinars was held with the THWI Technical Team to identify indicators of watershed health that are most relevant to Tennessee and its stakeholders and for which data were readily available. The discussion was framed around EPA's six attributes of watershed health to ensure that all aspects of watershed health were explored. Ecological indicators were calculated for the following attributes: 1) Landscape Condition, 2) Geomorphic Condition, 3) Hydrologic Condition, 4) Water Quality, 5) Habitat Condition, and 6) Biological Condition (**Figure 7**).

Figure 7. Watershed health metrics used for the Assessment.



Notes: 1 = unregulated streams, 2 = regulated streams; 3 = data only available for Ridge and Valley and Blue Ridge ecoregions. HAZ = Hydrologically Active Zone; IBI = Index of Biological Integrity.

The methods used for this Assessment have been used in similar assessments for Wisconsin, California, and Alabama. More information on these previous assessments is available on the EPA Healthy Watersheds Program Web site (http://www2.epa.gov/hwp).

Three approaches were used to calculate metrics of watershed health for all catchments within Tennessee. The first approach calculated metric values directly from geospatial data that have representation across the entire state (e.g., land use, percentage of forest cover, and percentage of imperviousness) and was used to calculate Landscape Condition and Geomorphic Condition Sub-Indices. The second approach used geospatial data to represent catchment conditions (e.g., drainage area, and soil conditions) as predictive variables in existing regression models to determine streamflow characteristics. These data were used to determine the Hydrologic Condition Sub-Index. The third approach used predictions from statistical models that relate landscape characteristics to stream conditions. The statistical models were based on field-collected monitoring data throughout the state. Because field-based monitoring data were not available for every catchment in the state, statistical models were used to predict conditions in catchments without data. This approach was used to determine Habitat Condition, Water Quality, and Biological Condition Sub-Indices. The combination of actual and predicted data was used to rank the relative health of watershed conditions. The ranking of the catchments is described in Appendix E.

The underlying sources of data for the Habitat Condition, Water Quality, and Biological Condition Sub-Indices were field-based samples collected across the region through various state and federal monitoring programs. Field-based data were not available for each of the NHDPlus catchments in Tennessee. The existing monitoring data were used to predict habitat, water quality, and biological condition in catchments without observed data using statistical regression models. These models quantified relationships among landscape and other catchment characteristics and predict the values of habitat, water quality, and biological condition for catchments without data. Landscape variables described land cover, elevation, geology, and stream channel characteristics at both incremental (catchment) and cumulative scales (see Figure 6). Other variables, such as sample date, corresponding to field data were also used. Landscape and other variables quantified for statistical modeling are presented in **Table 1**.

Table 1. Landscape and other variables used in statistical models.

Watershed Land Cover	Percent natural lands, percent forest canopy, percent agriculture, percent disturbed, percent forested land use, percent impervious surface (both within the catchment and cumulative)
Landscape	Catchment area, total drainage area, minimum and maximum stream elevation, mean catchment elevation, mean soil erodibility (K factor), dominant Omernik III and IV ecoregion
Geology	Depth to bedrock, dominant surface geology, dominant bedrock type
Stream Channel Characteristics	Sinuosity, stream length, stream order, channel slope
Sample	Sample date, sample month, sample year
Riparian Area Land Cover	Percent natural lands, percent forested, percent agriculture, percent disturbed areas, percent land use cover category, percent impervious surface (both within the catchment and cumulative)

Specific methods and statistical modeling approaches are described in the appropriate sections for each Assessment component, and additional information is provided in **Appendix B** (Geomorphic Condition), **Appendix C** (Hydrologic Condition), and **Appendix D** (Water Quality, Habitat, and Biological Condition).

Metrics of watershed health and vulnerability (see Section 2.5) were rank normalized for reporting the metric, sub-index, and final index calculations. Rank normalization transforms one or more variables to a uniform distribution and scale, typically from 0 to 100; this common scale allows for comparisons between variables that may exhibit different units and scales. Rank normalization is also insensitive to outlier or extreme values, which can overly compress a normalized distribution when other normalization methodologies are applied (Mitchell, 2012). Once rank normalized on a common scale, a correlation analysis between all possible pairings of the watershed health sub-indices was conducted to determine whether there is any relationship between these calculated measures that would ultimately prohibit combining the sub-indices into the Watershed Health Index without redundancy. The correlation results supported the use of all sub-indices to create a multi-metric index representing overall relative watershed health. More information on the rank-normalization methods and the results from the Correlation Analysis is provided in **Appendix E**.

2.4.1 Landscape Condition Metrics

Landscape condition is described by the extent of natural land cover throughout a watershed and within key functional zones such as floodplains, riparian areas, and wetlands. Land cover describes the physical cover of the earth's surface, including natural and man-made vegetative cover and related land uses, and plays a key role in the water cycle. When water falls as rain or melts as snow, the path the water travels to reach streams, lakes, and rivers can either soak through the soil and become ground water or travel over the land as runoff. The land cover determines which path the water takes; how long the water needs to travel; and the amount of sediment, nutrients, and other constituents that are in the water. For this Assessment, land cover representing naturally occurring communities such as forests and wetlands is assumed to represent a landscape condition that does not negatively affect overall watershed health. The first metric is based on the extent of natural land cover in the individual NHDPlus catchment, and the second metric is based on the extent of natural land cover within the floodplains and riparian areas of each catchment.

The 2011 National Land Cover Database (NLCD; Homer et al., 2015) was used to represent current landscape conditions in Tennessee. The NLCD has a 15-class land cover classification scheme and a spatial resolution of 30 meters. Additional NLCD products used elsewhere in this Assessment include the percent developed imperviousness (Xian et al., 2011) and the percent forest canopy data products. The NLCD 15-class scheme provides a coarse characterization of landscape conditions. To better represent actual land cover conditions, the NLCD scheme was refined using two data sources: land cover mapping from the Southeast Gap Analysis Program (SE-GAP) and mapping of managed forests produced by TNC to create the 17-class scheme used in this Assessment (**Table 2**).

There are 71 SE-GAP classification units in Tennessee and each SE-GAP had a corresponding NLCD category. This Assessment identified the nine naturally occurring SE-GAP communities that would otherwise have been categorized as non-natural or semi-natural based on the NLCD classification. A new land cover type listed as "SE-GAP" in Table 2 was the combination of these communities comprised of rocky summits, cliffs, grass and shrub balds, and prairie lands. The other new land cover category, Managed Forests, was used to differentiate forest lands that are managed and are often a monoculture of one species. Management activities can alter natural hydrology and affect water quality, habitat, and biological communities of surrounding streams. Therefore, this Assessment created a separate category of managed forests as a semi-natural land cover. Two sources of data were used to identify managed forests. One dataset was developed by the Open Space Institute (OSI; unpublished data) and is based on a survey of land ownership. The second dataset was created by TNC (Barnett, 2015 unpublished data) as a combination of SE-GAP communities classified as evergreen plantation and clear cut and merged with county-level parcel data based on land ownership by timber companies.

The Landscape Condition metrics were based on the amount of natural, semi-natural, and non-natural lands. Natural lands are defined as observed biological and physical condition of the Earth's surface that represent lands without obvious human modification, including lands that have previously been disturbed. Natural lands include forested lands, wetlands, cliffs, mountain balds, and prairie lands. Semi-natural lands also have vegetation but are being maintained in a non-natural condition or are in the process of recovering from disturbance. Semi-natural lands include shrublands, grasslands, and industrial forests. Non-natural lands have been altered by human use and are actively maintained and managed in way that is not consistent with natural vegetation composition. Non-natural lands includes parks, lawns, cities, residential housing developments, row crops, and pasture lands.

Table 2. Classification of natural, semi-natural, and non-natural cover types.

HWP Classification	NLCD Description and Classification Codes
Natural	Open water (11), deciduous forest (41), evergreen forest (42), mixed forest (43), woody wetlands (90), emergent herbaceous wetlands (95), SE-GAP (new category)
Semi-natural	Shrub/scrub(52), grassland/herbaceous (71), managed forest (new category)
Non-natural	Developed, open space (21); developed, low intensity (22); developed, medium intensity (23); developed, high intensity (24); barren land (31); hay/pasture (81); cultivated crops (82)

Percent Natural Land Cover: The significance of natural land cover to watershed health is represented in the Assessment with the percent natural land cover metric. Percent natural land cover metric is calculated as the sum of the area of natural cover types and 75% area of semi-natural cover type in a catchment divided by the catchment's area and multiplied by 100.

Percent Natural Land Cover in Hydrologically Active Zone (HAZ): The proximity of land cover to receiving rivers, streams, and lakes affects the degree to which the land cover will influence the condition of that aquatic system. For the Assessment, this area is represented as the HAZ, which is a combination of the riparian zone and the hydrologically connected zone developed by EPA Region IV as part of the Watershed Index Online (EPA, 2014). The hydrologically connected zone is based on a topographic index score and is contiguous to aquatic systems including streams and wetlands. The riparian zone is calculated as a 100-meter-per-side buffer around the NHD flowlines. Percent intact HAZ was determined for each catchment by combining the area of natural land cover types in the HAZ of each catchment and 75% of the area of semi-natural lands in the HAZ of each catchment, dividing by the

HAZ area, and multiplying by 100. See Table 2 for a list of natural, semi-natural, and non-natural cover types.

2.4.2 Geomorphic Condition Metrics

Fluvial geomorphology is the study of the shape of streams and their relationships with the landscapes they flow through. Streams are dynamic systems, constantly carving and shaping their channel through the movement of water. However, stream channels are subject to a wide variety of forces, both natural and anthropogenic. The Geomorphic Condition describes how changes to the landscape affect stream channel formation and evolution. It also helps predict whether a stream system can adjust to changes in the watershed while maintaining its physical, biological, and chemical integrity. The principles of fluvial geomorphology applied in this Assessment were developed by Leopold and others (1964) and Rosgen (2006).

Geomorphic assessments are often completed to determine channel stability and resiliency to watershed or reach-level disturbances. Channel stability does not mean that the stream's position and form will remain fixed within the context of its landscape. Rather, streams in low-gradient, alluvial valleys can naturally meander across a valley bottom, eroding an outside bend and depositing new sediment on the inside of the bend. This form of lateral migration is generally a slow process and results in only minor changes to a channel's dimensions (width, depth, area) even as the stream is actively creating a new path across the terrain. This process is known as dynamic equilibrium. Channel resiliency is the ability of the channel to maintain dynamic equilibrium as disturbances occur in the watershed or along the stream corridor.

Streams often become unstable because of disturbances in the watershed that change the amount of runoff and sediment that reaches the stream channel. Watershed and land use changes that cause instability are called indirect disturbances. Streams can also become unstable because of direct changes to the channel. Examples include channelization, removal of streamside vegetation, beaver dam and wood removal, and in-stream mining. These direct and indirect disturbances can cause instability in the vertical dimensions (e.g., streams can down-cut, becoming entrenched and isolated from their floodplains), lateral dimension (e.g., destabilized channels may become unnaturally widened by erosion, risking floodplain land loss while leaving a shallow stream that provides very poor habitat), or both. Geomorphic stability is an important part of overall stream and watershed condition. Unstable channels may increase fine sediment supply to the stream and downstream waterways, smothering benthic habitats and eliminating the niche spaces where aquatic biota shelter from predators, lay eggs, and forage for food. In addition, the subsequent increase in turbidity may lead to reduced primary productivity, increasing stress throughout the food web, and lead to changes in water chemistry (Castro et al. 1995). Other consequences of instability may include threats to human infrastructure and a reduction in natural flood controls.

The evaluation of Geomorphic Condition was based on multiple watershed variables to determine the balance of erosive and resistive forces at work within a catchment. Little field-based data were available to characterize geomorphic condition of the watersheds; therefore, geospatial data were used as proxies for field-based measurements (**Table 3**). For this Assessment, Geomorphic Condition for each catchment was characterized in three ways: erosive forces and susceptibility to erosion, resistive forces that abate erosion, and the integration of erosive and resistive forces to gauge the overall potential for geomorphic stability.

Table 3. Variables used to determine Geomorphic Condition.

Variable	Source (and Method)	Selection Rationale
Annual Flow	Calculated mean annual runoff (eastern Tennessee) and mean summer streamflow (western Tennessee)[1]	Erosive factor – Approximation of the strength of the hydrologic regime that drives channel formation and change
K-Factor	Soil erosion potential. attribute in SSURGO	Erosive factor – Natural susceptibility of soils along the stream channel to erosion
Land Cover (Imperviousness)	NLCD 2011, Impervious Surface	Erosive factor – Representative of anthropogenic influence within a catchment that will lead to changes in the timing, volume, and velocity of runoff entering a stream channel
Depth to Bedrock	Average depth to bedrock along each flowline was calculated using the Generalized Geologic Map of the Conterminous United States (Nicholson et al., 2005)	Resistive factor – Representative of the limit of change possible within a stream channel (i.e., a restrictive layer that is not reformed by erosion)
Land Cover (Forest, Impervious)	NLCD 2011, Cumulative NLCD, NLCD 2011 Canopy	Resistive factors – Approximation of the natural control and infiltration of runoff in a catchment
Land Cover (Natural Land in the HAZ)	NLCD 2011, NLCD 2011 Canopy	Resistive factor – Used as a gauge for an undisturbed riparian, with vegetative cover that provides natural checks on channel migration and widening

[1] These variables were calculated as metrics of Hydrologic Condition and are described in Section 2.5.3**.**

Erosion Metric: Three factors were used to assess the potential for the stream to incise (lower its bed) and to erode laterally and cause channel widening: percent impervious cover (for the cumulative land area draining to the catchment), soil erodibility, and annual flow (i.e., hydrologic force at work in the stream channel). Impervious cover increases the amount of water reaching the stream channel by runoff and that increase in runoff can lead to channel erosion. The erosion potential for the soil is measured as K-factor and was obtained from the Soil Survey Geographic Database (SSURGO) developed by the Natural Resources Conservation Service. Soils having a high silt content are the most erodible of all soils. They are easily detached and tend to crust and produce high rates of runoff. Values of K for these soils tend to be greater than 0.4. Medium-textured soils, such as the silt loam soils, have moderate K values, about 0.25 to 0.4, because they are moderately susceptible to detachment and they produce moderate runoff. Coarse-textured soils, such as sandy soils, have low K values, about 0.05 to 0.2, because of low runoff even though these soils are easily detached. Soils high in clay have low K values, about 0.05 to 0.15, because they are resistant to detachment. K-factor classifications were based on research by Jones and others (1996). The streamflow is a calculated quantitative measure of the stream's ability to do work, typically defined as moving sediment.

Resistance Metric: A high percentage of impervious cover in a catchment and an increase in stream power (i.e., an increase in the erosive forces at work in a stream channel) do not mean that the streambed will incise or that the stream channel will widen or migrate at an accelerated rate because other factors can limit erosion. The surrogates used to represent these resistive factors include depth to bedrock or other constraining layers such as hard claypan, percent forest cover (for the cumulative land area draining to the catchment), and the percent of natural cover within the HAZ. Streambeds that are composed of bedrock will not incise, regardless of changes in hydrology (runoff). Bedrock is a major form of grade control for the streambed. As the depth to bedrock increases, the potential for stream incision also increases. Streambeds that have a claypan restrictive layer, although not as resistant to erosion as bedrock, will also exhibit less incision and will erode more slowly. The percent of forest cover also mitigates the potential for incision by lowering the volume of runoff from the watershed (opposite to percent impervious cover). Vegetation within the HAZ may anchor stream banks and constrain excessive meandering. Vegetation with deep roots, especially near the channel, holds the bank together, thereby reducing the potential for erosion and subsequent stream migration.

A simple continuous scoring model (range: 0–100 points) was used for each factor included in the analysis (see **Appendix B** for details of the analysis, including the variable, their values, and scoring system was applied to those values). Each factor was scored so that higher point values indicated the factor would have a positive effect on stream resilience and stability (e.g., a lower percentage of impervious cover is less likely to alter the natural flow regime in a catchment and therefore would score more points than a catchment with a higher percentage of impervious cover). The three factor scores were then averaged to produce an erosion and a resistance metric score, respectively. If a value for a particular factor was not available, this factor was dropped from the average. In this manner, each catchment was given an erosion metric score and a resistance metric score. These two metric scores were averaged to determine the Geomorphic Condition Sub-Index.

2.4.3 Hydrologic Condition Metrics

A stream's flow regime refers to its characteristic pattern of flow magnitude, timing, frequency, duration, and rate of change (Poff et al., 1997). The flow regime plays a central role in shaping aquatic ecosystems and the health of biological communities. Alteration of natural flow regimes (e.g., more frequent floods) can reduce the quantity and quality of aquatic habitat, degrade aquatic life, and result in the loss of ecosystem services. Therefore, to assess Hydrologic Condition, we used metrics related to the flow regime in unregulated streams to determine which segments most closely resemble the natural flow regime through reference watersheds and were therefore assumed to be healthy. In regulated systems (i.e., streams below large dams), we used the ratio of the storage behind the dams to the expected mean annual natural streamflow to determine which regulated segments have lower volumes of storage compared with streamflow and therefore had greater potential to influence the natural flow regime. Individual dam operations and rules have the potential to mitigate these influences; however, these factors are not included in this Assessment. Information on dam operations is provided in Appendix C for qualitative assessment.

Unregulated Streams/Catchments

The regional regression models developed by Knight and others (2012) were used for the Tennessee and Cumberland River basins to determine streamflow characteristics (SFCs) by catchment for the eastern portion of the state. In the western portion of the state, SFC regression models developed by Law and others (2009) were used. Both models rely on basin characteristics such as drainage area and underlying geologic and soil conditions to predict the SFCs. Each calculated SFC at the catchment level was compared with a range of values expected for streams under natural or reference conditions, which was determined by first selecting catchments exhibiting more natural land cover and then calculating the interquartile range (IQR) of calculated SFC values for those catchments. The absolute value of the deviation from this range (giving both high and low deviations equal weight and assuming any deviation from natural is impactful to the flow regime), if any, was calculated for each SFC. The summation of deviations for all SFCs by catchment provided the overall hydrologic condition metric for unregulated streams (see Appendix C for more details).

East Tennessee: The USGS regional regression model (Knight et al., 2012) consists of 19 separate regression equations that predict a single SFC for unregulated streams (**Table 4**). The regression equations were derived based on 231 USGS streamflow monitoring sites (drainage areas spanning 1.67 to 3,035 square miles) across the two basins using geospatially derived sub-basin characteristics as independent variables. An additional USGS study (Knight et al., 2014) related SFCs to fish community structure and found that eight SFCs were influential to fish species richness in each of the three ecological regions (i.e., Blue Ridge, Ridge and Valley, and Interior Plateau) covered by the Tennessee River basin. Significant SFCs identified in that study were recalculated for this Assessment and used as a starting point to select a subset of ecologically relevant metrics to use in the eastern portion of the state to evaluate the streamflow regime (Appendix C).

Table 4. Hydrologic metrics predicted using regression analyses (Knight et al., 2012).

Hydrologic Characteristic	Metrics
Magnitude	**Mean annual runoff (MA41)**, **maximum October streamflow (AMH10)**, streamflow value exceeded 85% of time (e85), median September daily flow (Sep_med), **rate of streamflow recession (LRA7)**
Ratio	Average 30-day maximum (LDH13), base flow (ML20), **constancy (TA1)**, number of day rises (RA5)
Frequency	**Frequency of moderate flooding (three times the median annual flow [FH6])** and (seven times the median annual flow [LFH7])
Variability	Variability of March streamflow (MA26), variability in base flow (LML18), variability of annual minimum daily average streamflow (LDL6), **variability in high-pulse duration (LDH16)**, **variability in low-pulse count (FL2)**
Date	**Annual minimum flow (TL1)**, annual maximum flow (TH1), flow direction reversals (RA8)

Bold metrics are those found to be influential to fish species richness in the Tennessee River basin by Knight et al. (2014).

To calculate the SFCs for each NHDPlus catchment, the independent variables were calculated for each catchment through new geospatial analyses. A final selection of SFCs was made after comparing values for each SFC at the 231 monitoring site locations between the USGS study and this Assessment to determine which SFCs diverged least from the original study and best represented the gauged flows. Ultimately, three SFCs were chosen to provide a measure of Hydrologic Condition in eastern Tennessee:

mean annual runoff (MA41), date of annual minimum flow (TL1), and variation in high-pulse duration (LDH16). These three metrics assess magnitude, timing, and variability in the flow regime and, therefore, provide information on multiple aspects of the flow regime. A reference range for values of each of these three metrics was calculated by ecoregion by designating catchments with forest land use in the upper quartile of the range of values as reference catchments. The IQR for SFC values for these reference catchments designates the reference range from which deviations for all other catchments were calculated. The total deviation among the three SFCs for each catchment becomes the Hydrologic Condition metric for the eastern portion of the state.

West Tennessee: Assessment in the western portion of the state relied on the same independent variables calculated from geospatial analyses but applied regression models of various SFCs developed by Law and others (2009) from 124 streamflow gauges within the western portion of the state for flow magnitudes, frequencies, and durations. After comparison to the original data and consideration of the general hydrologic conditions of the western basins (i.e., groundwater driven), three SFCs were chosen for the western portion of Tennessee: lowest consecutive 7-day average flow that occurs every 10 years (7Q10), mean-summer streamflow in June through August (MS), and daily mean streamflow exceeded 10% of the time (q10). The regression equations determined by Law and others (2009) and used for this Assessment estimate flow magnitudes. To make relative comparisons across the region and apply the reference region deviation method, resulting SFCs were normalized by drainage area of the catchment. As in East Tennessee, the reference range was developed by selecting catchments with forest land use in the upper quartile range of values as reference catchments. Then the IQR for each of the three SFC values was used to designate the reference range and the total deviation from this range among the three SFCs became the Hydrologic Condition metric for the western portion of the state.

Regulated Streams

Dams have a major impact on natural riverine hydrology, primarily through changes in the timing, magnitude, and frequency of low and high flows. Major dams within Tennessee were identified as having greater than 10,000 acre-feet of normal storage. All catchments within the state that are located at or downstream of a dam of this size were classified as being regulated and were assessed separately from the unregulated portions of streams within the state.

Dam Storage Ratio: The ratio of the volume of water impounded by dams and the average annual predevelopment streamflow serves as an indicator of potential hydrologic alteration. Using data from the Tennessee State Wildlife Action Plan (TN SWAP), dams with greater than 10,000 acre-feet of normal storage were identified throughout the state and upstream areas. From this selection, any dams with a primary purpose of recreation were removed to eliminate counting natural lakes with spillways from the Assessment (located in western Tennessee). Catchments downstream from each of these dams were identified and indexed to all upstream dams. The storage volume of all upstream reservoirs was summed for each of these identified catchments based on the values provided by the TN SWAP dataset. Natural streamflows were provided for each catchment by the NHDPlus dataset. The dam storage ratio was calculated as the storage volume divided by the expected natural streamflow with conversion to number of days. Ratio values near or below zero indicate there is little dam storage (0 to less than 1 day of storage volume compared with annual average streamflow) within the drainage area; therefore, the hydrology is closer to natural conditions. Ratio values near one indicate drainage areas where the volume of water stored behind dams is approximately equal to the volume of water flowing through the catchment on a daily average across the year. Values greater than one highlight basins dominated by dams and reservoir storage over streamflow. Because the three different metrics were assessed as rank normalized values, they were combined into a single statewide coverage for comparison of all hydrologic regions of the state.

2.4.4 Water Quality Metrics

Water quality refers to a suite of physical and chemical parameters present in surface and ground waters. Water quality parameter values are influenced by a complex set of factors that interact across multiple spatial and temporal scales. Parameter values in a healthy watershed should fall within the range of naturally occurring variation for that water body. Values that exceed this natural variation can negatively impact the physical, chemical, and biological processes that occur in surface waters; these changes can in turn alter the fundamental dynamics of aquatic ecosystems.

The Water Quality assessment primarily considers “naturally occurring parameters,” a phrase that refers to physical and chemical characteristics that are likely to be present in surface waters regardless of watershed health. To assess Water Quality, a relational database was created using data collected by TDEC. Based on a survey of available data, feedback from the THWI Technical Team, and the goals of the Assessment, three stream water quality metrics were selected for analysis:

- stream total nitrogen concentration,
- stream total phosphorus concentration, and
- stream specific conductance.

These parameters were characterized as the annual post-2000 median value for catchments with five or more unique samples. **Appendix D** lists additional filters that were applied to the water quality parameter values. The final number of catchments with data are listed in **Table 5**.

Table 5. Sample counts for filtered water quality parameters.

Water Quality Parameter	Catchments with Data
Total Nitrogen	1,690
Total Phosphorus	1,828
Specific Conductance	1,677

These parameters were selected by the Technical Team because they represent important aspects of water quality health in Tennessee and monitoring data of sufficient spatial and temporal resolution was available to produce a relative statewide ranking of water quality condition on the catchment level.

Additional physical and chemical parameters may also impact water quality health in a given catchment. For example, parameters such as pH or organic and inorganic contaminants may be influential at local or regional scales. The interpretation of the Water Quality Sub-Index should always consider local conditions.

Not all catchments in the state have monitoring data, so statistical modeling was used to relate observed water quality data with watershed-scale predictor variables. Watershed-predictor variables were summarized at multiple spatial scales and evaluated land cover, geology, impervious cover, and other influential physical factors that were used as proxy variables for watershed-scale processes such as runoff, buffering capacity, and other fate and transport mechanisms (see Table 1). The modeled relationships between the selected water quality parameters and predictor variables were then used to predict water quality values for catchments without monitoring data. For this Assessment, a tree-based modeling approach called boosted regression tree modeling was used to characterize and predict water quality condition for all NHDPlus catchments in the state. Detailed information on the statistical modeling and water quality results can be found in **Appendix D**.

2.4.5 Habitat Condition Metrics

Aquatic habitat is an essential component of watershed health because it is often the limiting factor for biological communities. Even where water quality is in good condition, biota may not attain reference condition without the physical habitat features of their natural environment. Indeed, habitat loss and degradation are usually cited as the primary factors affecting biological diversity in streams worldwide. Habitat degradation can result from a variety of human impacts occurring within the water body itself or in the surrounding watershed. Typical in-stream impacts include sedimentation, channelization, and bank erosion and filling, such as mountain top removal. Urban development, timber harvesting, agriculture, livestock grazing, energy extraction, streamflow barriers/impediments (hydrologic alteration), and the draining or filling of wetlands are well-known examples of human activities affecting stream habitat at the watershed scale.

Rapid Bioassessment Protocol (RBP) Score: The RBP is a commonly used tool for assessing the condition of physical habitat in streams. RBP data are usually collected whenever benthic macroinvertebrate or fish samples are taken in streams. These data include the presence and quality of stream banks, riffles, pools, and other physical features that provide habitat for aquatic species. The RBP index has associated condition classes (usually four to five categories on a 20-point scale) that are benchmarked to conceptual reference conditions. TDEC usually assesses RBP statewide, wherever biological assessments are performed. Their database contains 4,175 unique sampling sites sampled from 2000 to 2013, distributed among the Level III ecoregions.

Habitat Suitability Scores: TNC worked with TWRA to develop TN SWAP (TNC, 2012). Toward this end, a GIS and relational database management system was developed to manage the large amounts of data on species of greatest conservation need (GCN), their habitats, and problems affecting these species and habitats. Terrestrial, aquatic, and subterranean habitats were classified and mapped, and habitat preferences for over 600 faunal species were assigned by taxonomic experts involved in the planning effort. The database contains over 52,000 occurrences of 664 GCN species, and 15,878 of these records are for aquatic species. Additionally, the database contains over 131,000 records of host fish for mollusk species occurrences. Predictor variables derived from the NHDPlus dataset were used to map expected species distribution for known occurrences, based on habitat availability. A model was developed to rank all catchments from low GCN species priority to very high. This model was based on an index of relative viability for every species occurrence in the database. Additionally, stream segments upstream and downstream of those with known occurrences were evaluated and scored, based on species rarity/legal status score, viability score, flow distance, and a percent deviation of mean annual flow volume from that of the stream segment with the documented occurrence. Dams were not crossed when assessing potential occurrence extent. Once an overall habitat priority for each stream segment was calculated, the amount of habitat represented by each stream segment was used to weight the overall catchment score.

2.4.6 Biological Condition Metrics

Biological Condition is the most integrative of the six healthy watershed attributes, representing the cumulative effect of biogeochemical features of the environment (including historical factors) on the communities of organisms within the watershed ecosystem. This may include affects from features that are unknown or impossible to measure. The use of biological condition indices (such as Indices of Biological Integrity [IBIs]) depends critically on the definition of reference condition so that naturally depauperate areas are not viewed as degraded. Benthic macroinvertebrates and fish assemblage metrics were used for this Assessment.

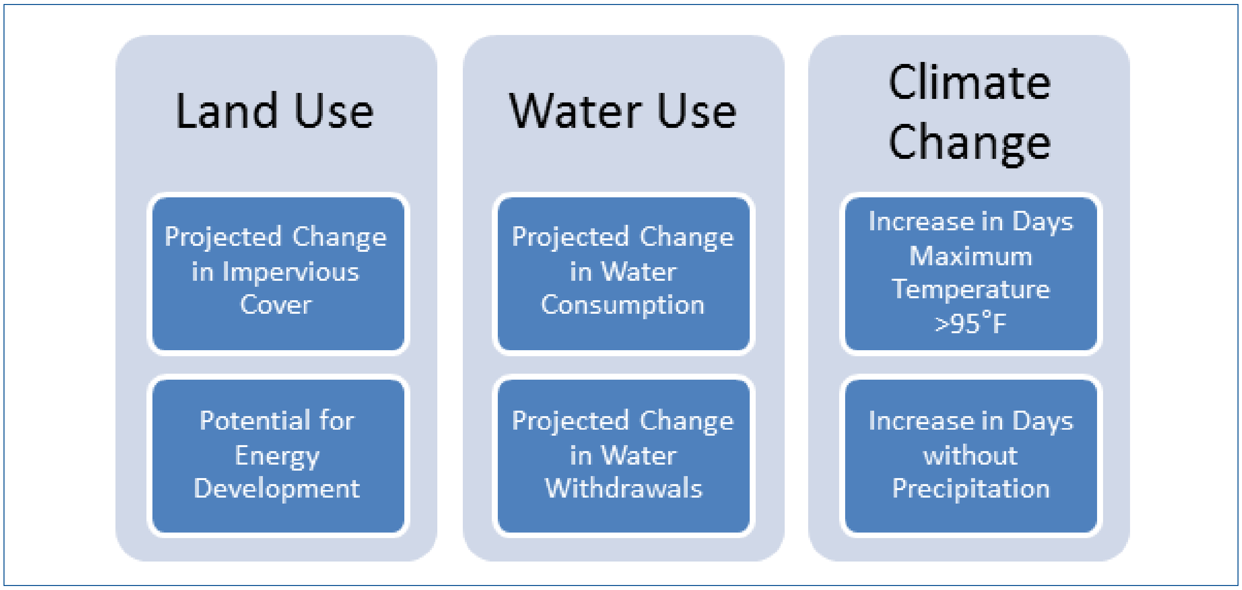
Benthic Macroinvertebrate Score: TDEC uses two different benthic macroinvertebrate sampling methods and index formulations (TDEC, 2011) to assess biotic condition of streams. A BioRecon method is used at most of the sites; this is a more rapid sampling method and generates either a family-level or genus-level assessment index. The semiquantitative method is more thorough and generates a Tennessee Macroinvertebrate Index (TMI). Both methods are used at ecoregion refinement and reference sites, while either method can be used at sites in other programs (depending on previous scores received). For this Assessment, the family-level BioRecon Score was used because it was sampled in more areas of the state and had a higher number sample count over time. From 1996 to 2014, the TDEC database contains 5,369 BioRecon Scores, spread among the Level III ecoregions.

Fish IBI: The TVA fish IBI data used for this Assessment were sampled between 1996 and 2013. The most recent sample date was used resulting in 789 records. TVA data were only collected in the Tennessee and Cumberland River basins (Figure 1). TWRA collects the same fish IBI data in eastern Tennessee (Ridge and Valley and Blue Ridge Mountains ecoregions). Because the same methods were used to sample the fish and calculate the IBI, these datasets were combined to increase the sample size for this analysis. Because of a low sample size in other ecoregions, fish IBI modeling was only performed in the Ridge and Valley and Blue Ridge ecoregions of the state.

2.5 Watershed Vulnerability Metrics

Watershed vulnerability is defined as the potential for future degradation of watershed processes and aquatic ecosystem health. Vulnerability within a watershed can be viewed as having two components: (1) the possible threat, which is the process or event that causes a negative impact, and (2) resilience, which is the sensitivity and adaptive capacity of the feature or process being impacted. The specific threats that we examined for this Assessment were Land Use Vulnerability, Water Use Vulnerability, and Climate Change Vulnerability (**Figure 8**). We evaluated the vulnerability of individual catchments to each of these stressors. This section describes the watershed vulnerability metrics, the reasoning for their selection, data sources, and methods applied to calculate metric values.

Figure 8. Watershed vulnerability metrics used for the Assessment.



Metrics of watershed vulnerability were rank normalized for reporting the metric, sub-index, and final index calculations. Rank normalization transforms one or more variables to a uniform distribution and scale, typically from 0 to 100; this common scale allows for comparisons between variables that may exhibit different units and scales. Rank normalization is also insensitive to outlier or extreme values, which can overly compress a normalized distribution when other normalization methodologies are applied (Mitchell, 2012). This method is described in Appendix E.

2.5.1 Land Use Vulnerability Metrics

Natural land cover is important to protecting healthy watershed functions. However, the population in Tennessee has been and is projected to continue to grow. This growth is located in urban areas with a decreasing trend in agricultural and forested lands. Urban growth is associated with an increase in impervious area. The resulting loss of natural land cover will increase the vulnerability of watersheds to degradation. In addition to growing populations, energy development for economic growth is also a potential threat to the landscape. The first step to assessing vulnerability due to land use change was to determine where these changes were likely to occur.

Projected Impervious Cover Change: To determine vulnerability to increased urbanization, the Assessment used percent impervious area projections produced by TNC (unpublished data). TNC used population growth projections developed by the Tennessee Advisory Commission on Intergovernmental Relations and the University of Tennessee Center for Business and Economic Research at 5-year intervals through 2040. These population densities were converted to estimates of percent total impervious area using the methods developed by the Greater Vancouver Sewerage and Drainage District and adopted by EPA. The projected change in impervious area between 2010 and 2040 was calculated and those data were used to determine this vulnerability metric. Additional information is available in the TN SWAP's 2012 Data and Methods Update. The percentage change in impervious area was determined for each catchment and the results were rank-normalized with the highest increase in impervious area having the greatest vulnerability.

Potential for Energy Development: Natural lands in Tennessee contain valuable energy resources. TNC, in cooperation with the Appalachian Landscape Conservation Cooperative (LCC), developed a spatially explicit model predicting the probability of coal mining, shale gas, and wind development (Dunscomb et al., 2014). This data layer was intersected with the data layers representing natural lands (forests and wetlands) to determine which natural lands could be vulnerable to development for energy resources. The probability for energy development was categorized at four levels: highest risk (> 75%), some risk (50%–75%), low risk (< 50%), and no risk (0%). Each NHD catchment was assigned a risk category based on these data. Note that the data were not available for the Mississippi Alluvial Plains, Mississippi Valley Loess Plain, and Southeastern Plains ecoregions.

2.5.2 Water Use Vulnerability Metrics

Humans can greatly affect a watershed's natural hydrologic regime by altering the stream network and underlying aquifers in the form of surface and groundwater withdrawals. These alterations have corresponding effects on the health of aquatic ecosystems. Future water demands will vary based on population growth, changes in the design and operation of the thermoelectric power industry, and expansion of agriculture, industry and mining. Vulnerability due to changing demands in water withdrawals and consumptive water use from these withdrawals between 2010 and 2040 is captured at the county level for this Water Use Vulnerability Metric.

The following steps were applied to calculate projected water use change for each county and are based on methods used in a study for TVA by Bohac and Bowen (2012) when developing projected water use for the Tennessee River watershed:

- County-level water withdrawal data by use sector for 2010 were obtained from the USGS for the state of Tennessee. The withdrawal data for the state were compiled using data from Memphis Light, Gas and Water, TDEC Division of Water Resources, TVA, and the U.S. Army Corps of Engineers (USACE) (Maupin et al., 2014).

- Total water withdrawals for 2010 were determined as the summation of total freshwater withdrawals (surface + groundwater) for the sectors of public supply, irrigation–crop, irrigation–golf, livestock, aquaculture, industry, and thermoelectric.

- Consumptive water use for 2010 was calculated by sector by applying the net water demand factor calculated by Bohac and Bowen (2012): thermoelectric 0.5%, industrial 6.5%, public supply 42.8% (also applied to irrigation–golf), and irrigation 100% (also applied to livestock and aquaculture).

- Total water withdrawals for 2040 were determined by sector using projection factors based on county-level population growth and irrigated acreage changes and generalized change factors calculated by Bohac and Bowen (2012).

  - Population projections for 2040 were obtained from the Tennessee State Data Center at the University of Tennessee (http://tndata.utk.edu/sdcdemographics.htm). The county-level population growth factor was calculated as the ratio of 2040 population to the 2010 population. This factor was applied to the water use sectors of public supply, industrial, and irrigation–golf.

  - Irrigated acreage by county was obtained for 2007 and 2012 from the 2012 Census of Agriculture conducted by the U.S. Department of Agriculture, National Agricultural Statistics Service. The ratio of change from 2007 to 2012 was applied to project changes into the future for irrigation–crop, livestock, and aquaculture.

  - Thermoelectric withdrawals in 2040 were calculated using the generalized factor of 31% decrease estimated by Bohac and Bowen (2012).

- Consumptive water use for 2040 was calculated by sector by applying the net water demand factor calculated by Bohac and Bowen (2012) for 2035 to the 2040 withdrawal estimates calculated using the above steps: thermoelectric 2%, industrial 7.3%, public supply 44.1% (also applied to irrigation–golf), and irrigation 100% (also applied to livestock and aquaculture).

- Change in water withdrawals and water consumption by county were calculated as the difference between the 2040 and 2010 estimates divided by the 2010 estimates. To present as the Water Vulnerability Metric, these changes were each rank normalized.

2.5.3 Climate Change Vulnerability Metrics

Changes in climate affect aquatic ecosystem health through multiple avenues including hydrologic, land form, and biologic alterations. Climate changes can take the form of different magnitudes, intensities, or frequencies of precipitation and temperature events. It is possible for overall average conditions, as measured by different climate metrics, to remain the same yet also have a completely different climate of more extreme values (e.g., in storm intensity or frequency, in temperature extremes, or in geospatial differences). The impact of climate-driven changes to aquatic ecosystem health depends on these various aspects of the climate experienced across the state.

This Assessment uses downscaled global climate model data of projected changes in temperature and precipitation to evaluate climate change across the state. To capture the different aspects of the climate regime related to drought and heat intensity, which are assumed to have the largest impact on the aquatic ecosystem health, two climate change vulnerability metrics were used:

- maximum number of consecutive days with zero to minimal (< 0.1 inch) rainfall across a 30-year period; and
- average annual number of days with maximum temperatures greater than 95°F across the 30-year period.

Both of these metrics were assessed as a change between the historic 30-year period (1980–2010) and the projected future 30-year period (2010–2040).

Data to calculate these metrics were obtained from the "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections" (http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/). The most extreme emissions scenario (RCP 8.5) from the Coupled Model Intercomparison Project 5 (CMIP5) was chosen to demonstrate a more extreme estimate of the potential climate changes (Taylor et al., 2012) in an attempt to better highlight the more vulnerable areas. Because the climate vulnerability metrics chosen relied on statistically downscaled, bias-corrected daily data (details of which can be found at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/downscaled_climate.pdf), a single global circulation model was used rather than an ensemble forecast or an average value across multiple models. The Coupled Physical Model GFDL CM3 run by the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory provided daily data for the selected time periods at a 1/8 degree spatial resolution (~12 km by 12 km) across the state (Bureau of Reclamation, 2013). While the Climate Vulnerability Sub-index is provided at this resolution, values by catchment were also determined for use in calculating the Watershed Vulnerability Index. Although catchments within the immediate vicinity of one another received the same Climate Vulnerability Sub-index value, the variability gradient across the state was large enough to provide useful information in the Watershed Vulnerability Index.

3. Results and Discussion

This section presents the analytical results and maps illustrating scores for the Watershed Health and Vulnerability Indices and the sub-indices for Landscape Condition, Hydrologic Condition, Geomorphic Condition, Water Quality, Habitat Condition, Biological Condition, Land Use Vulnerability, Water Use Vulnerability, and Climate Change Vulnerability (full-page maps of all sub-indices and metrics are provided in **Appendix A**).

3.1 Watershed Health Index

Watershed Health Index scores are mapped in **Figure 9**. The highest scoring areas are in the Blue Ridge and Appalachian Mountains in eastern Tennessee and scattered throughout the Interior Plateau in the central part of the state. These areas are influenced by stable geomorphology, low deviation from natural streamflow, and relatively high water quality and habitat conditions able to support diverse biological communities. The lowest scoring areas are in the Ridge and Valley in eastern Tennessee and the Mississippi Valley Loess Plains in western Tennessee. Land use in these regions is dominated by agricultural and urban use, which alters the natural land cover and hydrology. These changes negatively impact water quality and habitat leading to less diverse biological communities.

As described in Section 2, these scores were based on a collection of metrics that describe catchment land cover and the physical, chemical, and biological attributes of stream ecosystems. Scores were quantified from measured values of watershed health metrics (e.g., percent natural land cover, dam storage ratio) and from statistical models of stream conditions (e.g., stream total phosphorus concentration). Modeled metric values were based on a set of predictors that characterize both natural and anthropogenic watershed features across multiple scales. Watershed Health Index scores therefore reflect ecological condition gradients shaped by 1) natural variation in soils, topography, geology, hydrology, and similar factors, 2) anthropogenic stressors that have influenced measured metric values, and 3) incremental and cumulative scale anthropogenic stressors determined to be relevant to watershed health through regression modeling. High scoring areas possess natural watershed characteristics that are shared by healthy aquatic ecosystems and lack anthropogenic features associated with degraded ecosystem health.

3.2 Watershed Vulnerability Index

Watershed Vulnerability Index scores are mapped in **Figure 10**. Scores are highest in the southern Blue Ridge Mountains in eastern Tennessee, northwestern Interior Plateau region of central Tennessee, and Mississippi Valley Loess Plains in western Tennessee. Lowest vulnerability scores are in the Appalachian Mountains and eastern portion of the Interior Plateau and along the northeastern Tennessee border.

Watershed Vulnerability Index scores present an approximation of the potential for future degradation of aquatic ecosystem health. They depict projected exposure to climate, land use, and water use change, but do not explicitly quantify how projected exposure translates to changes in the physical, chemical, and biological makeup of a water body. The index is intended to be used in conjunction with Watershed Health Index scores to identify areas that are currently healthy but vulnerable and most in need of protection.

Figure 9. Watershed Health Index and sub-index scores for Tennessee.

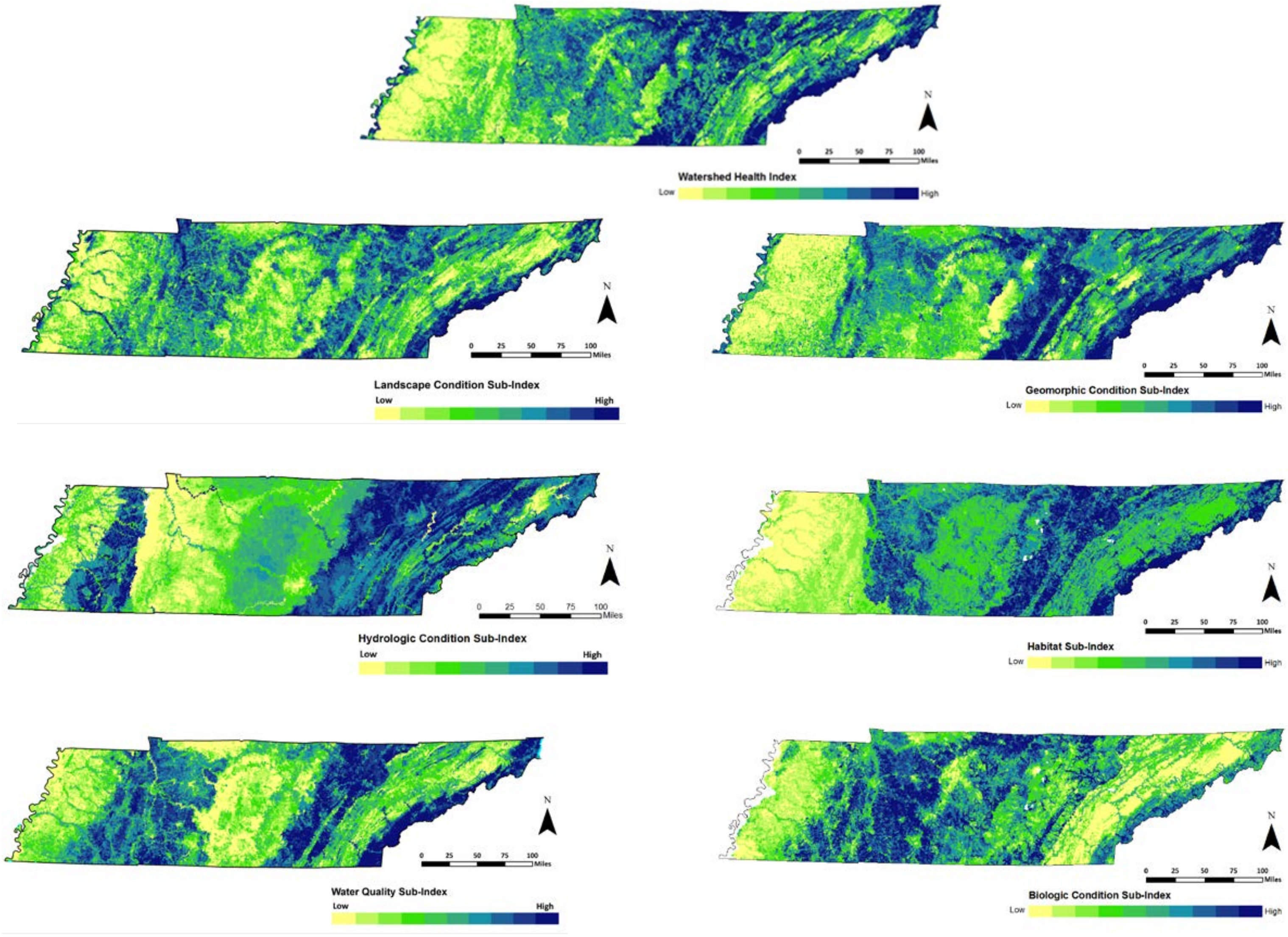
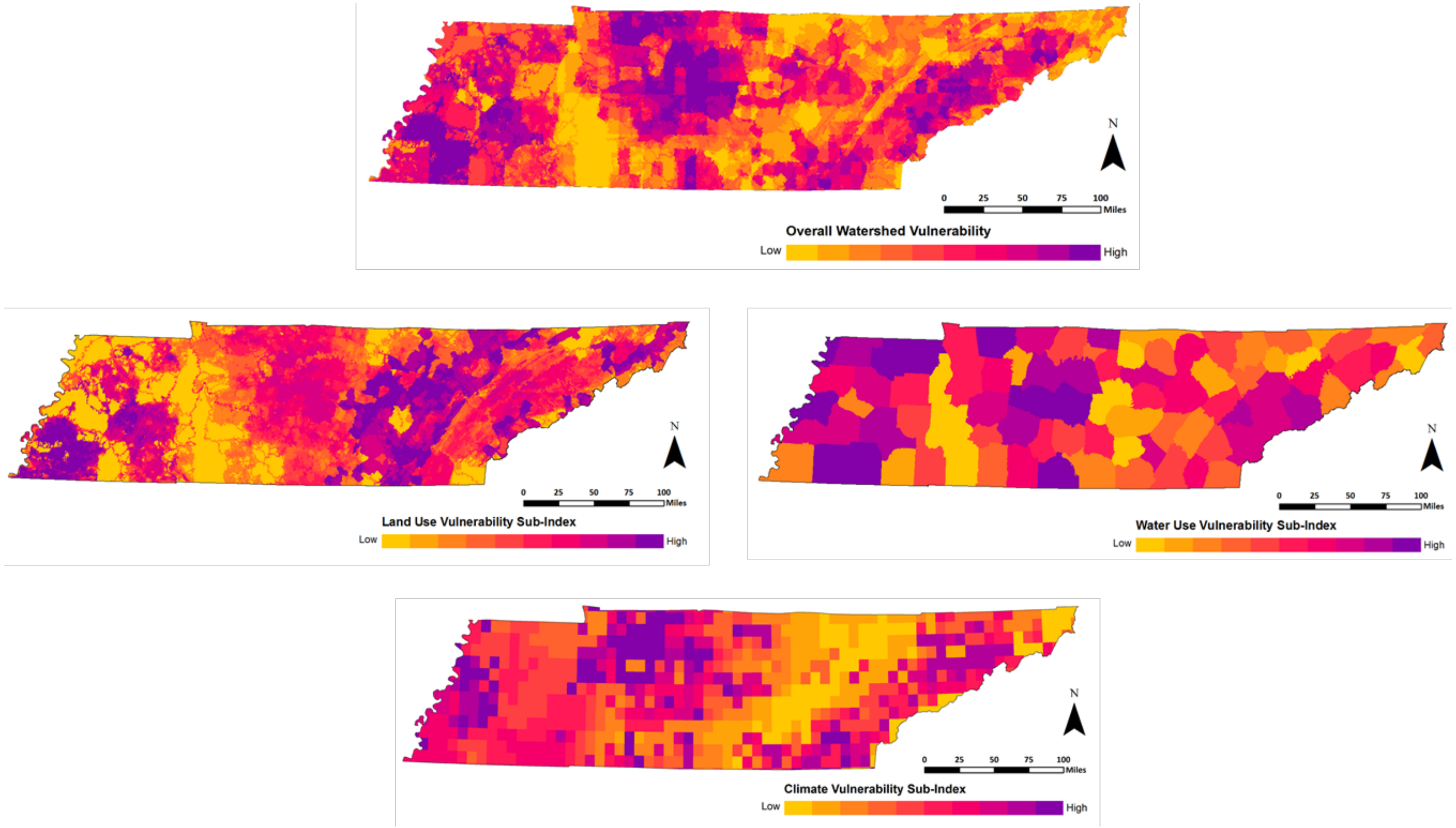


Figure 10. Watershed Vulnerability Index and sub-index scores for Tennessee.



4. Assumptions and Limitations

Assumptions were made throughout the development of this Assessment that may impose limitations on using the results for certain watershed protection planning efforts. These assumptions should be recognized by users of the Assessment output and are described below.

4.1 Spatial Framework

- The NHDPlus stream network is a medium-resolution (1:100,000) representation of water body locations in Tennessee. Although the accuracy of the NHDPlus stream network and catchment delineations were not verified as part of this project, they were determined to be sufficient for regional screening of watershed protection priorities.
- Metric, sub-index, and index scores describe overall or average conditions within a given NHDPlus catchment. Assessment results do not supply information at a resolution finer than the catchment scale (approximately 1 square mile).

4.2 Watershed Health Metrics and Sub-Indices

- Watershed health metrics were selected on the basis of data availability, data quality, spatial and temporal coverage, and expert judgment of relevance to watershed health. Index scores do not account for aspects of watershed health beyond those represented by selected metrics and the data from which they were derived.
- For statistical modeling, the Assessment assumed that the number and distribution of samples was adequate for creating valid models predicting condition by ecoregion and stream type (specifically that samples collected and metrics used in smaller streams could be applied to larger streams where no field data may have been collected).
- Correlation among metrics was not factored into the metric selection process. Correlation can suggest that one metric supplies “redundant” information that is already provided by another metric, thus resulting in index scores weighted towards the correlated metric results.

4.2.1 Landscape Condition Sub-Index

- The 2011 NLCD used in this Assessment was assumed to represent current landscape conditions. In addition, the NLCD has a spatial resolution of 30 meters or 0.25 acres; therefore, features or land use changes smaller than the minimum mapping unit were not captured.
- The categorization of NLCD classifications as natural, semi-natural, and non-natural was based on the descriptions of the classifications and agreed upon by the Technical Team. For example, shrub/scrub is defined as areas dominated by trees generally less than 16 feet (5 meters) tall and shrub canopy greater than 20% of the total vegetation canopy. This class includes young trees in the early successional state or trees stunted from environmental conditions. It is not until the tree height is greater than 16 feet (5 meters) that the area would be classified as a forest. Because of the transitional state,

the shrub/scrub and grassland/herbaceous classes were considered semi-natural lands, whereas forest lands were considered natural lands. Semi-natural lands represent a gradient in departure from natural conditions, but do not degrade watershed health as much as non-natural lands. Therefore, the semi-natural lands were weighted less than natural lands but still included in the Landscape Condition metrics. This means that catchments with semi-natural lands were ranked higher than catchments with a higher percentage of non-natural lands.

- Forest lands identified as lands managed, owned, or operated for timber production were classified as semi-natural lands for this Assessment. These managed forests differ from natural forests in that they consist of a monoculture of often the same age and are managed to maximize timber production through such activities as altered hydrology or application of herbicides. When timber harvesting occurs, aquatic ecosystems are stressed by increases in 1) water temperature range, 2) turbidity and sedimentation, 3) dissolved nutrients, 4) allochthonous organic detritus, and 5) streamflow (Lynch et al., 1980; Swank et al., 1989).

4.2.2 Geomorphic Condition Sub-Index

- Geomorphology attempts to describe and quantify a variety of forces and processes that form and shape dynamic river systems. The complexity of these channel-forming processes, and the fact that even when undisturbed, rivers move across their landscapes and are constantly being reshaped to some degree by the water flowing through, makes it challenging to create a state-level tool for predicting geomorphic stability. Typical field geomorphic measurements were not available at the catchment scale and are very site-specific. Unlike water quality and biological monitoring, geomorphic field assessment and monitoring are not performed frequently enough or at a broad enough scale to provide field-based datasets that can be used to develop statistical models to predict channel stability within unsurveyed catchments.

- Since a statistical model could not be developed, geospatial data were used to predict potential Geomorphic Condition within a catchment. Some of the variables that influence channel formation, such as bed roughness or the degree of a channel's connection to its floodplain, cannot be determined from or be substituted with the available hydrology, geologic, and landscape data. We focused on the factors that determine channel stability including streamflow and land cover types associated with runoff control and attenuation. The geospatial data used do not encompass all components of geomorphology and unique local conditions may drastically alter the character of individual catchments; therefore, the Geomorphic Condition Sub-index should be considered a coarse estimator of likelihood of stream channel alteration.

4.2.3 Hydrologic Condition Sub-Index

- Hydrologic condition was assessed in three distinct pieces: eastern unregulated waters, western unregulated waters, and statewide regulated waters. For the hydrologic condition, reference sub-basins determined by high percentages of forest area represent areas with least-disturbed streamflow. The equations created for the Tennessee and Cumberland River basins (eastern Tennessee) were used for the small portions of the Coosa basin (Alabama River) in the southeast portion of the state. The equations for eastern Tennessee were based on a variety of physical factors characterizing land use, slope, soils, subsurface, climate, and ecoregion. The equations for western Tennessee relied on three factors: drainage area, geologic factors, and soil factors, which were also used in the east (Appendix C).

4.2.4 Habitat Condition Sub-Index

- For Habitat Condition, the Assessment assumed that the RBP score was representative of the habitat of the catchment. While the RBP integrates many habitat metrics into one score, there are many components that are not measured. Habitat for individual species or guilds cannot be addressed due to data limitations, thus the focus was on generalized aquatic habitat condition.

4.2.5 Biological Condition Sub-Index

- Information was not available on all biological components of the ecosystem. For example, consistent fish IBI data are not available for the entire state. Both TVA and TWRA collect fish data, but IBI data was not reported for all sites. Therefore, there was only enough data for the Ridge and Valley and Blue Ridge Mountains ecoregions to be used in this Assessment. Other aquatic assemblages (mussels, periphyton) can be used to assess watershed health, but adequate data on these assemblages were not available. Samples were also limited in number and distribution by geography and gradient of disturbance.

4.3 Watershed Vulnerability Metrics and Indices

- Metrics of watershed vulnerability were selected on the basis of data availability, data quality, and expert judgment of relevance to watershed vulnerability. Index scores did not account for aspects of watershed vulnerability beyond those represented by selected metrics.

- Values of the projected impervious cover change metric reflect estimated changes in impervious cover due to urban expansion only. Land use changes resulting from agricultural expansion were not accounted for in the Assessment due to a lack of data.

- For water use vulnerability, individual power plants were not assessed for specific planned changes in the future (i.e., conversion of a coal-fired steam plant to a combined turbine plant); instead, a blanket rate of change to withdrawals and consumption was used on all 2010 power plant water use data to predict future conditions. Additionally, water use from interbasin transfers, irrigation, and aquaculture were not considered. The rate of increase/decrease in irrigated agriculture by county from 2007 to 2012 remains constant from 2010 to 2040.

- Climate vulnerability was assessed through the results of a single global circulation model scenario (created by NOAA) intended to represent a worst-case scenario.

5. Potential Applications of Assessment Results

This Assessment integrated many datasets to characterize watershed health and vulnerability across Tennessee. The results are intended to support screening-level assessments of protection priorities and are not intended to be used to determine the absolute condition of aquatic ecosystems. Results can also serve as a baseline for evaluating change in watershed health over time and to assess the effectiveness of existing protection strategies. In addition to this static report, the results are available as geospatial data layers, which enables users to analyze the results at different spatial scales. The results presented in this report are at the finest spatial resolution of individual catchments (median size of 0.6 square miles), but the results could be aggregated up to HUC12 or HUC10 scale or within ecoregions. The following is a summary of potential application of the Assessment results proposed by the THWI Technical Committee.

Watershed Planning. This Assessment complements Tennessee's existing watershed-based approach to resource management. Watershed planning occurs at a state, local, and regional level. The results from this Assessment can provide a common framework to identify future watershed protection and restoration goals. Results can also be used in conjunction with field observations to help determine appropriate management actions in a watershed as part of the planning process.

Improved Monitoring and Assessment. Assessment results can inform aquatic ecosystem monitoring programs that aim to collect data across a broad range of watershed conditions. Results can be used to evaluate the range of watershed conditions currently monitored and to screen priority watersheds for expanded monitoring. Results can also guide the selection of reference watersheds for developing biological condition gradients and tracking changes in reference watersheds over time to validate the effectiveness of watershed protection actions.

Outreach and Communication. Maps and other projects derived from the Assessment can communicate information on the importance of watershed protection with nontechnical audiences and the public, as well as gaining attention from national and regional decision makers. This information can support the efforts of existing watershed protection organizations and identify where new organizations are needed.

Improved Decision Making. The identification of healthy intact watersheds could inform a variety of decision-making processes including compensatory mitigation, land acquisition, and mine reclamation projects. The results can foster cooperation across agencies and with other partners to protect priority watersheds.

Economic Assessment. The Assessment results can be used as an input basis for conducting a cost/benefit analysis focused on communicating the economic importance of protecting the most ecologically healthy areas of Tennessee. The results are particularly useful for weighing the impact of land use and water use decisions on health of aquatic ecosystems across the state.

Filling Data Gaps. The Assessment reflects a comprehensive inventory of available data for characterizing watershed health and vulnerability. This process identified data gaps in current monitoring programs and areas where different agencies could collaborate to improve comparability methods. For example, while fish data are available across the state, there is not a standard method for calculating IBIs. Therefore, Fish IBI scores were used as a metric only in the Ridge and Valley and Blue Ridge Mountain ecoregions. Developing this Assessment has revealed opportunities like these for improving incomplete datasets and creating others that can strengthen the Assessment and its application.

6. References

Barnett, A. 2015. The Nature Conservancy. 100 Peachtree St. Atlanta, GA. E-mail Communication with RTI. April 2015.

Bohac, C.E., and A.K. Bowen. 2012. *Water Use in the Tennessee Valley for 2010 and Projected Use in 2035*. Tennessee Valley Authority. 89 pp.

Bureau of Reclamation. 2013. *Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with preceding Information, and Summary of User Needs*. 47 pp. Denver, CO: U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center.

Castro, J., F. Reckendorf, and U.S. Natural Resources Conservation Service. 1995. *RCA III, Effects of Sediment on the Aquatic Environment: Potential NRCS Actions to Improve Aquatic Habitat*. U.S.

Dunscomb J.K., J.S. Evans, J.M. Strager, M.P. Strager, and J.M. Kiesecker. 2014. *Assessing Future Energy Development across the Appalachian Landscape Conservation Cooperative*. Charlottesville (VA): The Nature Conservancy. 48 pp with appendices. Appalachian Landscape Conservation Cooperative Grant #2012-02.

Griffith, G.E., J.M. Omernik, and S.H. Azevedo. 1997. *Ecoregions of Tennessee*. Corvallis, OR: U.S. Environmental Protection Agency, EPA/600R-97/022, 51 p.

Jones, D.S., D.G. Kowalski, and R.D. Shaw. 1996. *Calculating Reviewed Universal Soil Loss Equation (RUSLE) Estimates on Department of Defense Lands: A Review of RUSLE Factors and U.S. Army Land Condition-Trend Analysis (LCTA) Data Gaps*. Fort Collins, CO: Center for Ecological Management of Military Lands. Department of Forest Science, Colorado State University.

Knight R.R., W.S. Gain, and W.J. Wolfe. 2012. Modelling ecological flow regime: an example from the Tennessee and Cumberland River basins. *Ecohydrology* 5: 613–627.

Knight, R.R., J.C. Murphy, W.J. Wolfe, C.F. Saylor, and A.K. Wales. 2014. Ecological limit functions relating fish community response to hydrologic departures of the ecological flow regime in the Tennessee River basin, United States. *Ecohydrology* 7(5): 1292–1280.

Law, G.S., G.D. Tasker, and D.E. Ladd. 2009. *Streamflow-Characteristic Estimation Methods for*

Leopold, L.B., M.G. Wolman, and J.P. Miller. 1964. *Fluvial Processes in Geomorphology*. W.H. Freeman

Lynch, J.A., E.S. Corbett, and W.E. Sopper. 1980. *Evaluation of management practices on the biological*

Maupin, M.A., J.F Kenny, S.S. Hutson, J.K. Lovelace, N.L. Barber, and K.S. Linsey. 2014. *Estimated Use of Water in the United States in 2010*. U.S. Geological Survey Circular 1405, 56 p., http://dx.doi.org/10.3133/cir1405.

Mitchell, H.B. 2012. *Data Fusion: Concepts and Ideas*. Springer, 2nd edition. 346 pages.

Nicholson, S.W., C.L. Dicken, J.D. Horton, K.A. Labay, M.P. Foose, and J.A.L. Mueller. 2005. *Preliminary integrated geologic map databases for the United States: Kentucky, Ohio, Tennessee, and West Virginia*. Version 1.1. U.S. Geological Survey Open-File Report 2005-1324, digital dataset.

Omernik, J., and G. Griffith. 2009. *Ecoregions of Tennessee (EPA).* Available at http://www.eoearth.org/view/article/152206

Poff, N.L, J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks, and J.C. Stromberg. 1997. The natural flow regime: A paradigm for river conservation and restoration. *Bioscience* 47(11): 769–784.

Rosgen, D. 2006. *Watershed Assessment of River Stability and Sediment Supply*. Wildland Hydrology, Fort Collins, CO.

Swank, W.T., L.F. DeBano, and D. Nelson. 1989. Effects of timber management practices on soil and water. Pages 79–106 in R. Burns (Tech. comp.), *The Scientific Basis for Silvicultural and Management Decisions in the National Forest System*. GTR-WO-55. Washington, DC. USDA Forest Service.

Taylor, K.E., R.J. Stouffer, and G.A. Meehl. 2012. An Overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, 93: 485-498. doi:10.1175/BAMS-D-11-00094.1

Tennessee Department of Environment and Conservation (TDEC). 2011. *Quality System Standard Operating Procedure for Macroinvertebrate Stream Surveys.* State of Tennessee, Department of Environment and Conservation, Division of Water Pollution Control.

Tennessee Healthy Watershed Initiative (THWI). 2015. Watershed Stewardship. Tennessee Department of Environment and Conservation. Available at https://www.tn.gov/environment/article/tennessee-healthy-watershed-initiative

The Nature Conservancy (TNC). 2012. *Database Development and Spatial Analyses in Support of Tennessee's State Wildlife Action Plan, 2012 Data and Methods Update*. Available at http://teaming.com/sites/default/files/TN-SWAP%20Data%20and%20Methods%20Update%20Report%202012.pdf.

U.S. Environmental Protection Agency (USEPA). 2012. *Identifying and Protecting Healthy Watersheds: Concepts, Assessments, and Management Approaches.* EPA 841-B-11-002. Washington, DC: U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (USEPA). 2014. *Watershed Index Online (WSIO)*. Available at http://gispub.epa.gov/wsio/.

Appendix A: Map Atlas

This appendix contains full page maps for all watershed health and vulnerability metrics, sub-indices, and indices for all National Hydrography Dataset Plus (NHDPlus) catchments in Tennessee. The following guidelines were used for map development:

- Maps display rank-normalized metric, sub-index, or index scores.
- Maps were created using 10 equal-interval color classes. Because scores are rank-normalized, these classes generally correspond to deciles.
- Maps display metrics in their directionally aligned scores used for sub-index and index calculations rather than original directionality (see **Table E-1**). For example, catchments with low total nitrogen concentrations have a high affinity for watershed health and therefore are scored high for the total nitrogen metric.

Figure A-1. Watershed Health Index.

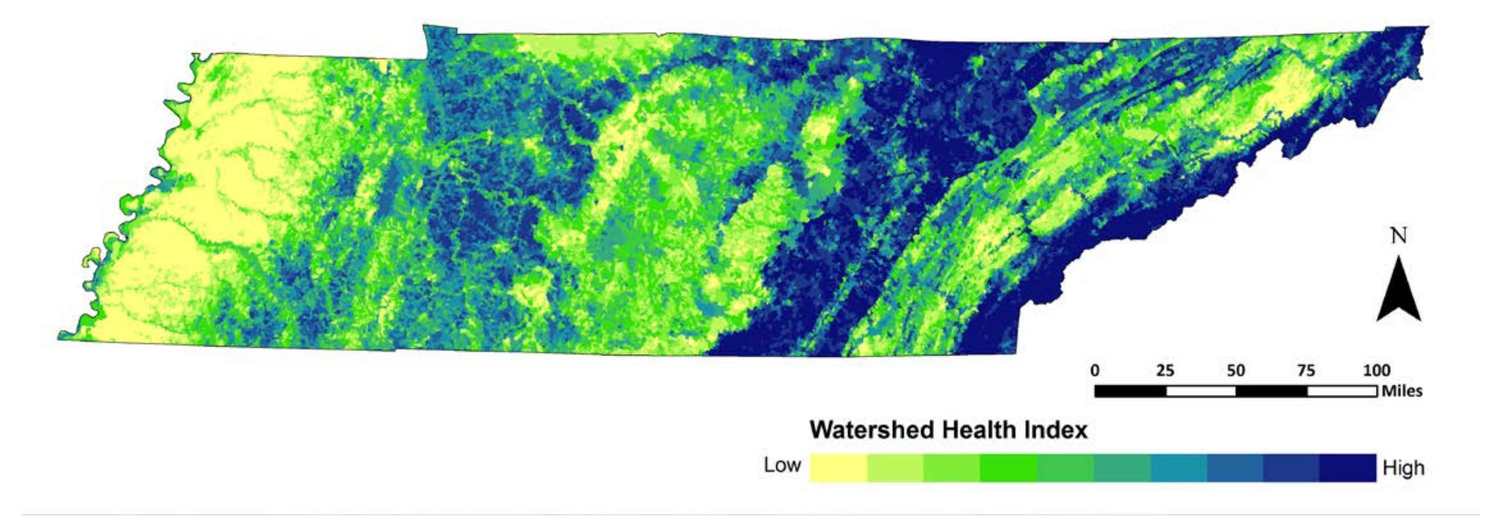


Figure A-2. Landscape Condition Sub-Index.

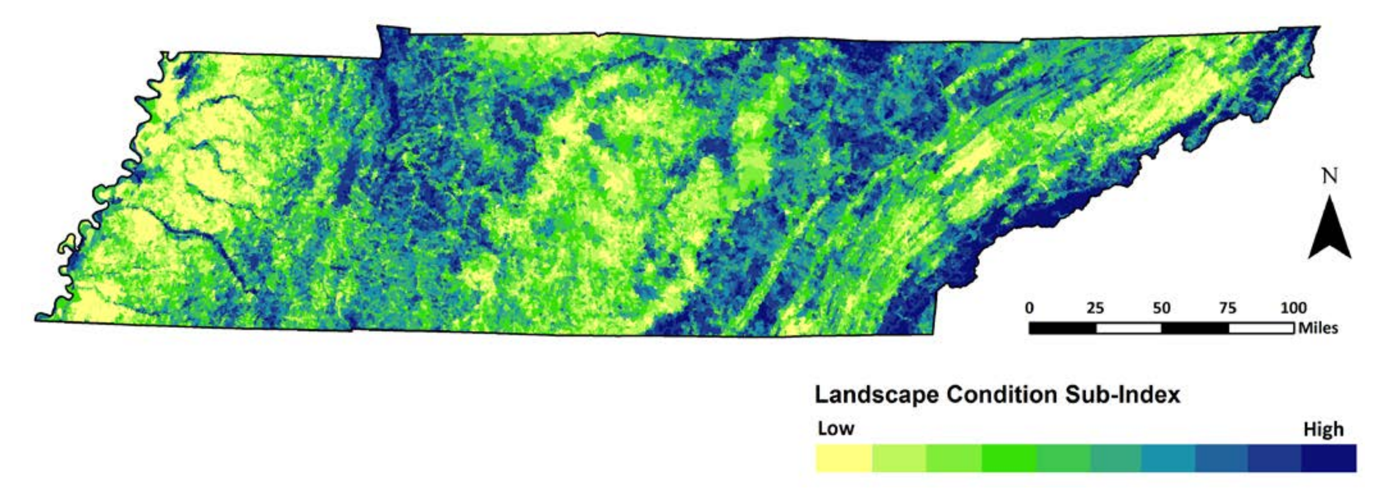


Figure A-3. Landscape Condition Metric: Percent natural land cover.

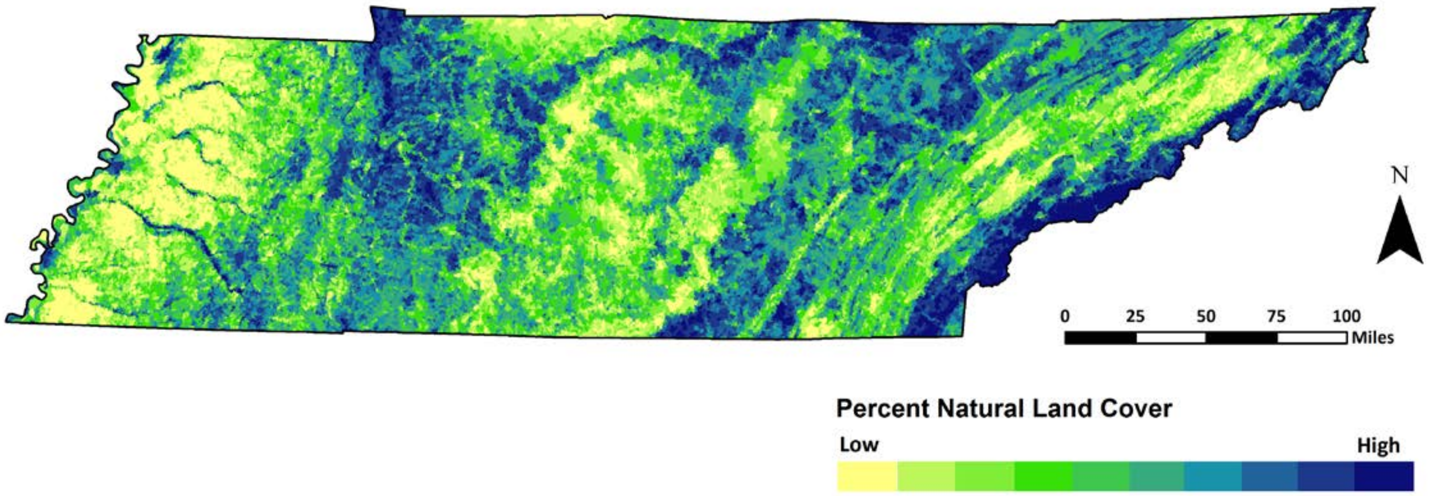


Figure A-4. Landscape Condition Metric: Percent natural land in hydrologically active zone.

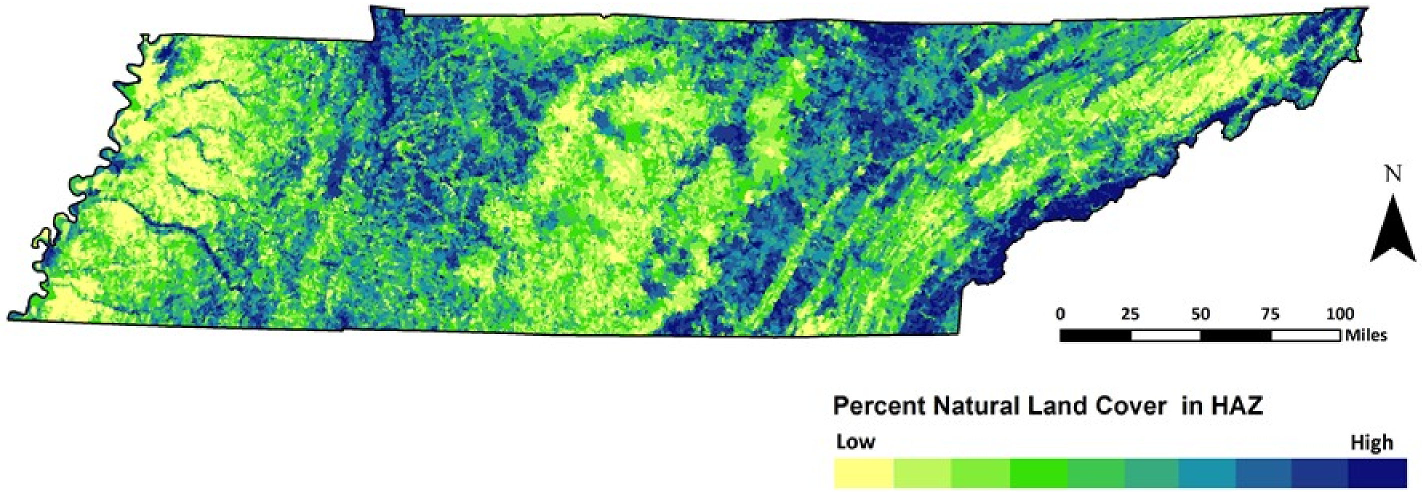


Figure A-5. Geomorphic Condition Sub-Index.

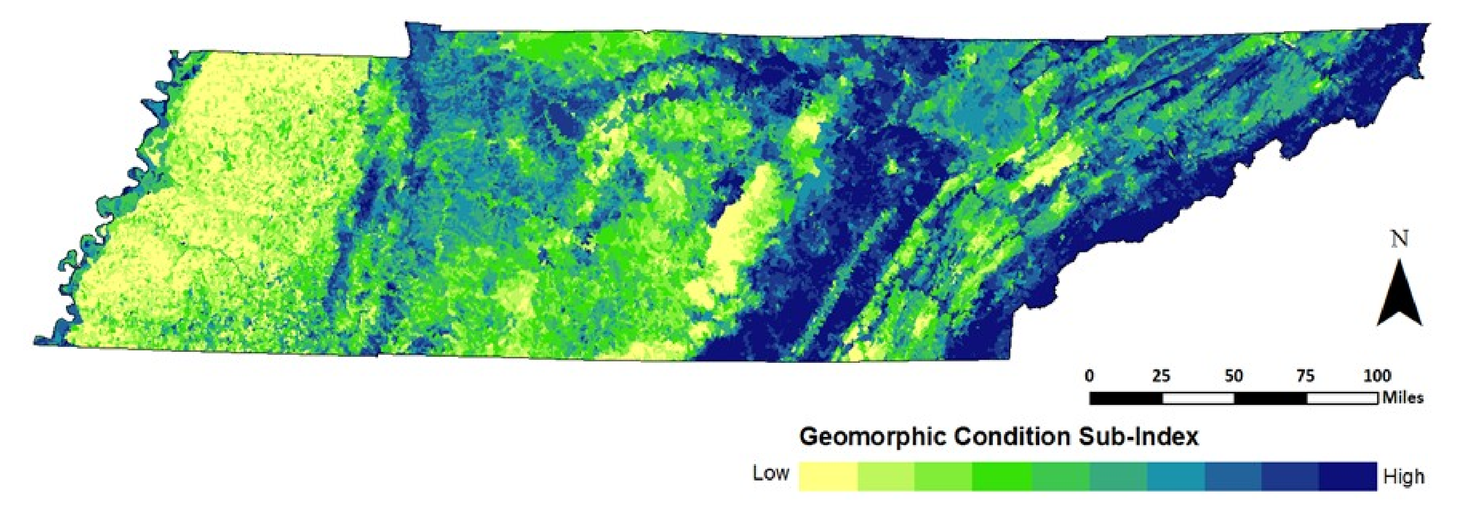


Figure A-6. Geomorphic Condition Metric: Erosive forces.

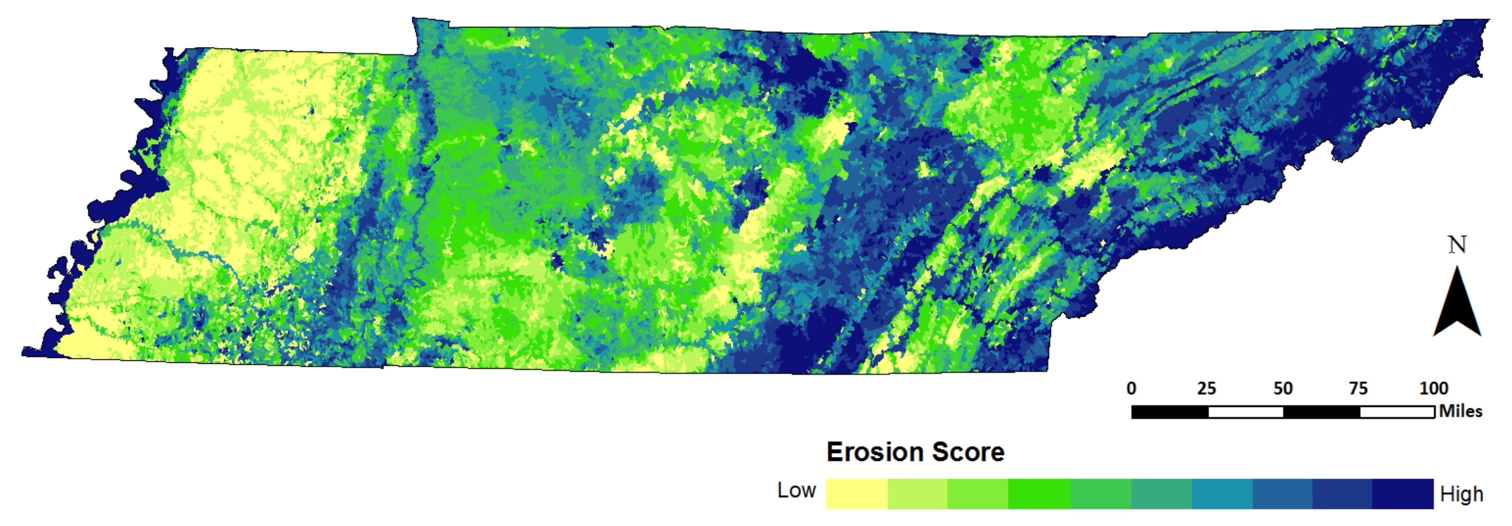


Figure A-7. Geomorphic Condition Metric: Resistive forces.

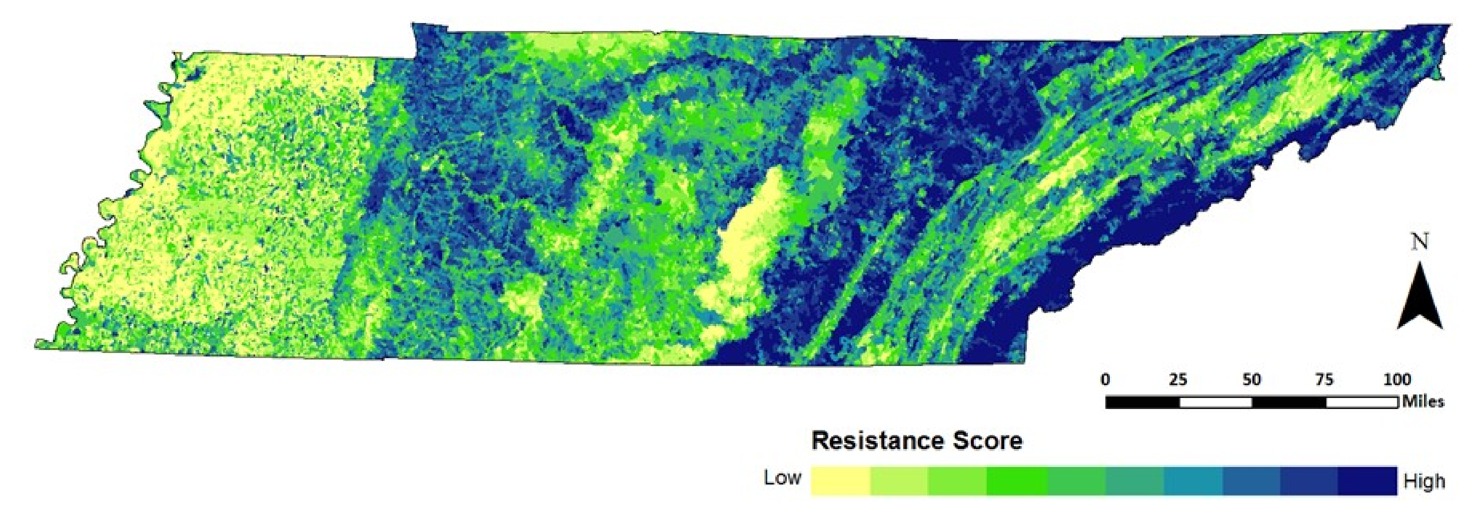


Figure A-8. Hydrologic Condition Sub-Index.

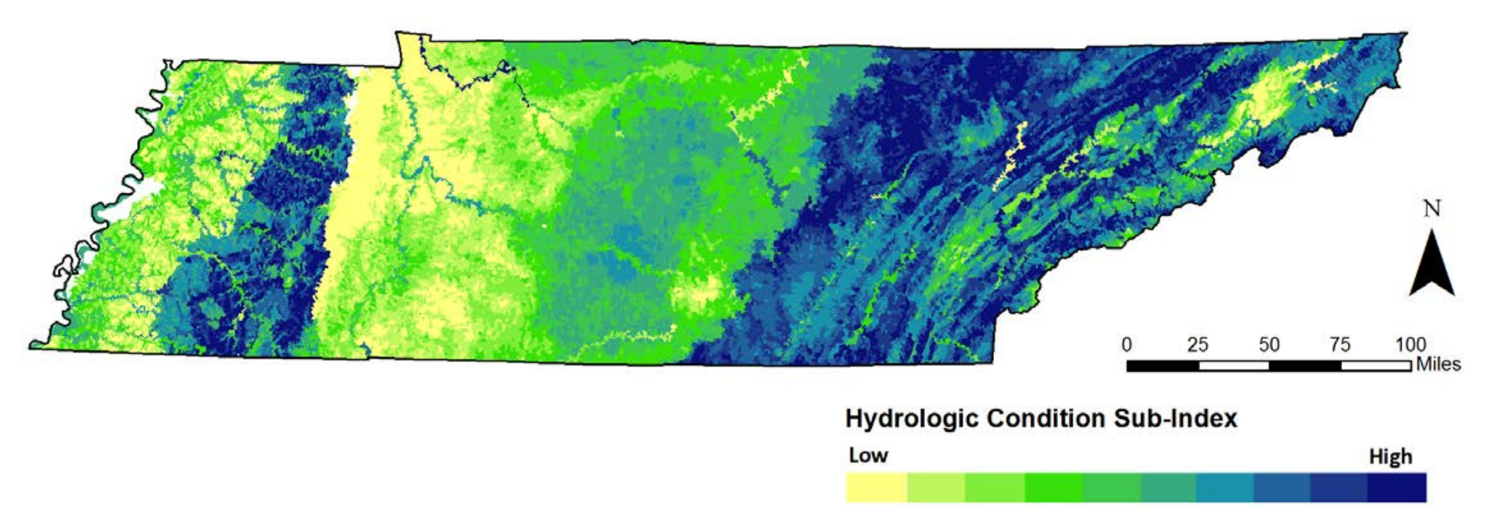


Figure A-9. Hydrologic Condition Metric: Streamflow characteristics deviation from reference condition (unregulated streams).

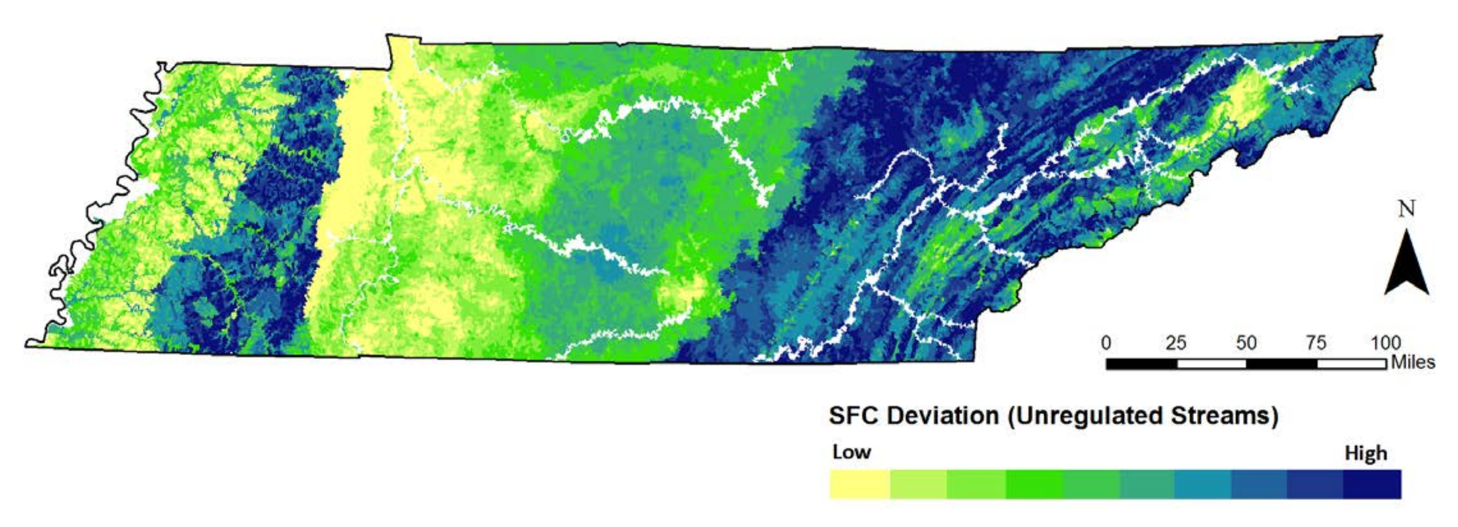


Figure A-10. Hydrologic Condition Metric: Dam storage ratio (regulated streams).

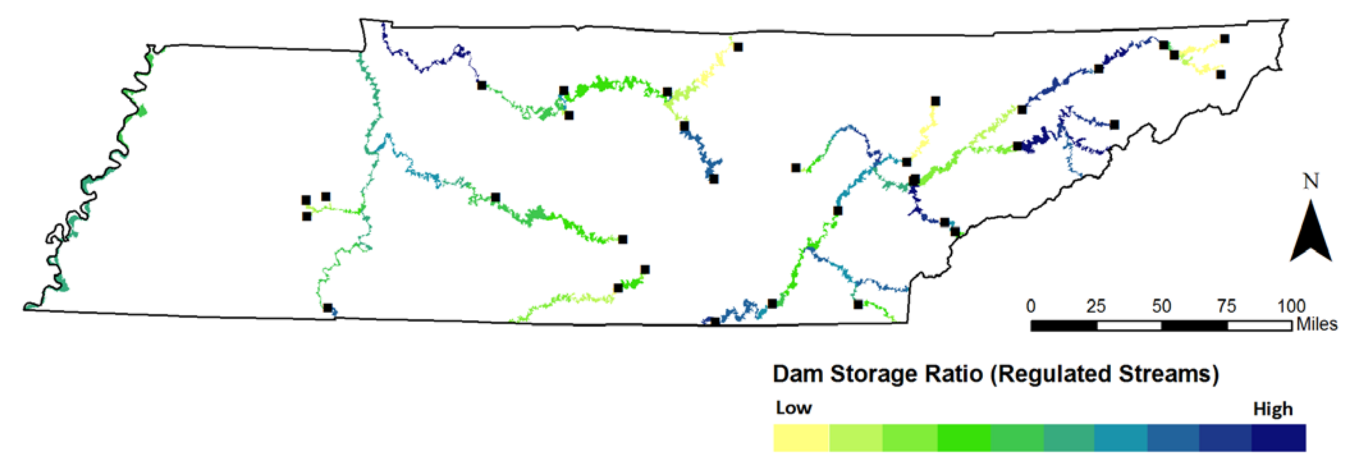


Figure A-11. Water Quality Sub-Index.

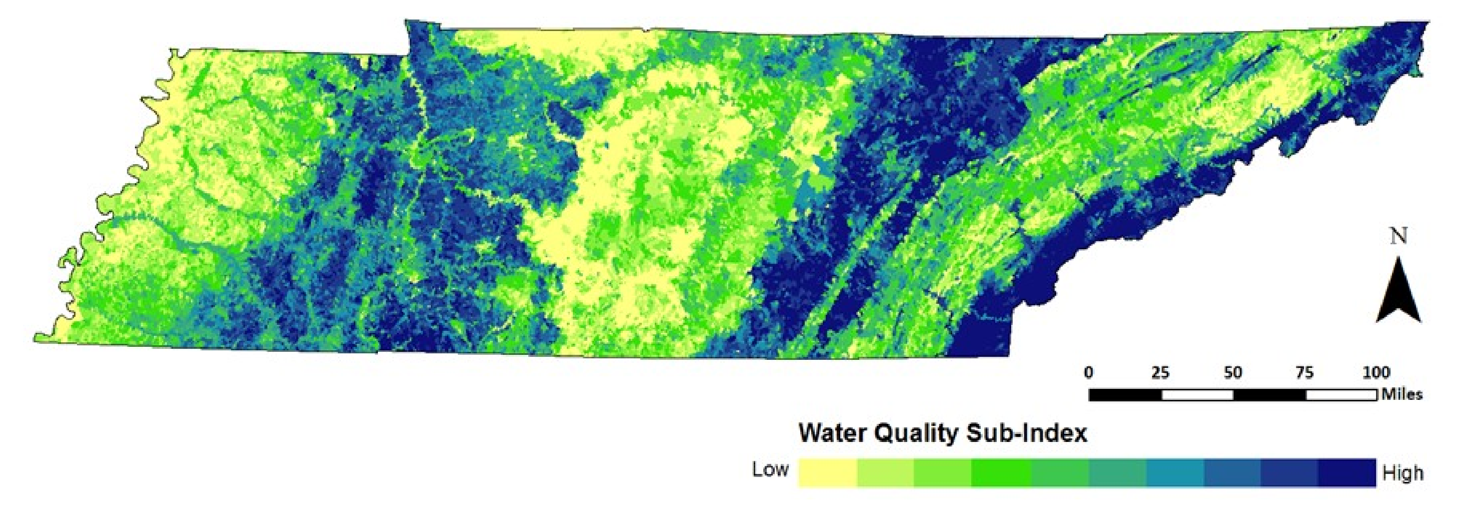


Figure A-12. Water Quality Metric: Stream total nitrogen condition. Note: High condition values indicate relatively lower total nitrogen concentrations.

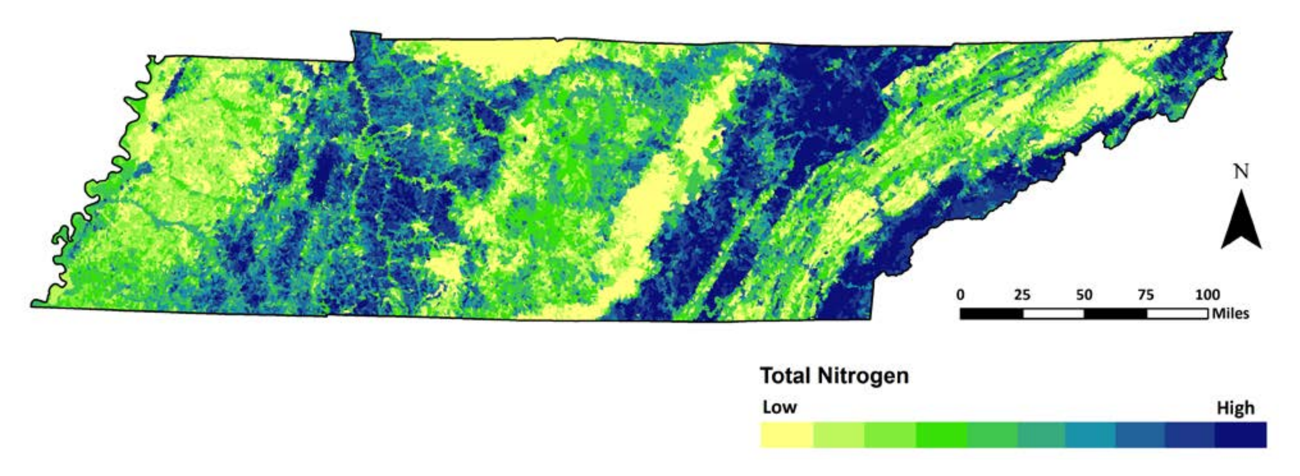


Figure A-13. Water Quality Metric: Stream total phosphorus condition. Note: High condition values indicate relatively lower total phosphorus concentrations.

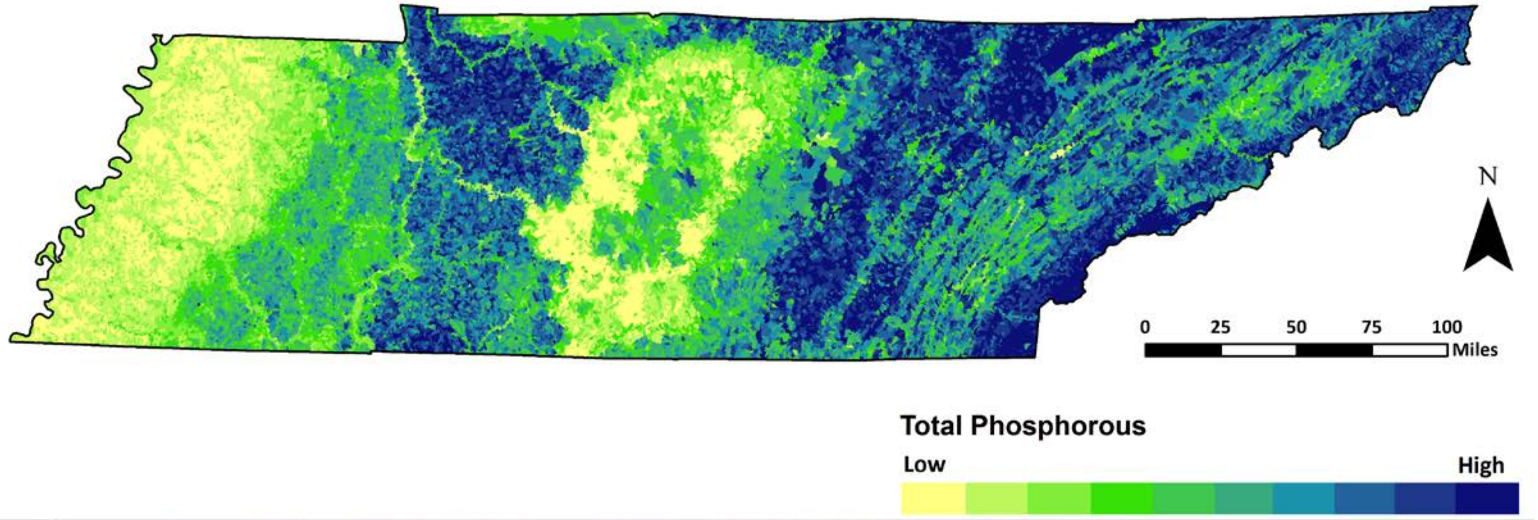


Figure A-14. Water Quality Metric: Stream specific conductance condition. Note: High condition values indicate relatively lower specific conductance values.

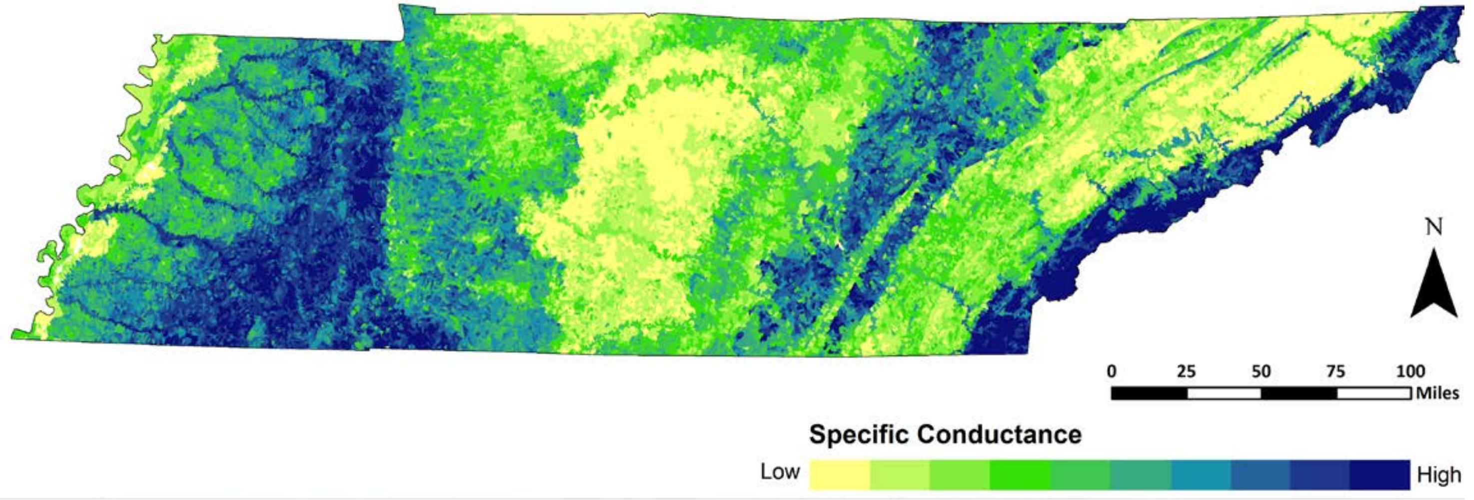


Figure A-15. Habitat Condition Sub-Index.

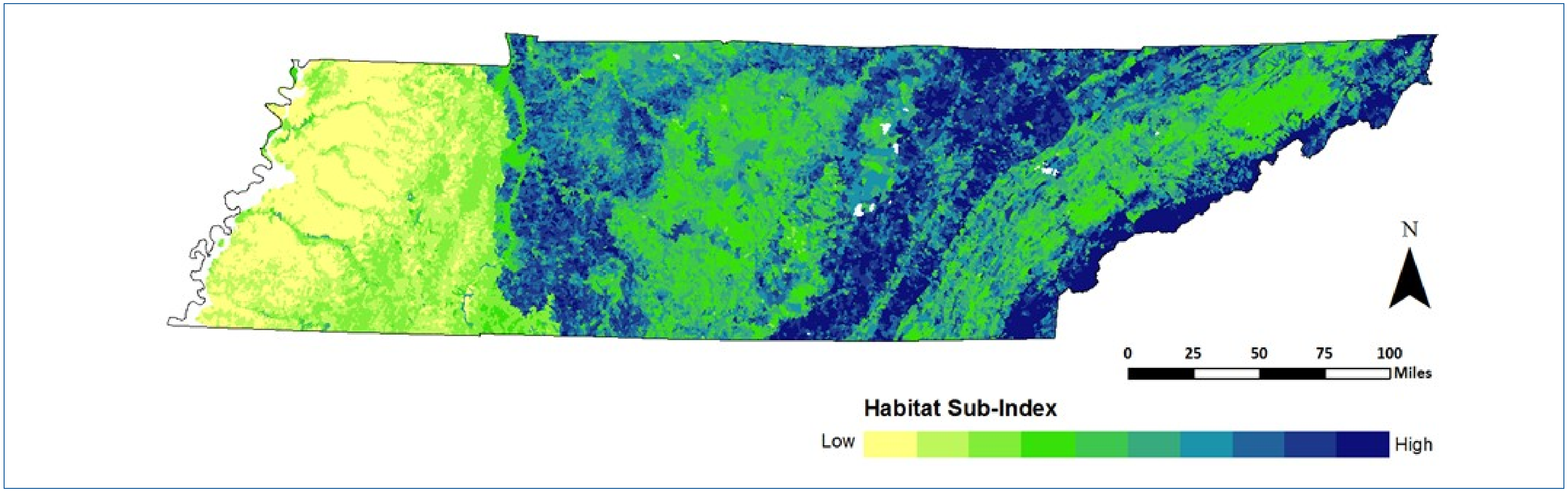


Figure A-16. Rapid Bioassessment Protocol (RBP) scores.

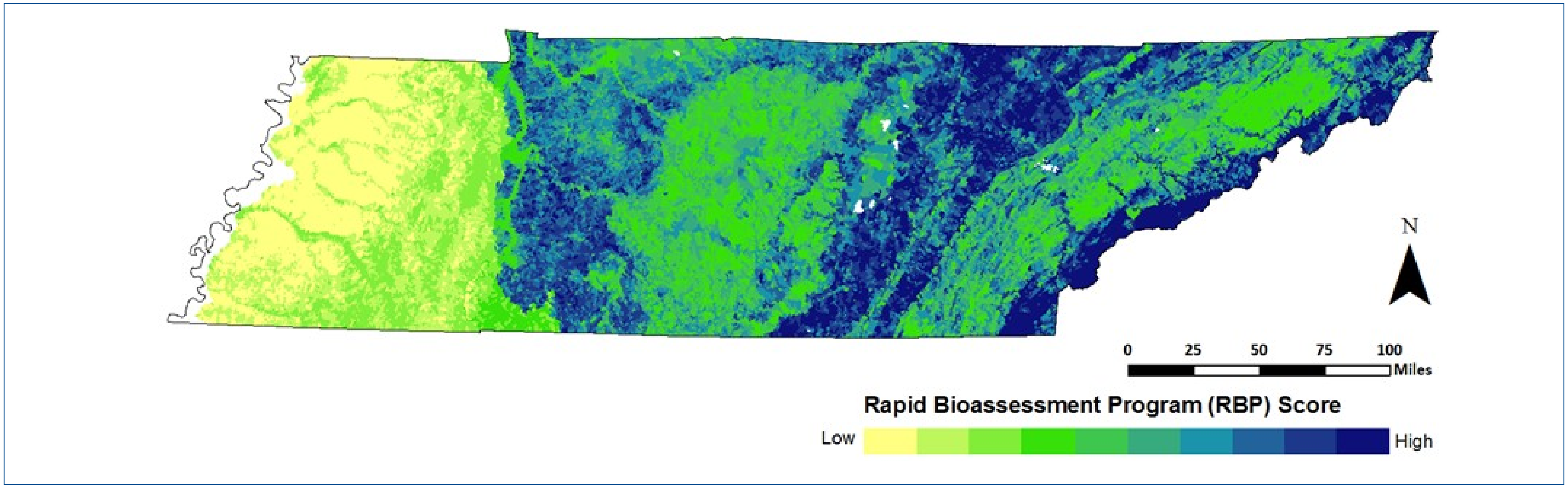


Figure A-17. Habitat Suitability scores.

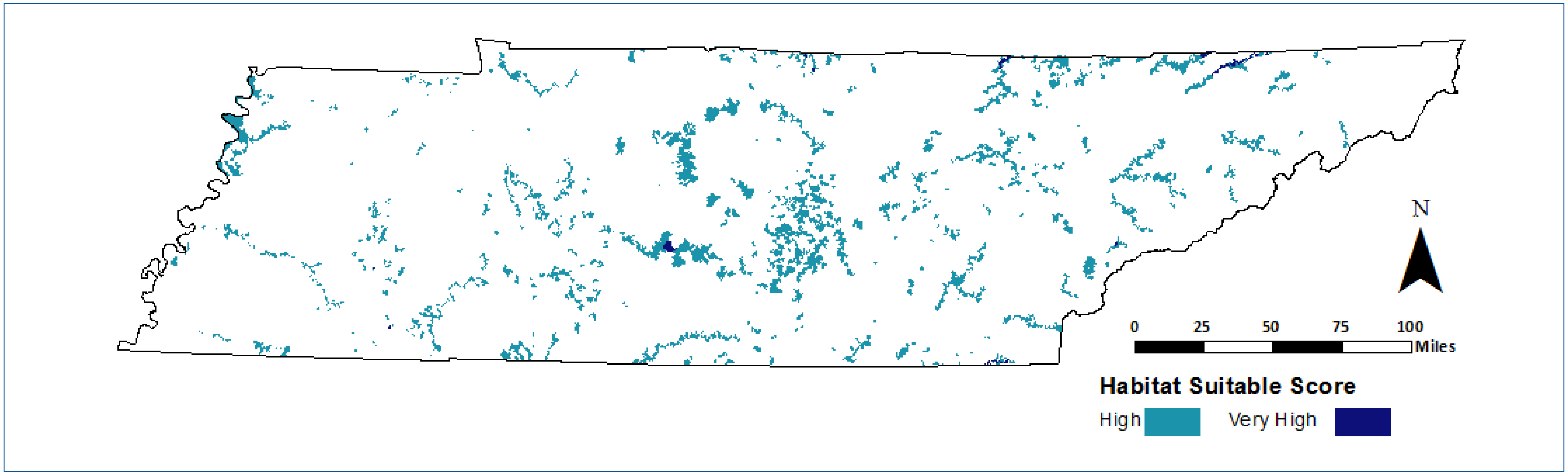


Figure A-18. Biological Condition Sub-Index.

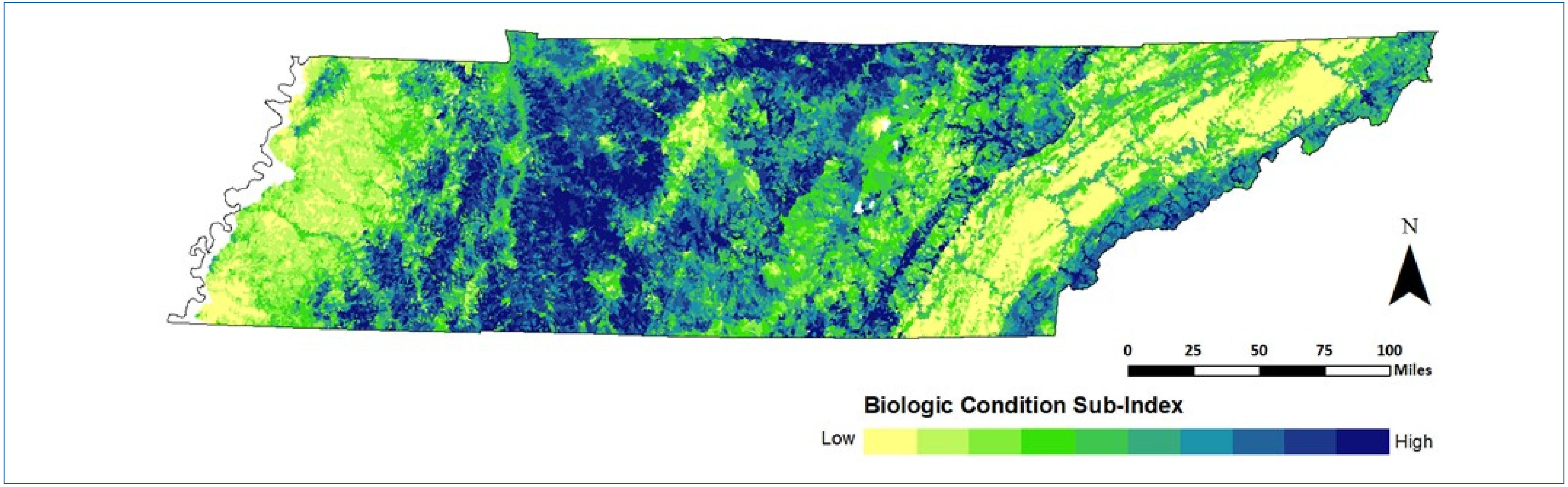


Figure A-19. Biological Condition Metric: Benthic macroinvertebrate Index of Biological Integrity (IBI) rating.

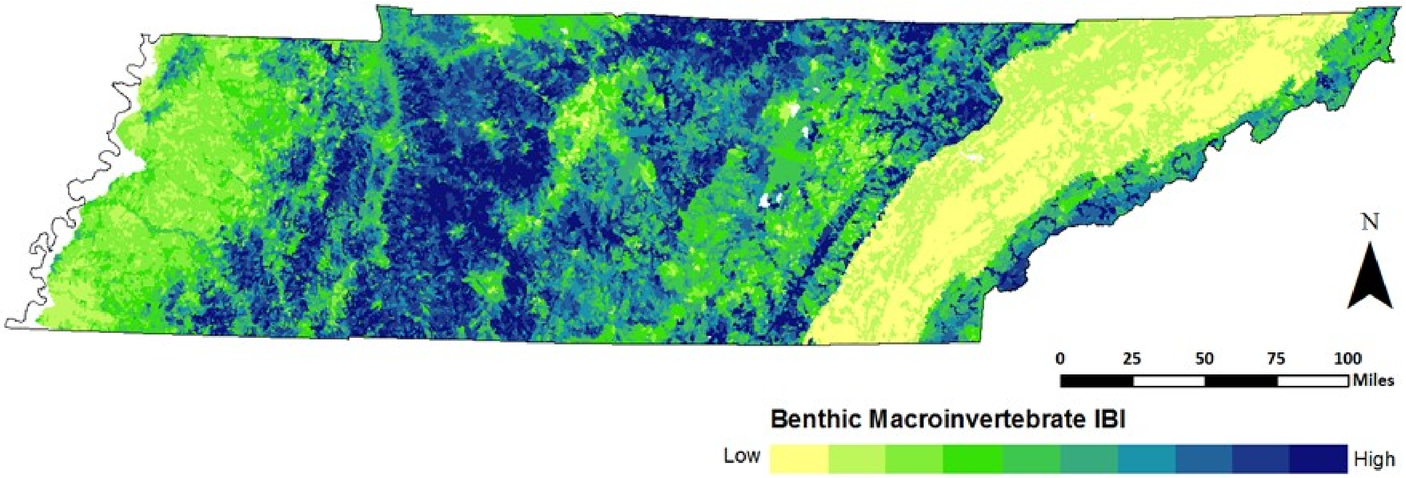


Figure A-20. Biological Condition Metric: Fish Index of Biological Integrity (IBI) rating.

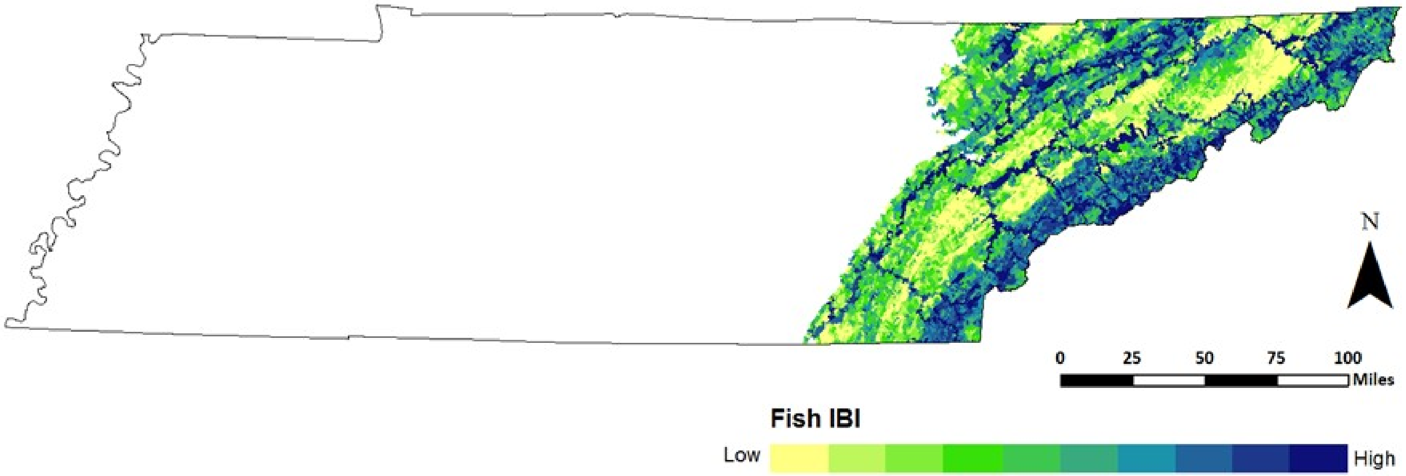


Figure A-21. Watershed Vulnerability Index.

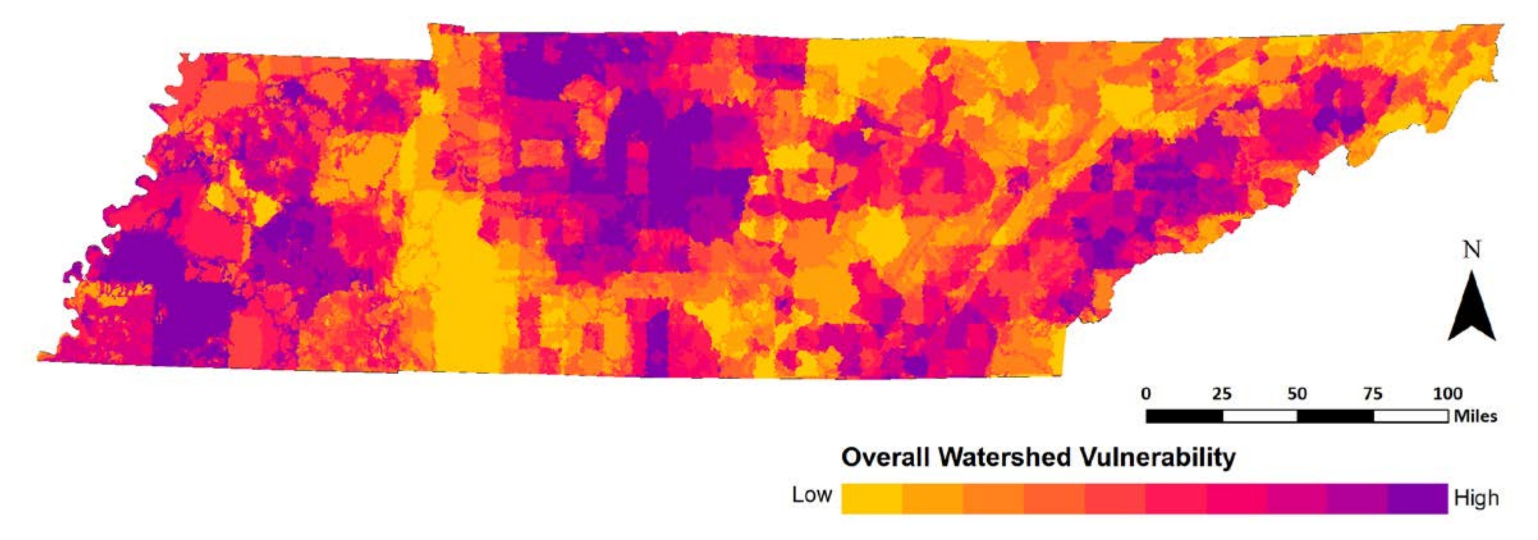


Figure A-22. Land Use Vulnerability Sub-Index.

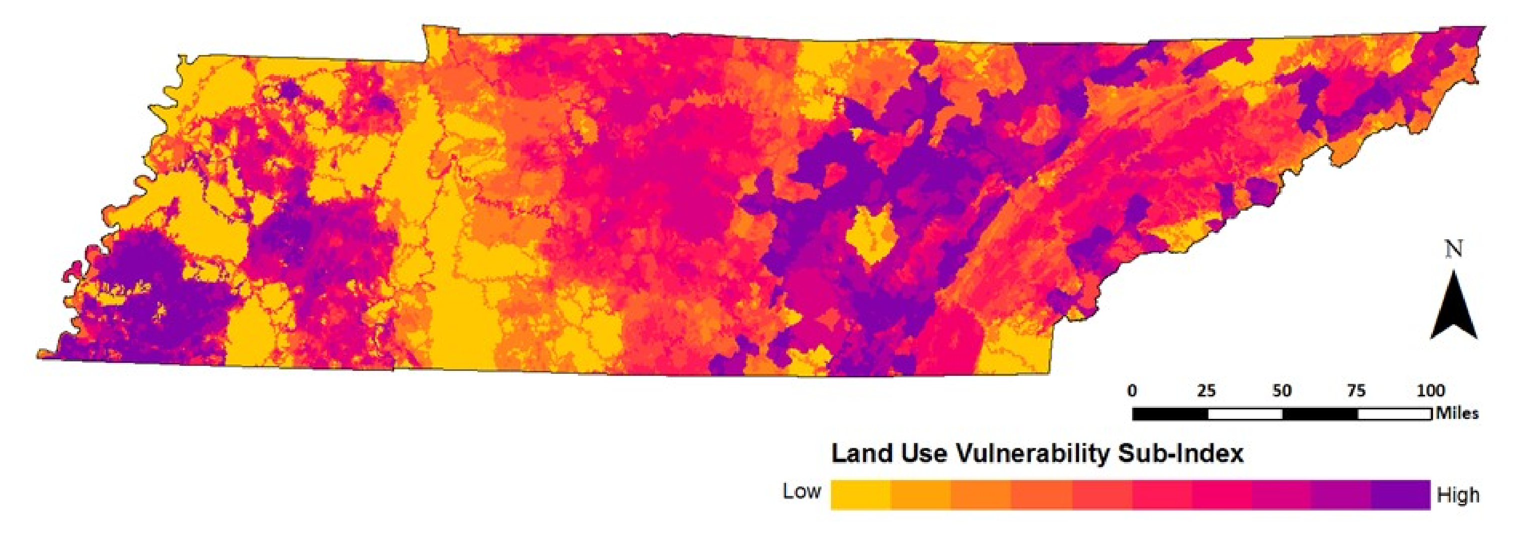


Figure A-23. Land Use Vulnerability Metric: Projected change in impervious cover.

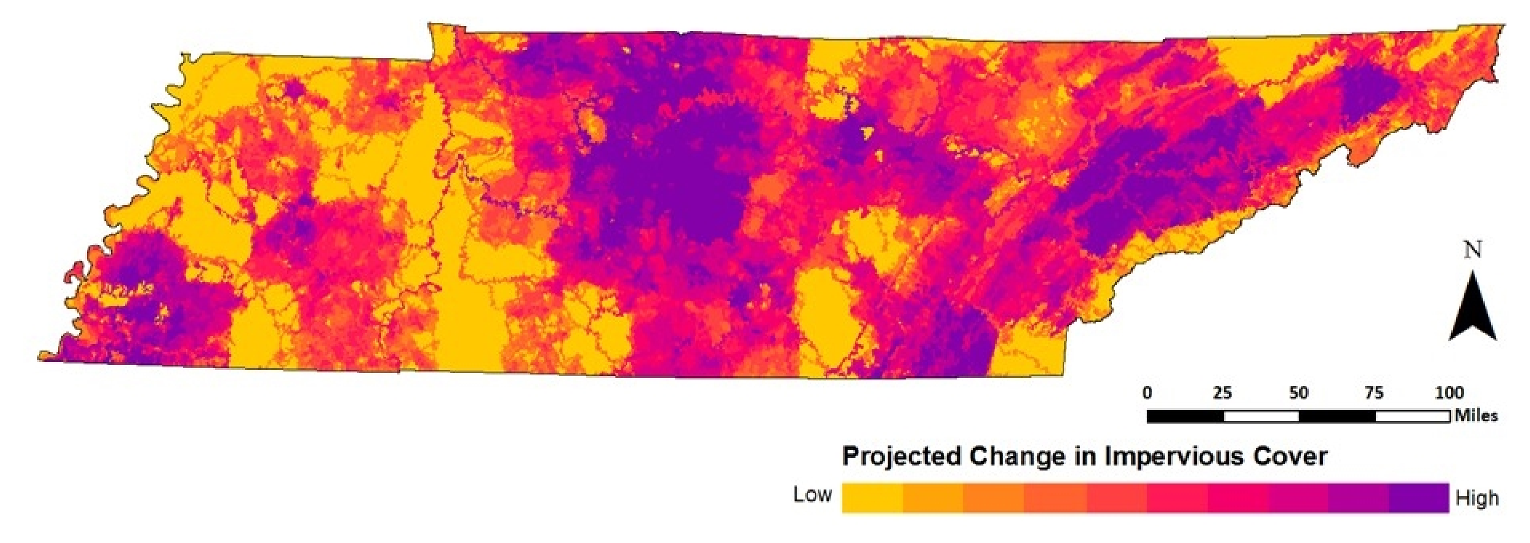


Figure A-24. Land Use Vulnerability Metric: Potential for energy development.

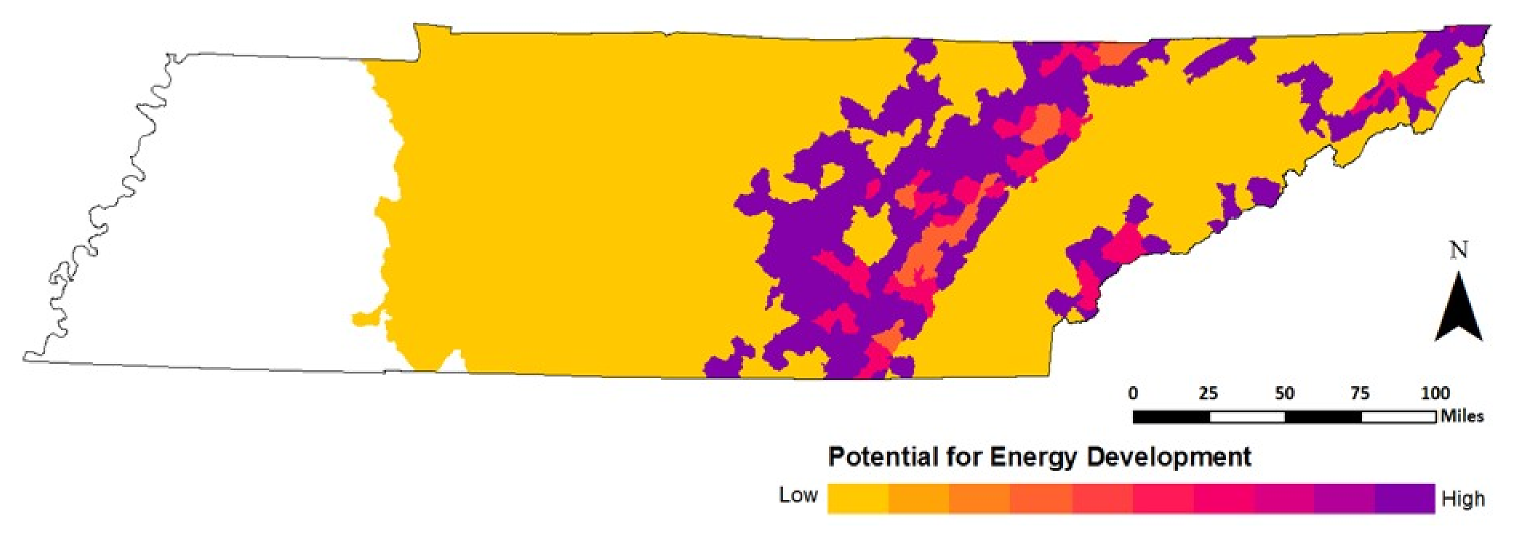


Figure A-25. Water Use Vulnerability Sub-Index.

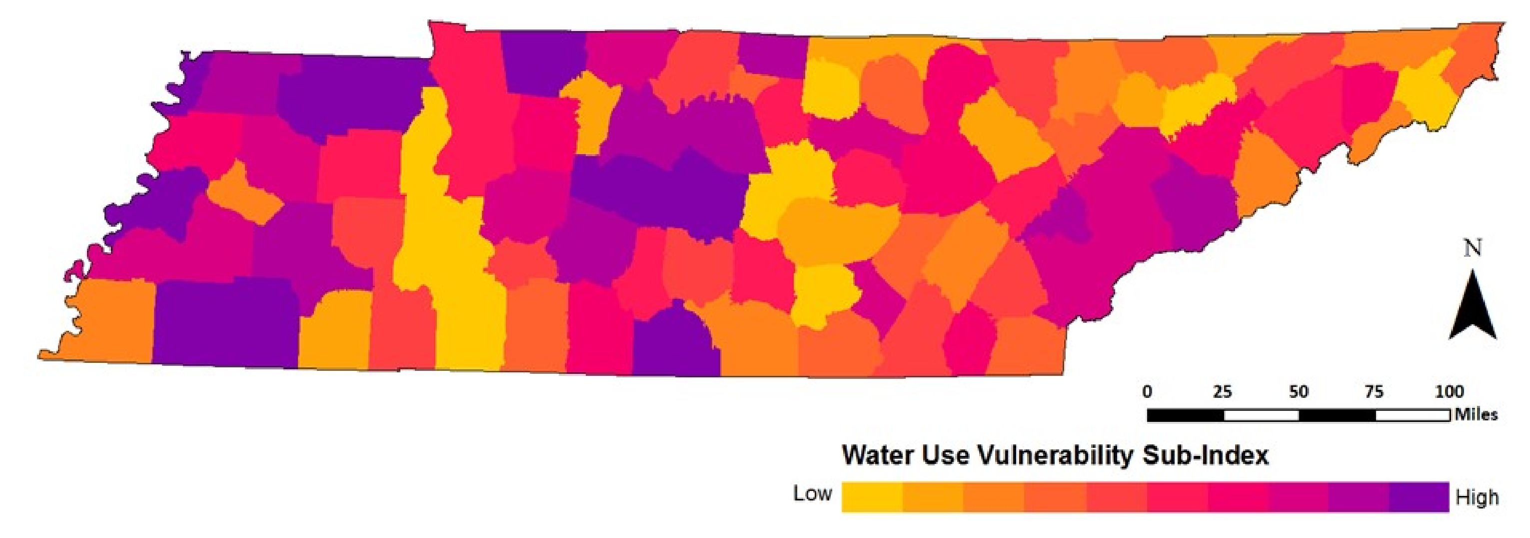


Figure A-26. Water Use Vulnerability Metric: Projected change in water consumption.

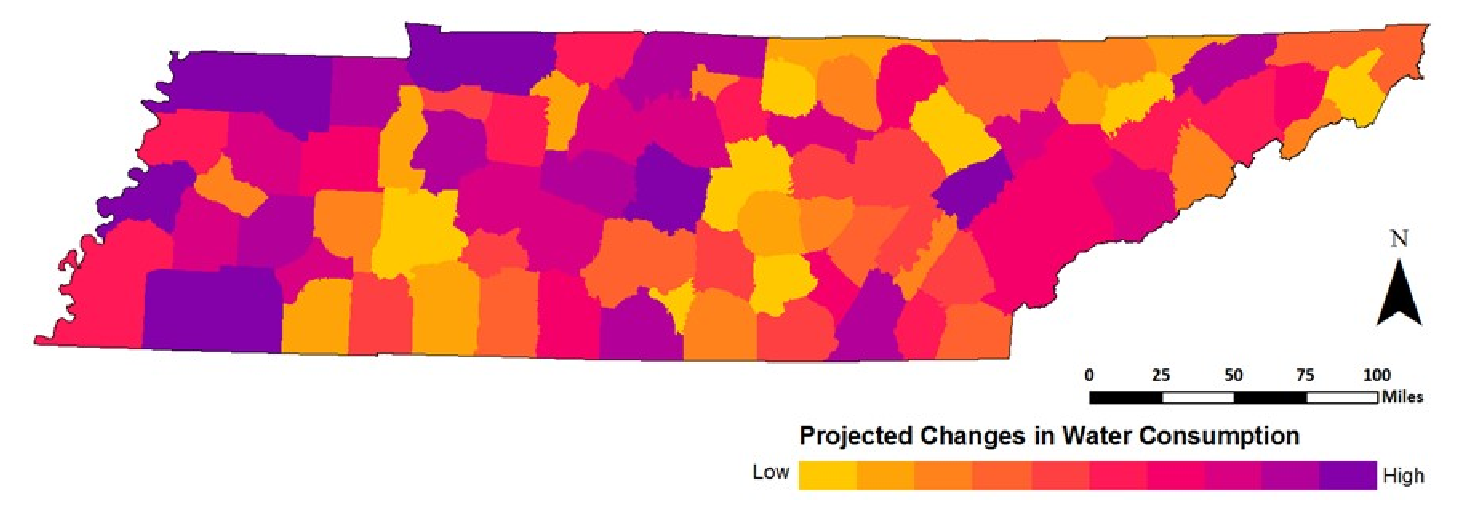


Figure A-27. Water Use Vulnerability Metric: Projected change in water withdrawals.

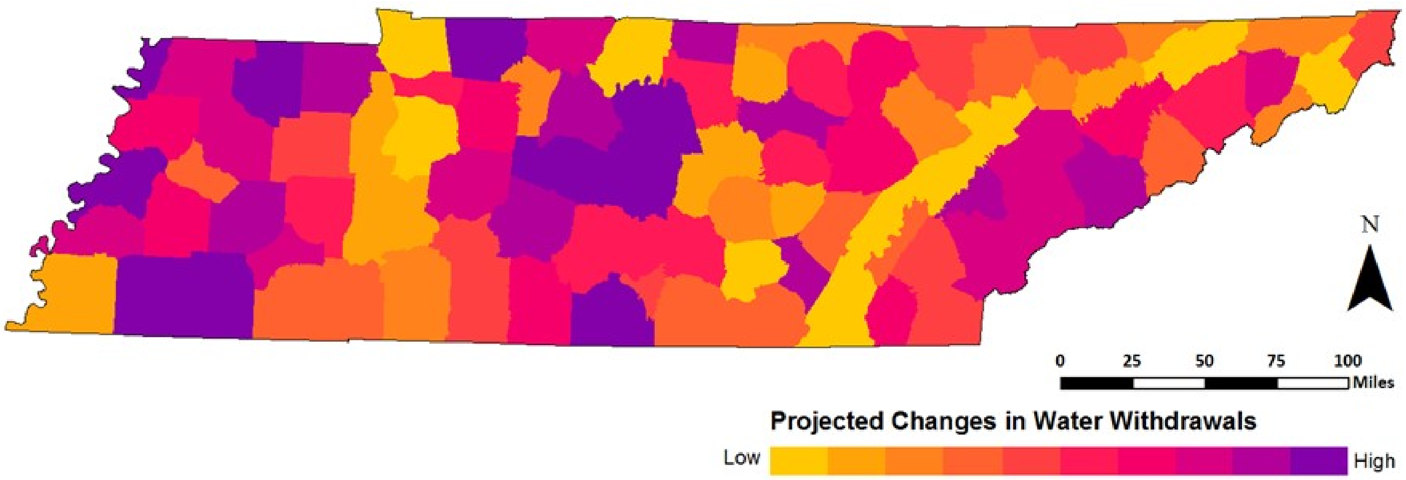


Figure A-28. Climate Change Vulnerability Sub-Index.

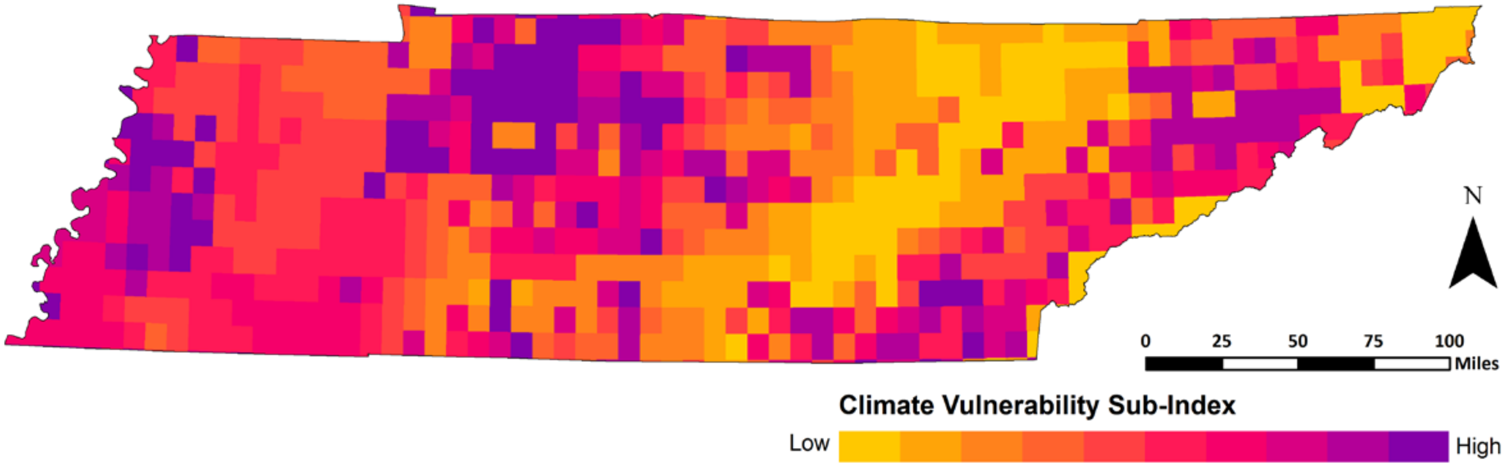


Figure A29. Climate Change Vulnerability Metric: Increase in days with maximum temperature greater than 95°F.

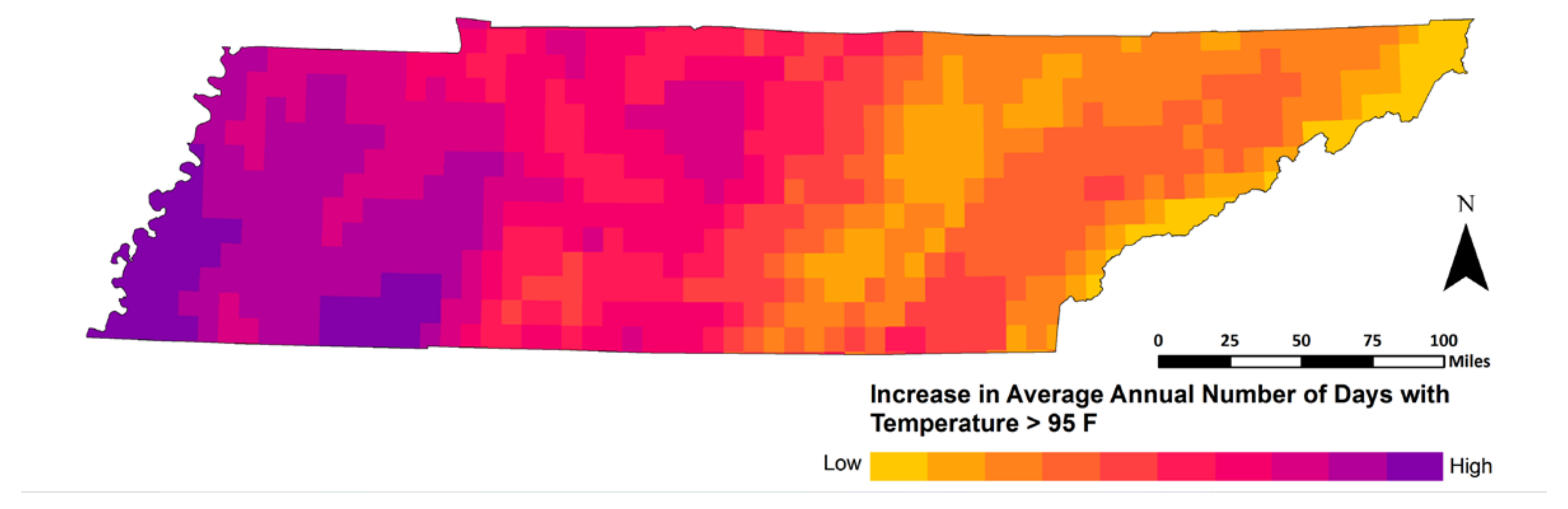
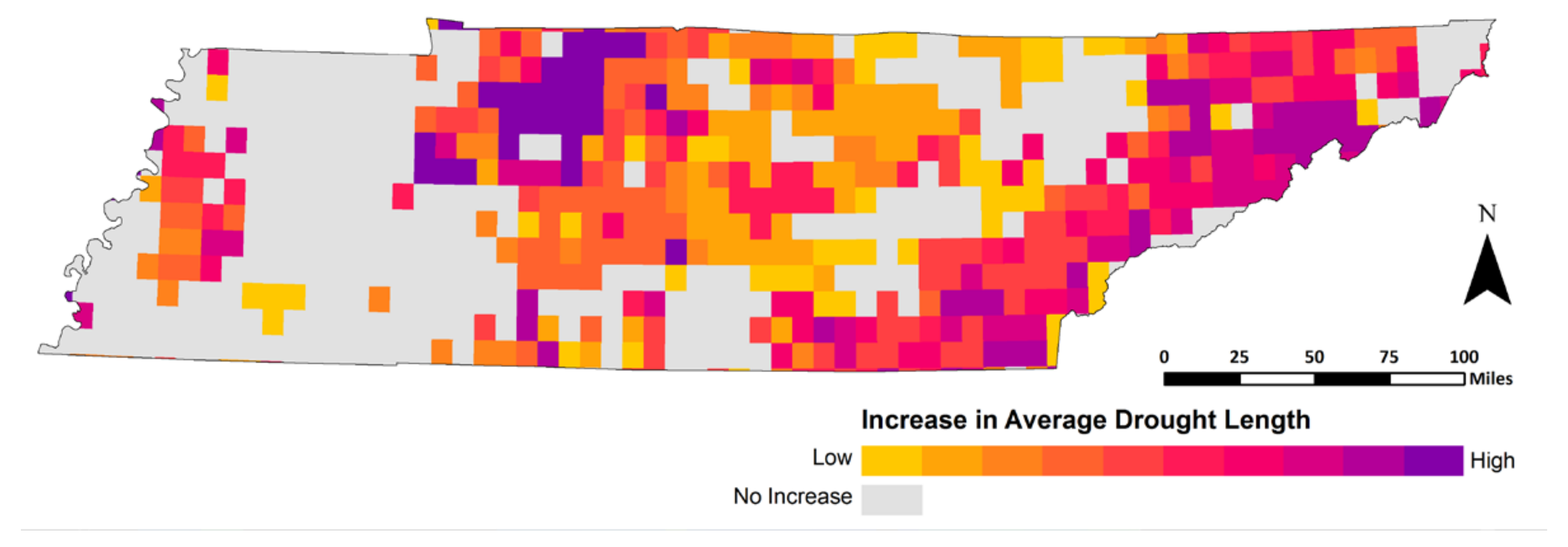


Figure A-30. Climate Change Vulnerability Metric: Increase in consecutive days without precipitation (> 0.1 inch).



Appendix B: Geomorphic Condition

B.1 Introduction

A combination of stream channel characteristics and landscape conditions derived primarily from the 2011 National Land Cover Database (NLCD 2011) was used to predict the Geomorphic Condition of catchments within Tennessee. A simple comparative analysis was used to attempt to gauge the relative potential for channel stability and resiliency among the catchments.

Separate metric analyses were performed to evaluate the erosive forces and the resistive capacity within stream channels for each catchment. Then elements of the two were combined to determine overall Geomorphic Condition.

B.2 Preparation of Data and Geomorphic Condition Sub-Index

Landscape factors, such as percent impervious cover and percent forest cover (for the cumulative land area draining to the catchment), and percent natural land cover within the Hydrologically Active Zone (HAZ), were calculated using NLCD 2011 datasets. Other variables, such as K-factor and depth to bedrock were obtained from National Hydrography Dataset Plus (NHDPlus), Soil Survey Geographic Database (SSURGO), and U.S. Geological Survey (USGS) datasets. The streamflow factors used for this analysis were taken from the modeling run for the Hydrologic Condition Sub-Index.

A simple continuous scoring model (range: 0–100 points) was used for each factor included in the analysis (**Tables B-1**). Each was scored so that higher point values indicated the factor would have a positive effect on stream resilience and stability (e.g., a lower percentage of impervious cover is less likely to alter the natural flow regime in a catchment and therefore would score more points than a catchment with a higher percentage of impervious cover).

Table B-1. Scoring components of the Geomorphic Condition Sub-Index.

Factor	Minimum Value (Point Score)	Maximum Value (Point Score)
Erosion Metric		
% Impervious Cover (cumulative)	0% (100 points)	65.06% (0 points)
K-Factor	0.0000681[1] (100 points)	0.55 (0 points)
Eastern Tennessee – Mean Annual Runoff	0.535 (100 points)	4.542 (0 points)
Western Tennessee – Mean Summer Streamflow	0.00 (100 points)	0.85 (0 points)
Resistance Metric		
% Forest Cover (cumulative)	0% (0 points)	100% (100 points)
Depth to Bedrock (cm)	0 (100 points)	153 (0 points)
% Natural Cover in HAZ (local)	0% (0 points)	100% (100 points)

[1] Note that K-factor values of less than 0.02 were possible in this analysis due to this value being a calculated, length-weighted average

The values for each factor were assigned points by rescaling the range of actual values for that factor from 0 to 100. The three factor scores were then averaged to produce a metric score. If a value for a particular factor was not available, this factor was dropped from the average. In this manner, each catchment was given an erosion metric score and a resistance metric score. The scores for each respective metric were then rank normalized. The rank normalized metric scores were then averaged and that average was rank normalized to produce a Geomorphic Condition Sub-Index score.

B.3 Model Development

Experience with a previous large-scale geomorphic condition assessment performed under the Healthy Watersheds Program helped guide the approach to and development of this model. Previous attempts to classify catchments based on Rosgen stream type proved untenable with the datasets available at the broad, statewide scale, so that approach was not attempted for this model.

Various discussions were had regarding complicating factors within the state, such as karst geology and the inconsistent availability of flow metrics on a statewide basis. Geographic datasets for karst geology were obtained from USGS; however, the data were too coarse for targeted application of karst data as either an additional metric factor or as a sieve for eliminating catchments from evaluation where the model might be rendered less effective due to the effects of the karst. Discussions with the Tennessee Healthy Watershed Initiative also raised the counterpoint that perhaps the impacts of karst were isolated enough as to be a minor concern for the statewide assessment.

B.4 Model Evaluation

Sampling and surveys performed for water quality and stream biota, although not always comprehensive for every basin or watershed within a state the size of Tennessee, typically cover a great number of locations and can be used to generalize reaches of stream (or even entire catchments) beyond where they occur. Geomorphological surveys are not performed as often or at as many locations, and the type of data collected are extremely site specific. This makes it difficult to apply data collected in one area to others or develop broader statistical models based on the types of stream channel measurements that are available. For this reason rather than attempting to use such a limited dataset to make weak statistical correlations, a different approach was used.

Many of the processes and forces that contribute to channel stability are well known and understood. Based on knowledge of these processes and the available data, best professional judgment was used to select factors that would approximate the forces that lead to or resist the erosion that influences channel morphology.

One of the strengths of this analysis is that it was based on data that were generally available for all catchments within Tennessee. Although localized conditions may lead to conditions in individual catchments that disagree with this Assessment, overall it is felt to be a good representation of the relative potential channel stability among all of the catchments.

Appendix C: Hydrologic Condition

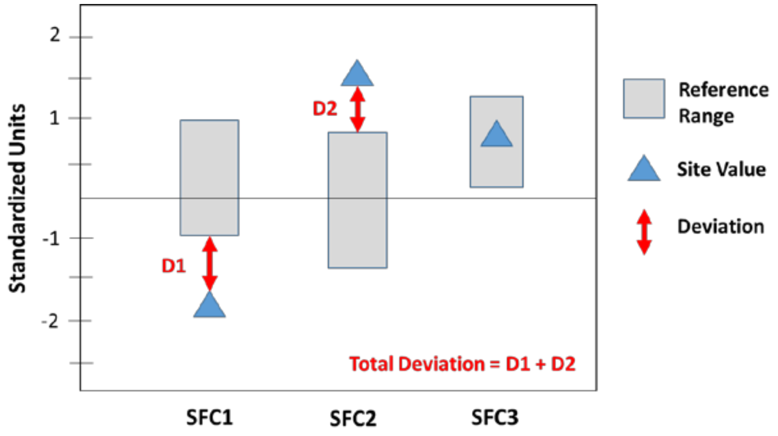
A stream's flow regime refers to its characteristic pattern of flow magnitude, timing, frequency, duration, and rate of change (Poff et al., 1997). The flow regime plays a central role in shaping aquatic ecosystems and the health of biological communities. Alteration of natural flow regimes (e.g., more frequent floods) can reduce the quantity and quality of aquatic habitat, degrade aquatic life, and result in the loss of ecosystem services. Therefore, to assess Hydrologic Condition, we use metrics related to the flow regime in unregulated streams to determine which segments most closely resemble the natural flow regime through reference watersheds and are therefore assumed to be healthy. In regulated systems (i.e., streams below large dams), we use the ratio of the storage behind the dams to the expected mean annual natural streamflow to determine which regulated segments have lower volumes of storage compared to streamflow.

C.1 Unregulated Streams

Independent variables used in the regression models for streamflow characteristics (SFCs) represent four categories (i.e., climate, land use, physical landscape, and regional indicators) and are listed in **Table C-1**. The independent variables either represent an average value or a percentage of land area across the drainage area of each site.

To use these regression equations to determine the deviation of the flow regime from a natural state within each catchment, the numeric value calculated for each utilized SFC was compared to a reference range determined for each SFC. The deviation was assumed to be zero if the calculated SFC fell within the reference range. For values outside the reference range, the absolute deviation was calculated as the difference between the SFC value and the lower or the upper bound of the reference range (depending on where the value falls). For each catchment, all absolute deviations for the used SFCs were then added together to calculate a single deviation metric (**Figure C-1**).

Figure C-1. Calculation method for Hydrologic Condition using deviation from reference range for streamflow characteristics (SFCs).



In the east, the reference ranges vary by ecoregion (**Table C-2**). These reference ranges are based on the interquartile range of values across all monitoring sites used in the analysis and are differentiated between the Blue Ridge, Ridge and Valley, and Interior Plateau ecoregions. (Note that these calculations are completed with normalized values.) Catchments that have sub-basins with forest land use in the upper quartile of the range of values (**Table C-2**) were used in calculating the interquartile range.

Table C-1. Definitions for independent variables used in predictive equations (adapted from Knight et al., 2012).

Variable	East/ West	Definition (Data Source)	Variation from USGS Study
Climate			
Monthly Mean Precipitation	E	Average annual precipitation divided by 12 (PRISM, 2004)	Same
January Precipitation Deviation	E	Mean January precipitation divided by monthly precipitation mean (PRISM, 2004)	Same
Daily Temperature Range	E	Mean maximum daily temperature minus mean minimum daily temperature (PRISM, 2004)	Same
August Temperature Deviation	E	Mean August maximum temperature minus mean annual temperature divided by mean annual temperature (PRISM, 2004)	Same
Land Use			
Percent Forest Cover	E	The total percentage of land cover in a catchment that is considered to be forested (Jin et al., 2013)	2011 land use in place of 2001 land use dataset
Percent Agricultural Cover	E	The total percentage of land cover in a catchment that is considered to be agricultural (Jin et al., 2013)	2011 land use in place of 2001 land use dataset
Physical			
Horton	E	Index of Hortonian overland (infiltration excess overland flow) (dimensionless) (Wolock et al., 2003a and 2003b)	Same
Mean Elevation	E	Mean basin elevation derived from digital elevation model (Gesch et al., 2002; Gesch, 2007)	Derived from more recent digital elevation dataset
Soil Factor	E, W	Percentage of area underlain by soil with a permeability of at least 5 cm/h (Greene and Wolfe, 1998)	Same
Rock Depth	E	Average depth of soil above bedrock (Wolock, 1997)	Same
Regional			
Geologic Factor	E, W	Measure of the number of days that pass as discharge recedes one complete log cycle of streamflow (days) (Bingham, 1986)	Same
Blue Ridge	E	Percentage of the watershed that lies within the Blue Ridge Level 3 ecoregion (Omernik, 1987)	Same
Interior Plateau	E	Percentage of the watershed that lies within the Interior Plateau Level 3 ecoregion (Omernik, 1987)	Same
Interaction Terms			
Soil Factor	E	Soil factor multiplied by monthly mean precipitation	N/A
Rock Depth	E	Rock depth multiplied by monthly mean precipitation	N/A
Geologic Factor	E	Geologic factor multiplied by monthly mean precipitation	N/A

All variables represent average values for a basin with the exception of Blue Ridge, Interior Plateau, forest, and agriculture, which are expressed as the percentage of total catchment area.

Table C-2. Interquartile ranges and forest land use threshold for ecoregion-specific hydrologic reference profiles calculated for eastern Tennessee.

		MA41		TL1		LDH16	
Ecoregion	Forest %	25th	75th	25th	75th	25th	75th
Blue Ridge	97.1	0.1507	2.2775	-0.2672	0.5900	-0.4428	0.6654
Central Appalachians	90.7	-0.3240	0.7831	-0.6850	-0.4541	-0.7015	0.0140
Interior Plateau	73.3	-0.7080	-0.3763	-0.1712	0.5762	-1.9631	-1.4628
Ridge and Valley	66.4	-0.9566	-0.4065	-0.7996	-0.2818	-0.8873	-0.0640
Southeastern Plains	69.6	-0.5368	-0.1553	-0.1948	0.8101	-2.2207	-1.6972
Southwestern Appalachians	80.1	-0.3421	0.5283	-0.9880	-0.4238	-1.1340	-0.7879

MA41 = mean annual runoff; TL1 = date of annual minimum flow; LDH16 = variability in high-pulse duration; Values are normalized by mean and standard deviation

In the west, there is only one reference range for each SFC, which is again defined as the interquartile range of reference catchments. For the west, reference catchments were those that had forest land use in the upper quartile of the range of values (**Table C-3**).

Table C-3. Interquartile ranges and agriculture land use threshold for hydrologic reference profiles calculated for western Tennessee.

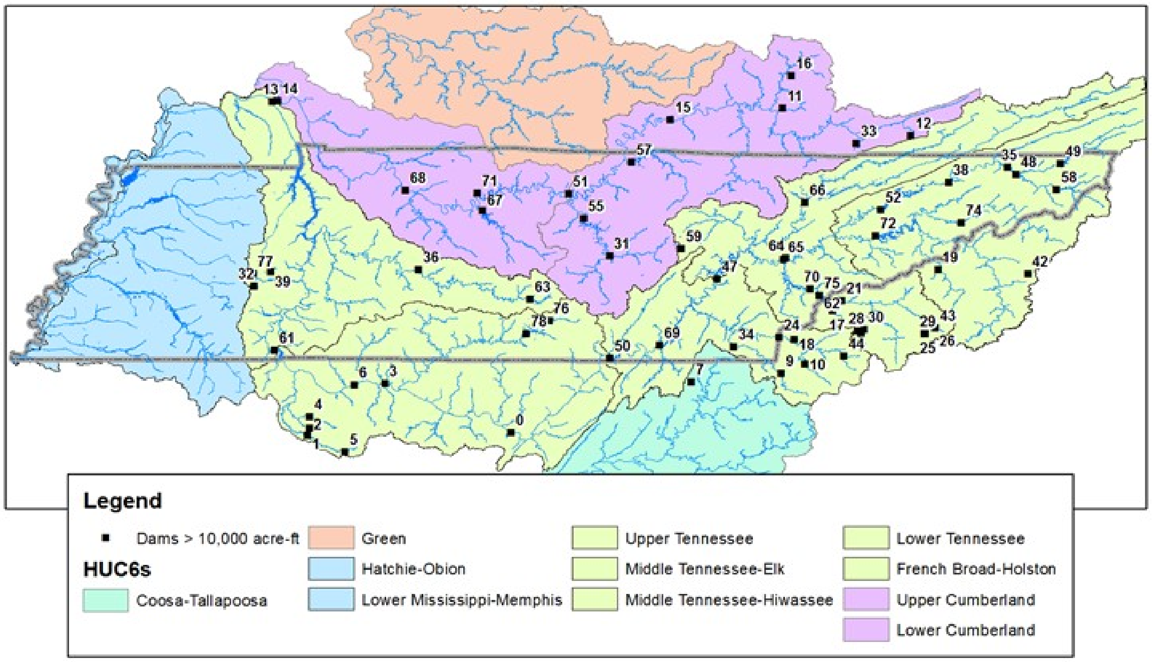
	7Q10		MS		q10	
Forest %	25th	75th	25th	75th	25th	75th
45.2	0.0362	0.1543	0.4146	0.6385	2.7424	3.0796

7Q10 = lowest consecutive 7-day average flow in a 10-year period; MS = mean-summer streamflow in June through August; q10 = daily mean streamflow exceeded 10% of the time; Regression values are normalized by drainage area

C.2 Regulated Streams

Regulated streams were assessed by first identifying all large dams within the hydrologic units that cross the state. Dams were restricted to those that stored at least 10,000 acre-feet of volume according to the TN SWAP dataset, were not primarily for recreational use, and had a National Inventory of Dams (NID)-reported normal storage above zero (**Figure C-2**). The final dams were compared with listings in Bohac and Bowen (2012) and Robinson (2014) for the Tennessee and Cumberland River systems, respectively, to ensure all large operated dams were selected using these criteria.

Figure C-2. Dams with greater than 10,000 acre-feet of storage within the hydrologic units crossing Tennessee. Numeric labels relate to the ID field in Table C-4.



Information on each dam was gathered from TN SWAP, NID, and generalized searches on the owning organizations (**Table C-4**). Attempts were made to qualify each dam based on the operating principles to potentially provide a secondary metric in the ranking of regulated streams. Because the information was only readily available for the larger management organizations (e.g., TVA) and a method of standardization/categorization of the different guide curves and operating levels to calculate a hydrologic metric was not objectively available given the screening level focus of this analysis, these data are instead provided in tabular form and are not used in metric rankings.

C.3 References

Bingham, R.H. 1986. *Regionalization of Low-Flow Characteristics of Tennessee Streams*. Water-Resources Investigations Report 85–4191, 63.2 plates.

Bohac, C.E. and A.K. Bowen. 2012. Water use in the Tennessee Valley for 2010 and projected use in 2035. Tennessee Valley Authority, River Operations and Renewables. 83 pp.

Gesch, D., M. Oimoen, S. Greenlee, C. Nelson, M. Steuck, and D. Tyler. 2002. The national elevation dataset. *Photogrammetric Engineering and Remote Sensing* 68: 5–11.

Gesch, D.B. 2007. The national elevation dataset. In *Digital Elevation Model Technologies and Applications: The DEM Users Manual, 2nd edition*, Maune, D. (ed). American Society for Photogrammetry and Remote Sensing: Bethesda, MD; 99–118.

Greene, D.C., and W.J. Wolfe. 1998. Superfund GIS—Soil thickness, permeability, texture, and classification in Tennessee. Available at http://catalog.data.gov/dataset.

Jin, S., L. Yang, P. Danielson, C. Homer, J. Fry, and G. Xian. 2013. A comprehensive change detection method for updating the National Land Cover Database to circa 2011. *Remote Sensing of Environment 132*:159–175.

Knight, R.R., W.S. Gain, and W.J. Wolfe. 2012. Modelling ecological flow regime: an example from the Tennessee and Cumberland River basins. *Ecohydrology* 5: 613–627.

Omernik, J.M. 1987. Ecoregions of the conterminous United States. *Annals of the Association of American Geographers* 77: 118–125.

Poff, N.L, J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks, and J.C. Stromberg. 1997. The natural flow regime: A paradigm for river conservation and restoration. *Bioscience* 47(11): 769–784.

PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 4 Feb 2004.

Robinson, J.A. 2014 (draft). Estimated use of water in the Cumberland River Watershed in 2010 and projections to 2040: U.S. Geological Survey Scientific Investigations Report 14-xxxx, xx p. Available online at http:pubs.usgs.gov/circ/14-xxxx.

Wolock, D.M. 1997. STATSGO soil characteristics for the conterminous United States. U.S. Geological Survey Open-File Report 97–656. Digital dataset.

Wolock, D.M. 2003a. Saturation overland flow estimated by TOPMODEL for the conterminous United States. U.S. Geological Survey Open-File Report 2003-264, raster digital data.

Wolock, D.M. 2003b. Infiltration-excess overland flow estimated by TOPMODEL for the conterminous United States. U.S. Geological Survey Open-File Report 03–310, digital dataset.

Table C-4. Dams used to assess regulated stream reaches for the hydrologic basins within Tennessee.

NIDID	ID	Dam Name	Owner Name	Primary Purpose	Hydrologic Operations Notes[1]	Water Quality Operations[2]	NID Storage (TN SWAP)	Normal Storage	Max Storage
AL05901	1	Bear Creek	TVA	Flood Control	Guide curve	No	78580	9915	78580
AL05902	4	Cedar Creek	TVA	Flood Control	Guide curve, Low notch	No	173490	93201	173490
AL05903	2	Little Bear Creek	TVA	Flood Control	Guide curve, Low notch	No	74855	45609	74855
AL07701	3	Wheeler	TVA	Flood Control	Operating range	No	1358355	1049007	1358355
AL07702	6	Wilson	TVA	Flood Control	Operating range	No	674220	636543	674220
AL09301	5	Upper Bear Creek	TVA	Flood Control	Spillway crest, Low Notch, Recreation release schedule	No	69810	37677	69810
AL09501	0	Guntersville	TVA	Flood Control	Operating range	No	1405947	1019262	1405947
GA00730	7	Upper Haig Mill Lake Dam	City of Dalton	Flood Control			27728	483	27728
GA11101	9	Blue Ridge	TVA	Hydroelectric	Balancing guide, flood guide with expected elevation range	Yes	228045	182436	228045
GA29101	10	Nottely	TVA	Flood Control	Balancing guide, flood guide with expected elevation range	Yes	216147	162606	216147
KY00088	16	Wood Creek Lake Dam	Commonwealth of Kentucky	Water Supply			29101	23270	29101
KY00275	33	Cannon Creek Dam	Commonwealth of Kentucky	Water Supply			11300	11300	0
KY03001	14	Barkley Dam	USACE – Nashville District	Hydroelectric	Guide curve	Yes	2082000	869000	2082000
KY03010	15	Wolf Creek	USACE – Nashville District	Hydroelectric	Upper and lower guide curves, minimum power pool	Yes	6089000	2142000	6089000
KY03046	11	Laurel Dam	USACE – Nashville District	Flood Control	Power marketing curve	No	435600	185000	435600
KY03061	12	Martins Fork Dam	USACE – Nashville District	Flood Control	Seasonal operating curve	No	21100	3700	21100
KY15701	13	Kentucky	TVA	Flood Control	Operating range, Summer Flowage Easement	No	7535400	6127470	7535400
NC00181	24	Appalachia	TVA	Hydroelectric	Operating range	Yes	63456	55524	63456
NC00288	42	North Fork Reservoir Dam	City of Asheville Department of Water Resources	Water Supply			21700	17600	21700
NC00298	21	Fontana	TVA	Flood Control	Balancing guide, flood guide with expected elevation range	Yes	1552689	1370253	1552689

(continued)

Table C-4. Dams used to assess regulated stream reaches for the hydrologic basins within Tennessee. (continued)

NIDID	ID	Dam Name	Owner Name	Primary Purpose	Hydrologic Operations Notes[1]	Water Quality Operations [2]	NID Storage (TN SWAP)	Normal Storage	Max Storage
NC00318	19	Walters	Duke Energy Carolinas, LLC	Hydroelectric	Recreation release schedule		17000	17000	17000
NC00336	26	Bear Creek	Duke Energy Carolinas, LLC	Hydroelectric	Guide curve, min and max curves, low inflow protocol		34600	34600	34600
NC00371	28/ 30	Dicks Creek Dam/Nantahala/White Oak Creek Dam	Duke Energy Carolinas, LLC	Hydroelectric	Guide curve, min and max curves, low inflow protocol		126000	126000	126000
NC00378	25/ 29	Glenville Saddle Dike/Thorpe	Duke Energy Carolinas, LLC	Hydroelectric	Guide curve, min and max curves, low inflow protocol		67100	65600	67100
NC00391	44	Chatuge	TVA	Flood Control	Balancing guide, flood guide with expected elevation range	Yes	285552	226062	285552
NC00392	17	Santeetlah	ALCOA Power Generating Inc., TAPOCO Division	Hydroelectric	Guide curve, release schedule		207000	160000	207000
NC00419	18	Hiwassee	TVA	Flood Control	Balancing guide, flood guide with expected elevation range	Yes	471954	398583	471954
TN00904	70	Chilhowee	ALCOA Power Generating Inc., TAPOCO Division	Hydroelectric	Run-of-river		49251	49251	49251
TN00906	62/ 75	Calderwood	ALCOA Power Generating Inc., TAPOCO Division	Hydroelectric	Run-of-river		43500	41100	43500
TN01302	66	Norris	TVA	Flood Control	Balancing guide, flood guide with expected elevation range, recreation release schedule	Yes	3363168	2040507	3363168
TN01903	58	Watauga	TVA	Flood Control	Balancing guide, flood guide with expected elevation range, recreation release schedule	Yes	751557	569121	751557
TN02101	68	Cheatham Dam	USACE – Nashville District	Hydroelectric	No guides	Yes	104000	84200	104000
TN02702	57	Dale Hollow Dam	USACE – Nashville District	Hydroelectric	Upper and lower guide curves, minimum power pool	Yes	1706000	857000	1706000
TN03107	63	Normandy	TVA	Hydroelectric	Guide curve	No	126000	116997	126000

(continued)

Table C-4. Dams used to assess regulated stream reaches for the hydrologic basins within Tennessee. (continued)

NIDID	ID	Dam Name	Owner Name	Primary Purpose	Hydrologic Operations Notes[1]	Water Quality Operations[2]	NID Storage (TN SWAP)	Normal Storage	Max Storage
TN03504	59	Lake Tansi	Lake Tansi Village P.O.A.	Other			13806	9000	13806
TN03701	67	J Percy Priest Dam	USACE – Nashville District	Flood Control	Upper and lower guide curves	Yes	652000	202000	652000
TN03702	71	Old Hickory Dam	USACE – Nashville District	Hydroelectric	Minimum power pool	Yes	545000	420000	545000
TN04102	55	Center Hill Dam	USACE – Nashville District	Flood Control	Upper and lower guide curves, minimum power pool	yes	2092000	1330000	2092000
TN05101	76	Elk River Dam	U.S. Air Force Air Force Materiel Command	Flood Control			101844	77915	101844
TN05102	78	Tims Ford	TVA	Flood Control	Guide curve, Flood guide, Minimum Recreation level, Recreation release schedule	Yes	608000	325400	608000
TN05903	74	Nolichucky	TVA	Other	No information		19525	1715	19525
TN06504	69	Chickamauga	TVA	Flood Control	Operating range	No	943908	622662	943908
TN07101	61	Pickwick Landing	TVA	Flood Control	Operating range	No	1546740	1118412	1546740
TN07305	38	John Sevier	TVA	Water Supply	No information		52650	7735	52650
TN07705	77	Beech	TVA	Flood Control	No information		28602	11105	28602
TN07706	32	Pine	TVA	Flood Control	No information		12260	5155	12260
TN07710	39	Pin Oak	TVA	Flood Control	No information		13815	8925	13815
TN08903	52	Cherokee	TVA	Flood Control	Balancing guide, flood guide with expected elevation range	Yes	1699431	1421811	1699431
TN10501	64	Fort Loudoun	TVA	Flood Control	Operating range	No	475920	362889	475920
TN10502	37	Melton Hill	TVA	Hydroelectric	Operating range	No	150708	105099	150708
TN10506	65	Tellico	TVA	Flood Control	Operating range	No	513597	392634	513597
TN11502	50	Nickajack	TVA	Hydroelectric	Operating range, Bottom of operating zone during high flows	No	402549	246130	402549
TN11929	36	Solutia #15	Rlf Duck River, LLC, et al.	-			32945	23614	32945
TN12102	47	Watts Bar	TVA	Flood Control	Operating range	No	1415862	1009347	1415862
TN13905	34	Ocoee No. 1	TVA	Flood Control	Guide curve, recreation release schedule at Ocoee 2 and 3	No	79320	79320	48350

(continued)

Table C-4. Dams used to assess regulated stream reaches for the hydrologic basins within Tennessee. (continued)

NIDID	ID	Dam Name	Owner Name	Primary Purpose	Hydrologic Operations Notes[1]	Water Quality Operations [2]	NID Storage (TN SWAP)	Normal Storage	Max Storage
TN15501	72	Douglas	TVA	Flood Control	Balancing guide, flood guide with expected elevation range	Yes	1626060	1223511	1626060
TN15901	51	Cordell Hull Dam	USACE – Nashville District	Hydroelectric	Upper and lower guide curves		310900	258000	310900
TN16305	49	South Holston	TVA	Flood Control	Balancing guide, flood guide with expected elevation range	Yes	890367	658356	890367
TN16306	48	Boone	TVA	Flood Control	Guide curve, flood guide	Yes	216147	180453	216147
TN16307	35	Fort Patrick Henry	TVA	Flood Control	Operating range	Yes	31728	25779	31728
TN17704	31	Great Falls	TVA	Hydroelectric	Guide curve	No	64800	39660	64800

[1] Sources for operating notes:
http://www.lrn-wc.usace.army.mil/hh/WM_Info.htm
http://www.brookfieldrenewable.com/content/smoky_mountain_hydro/recreation_and_flow-39611.html
http://www.duke-energy.com/lakes/nantahala/nantahala-lake-levels.asp
http://www.duke-energy.com/power-plants/hydro/walters.asp

[2] Source for water quality operations:
http://www.tva.gov/environment/water/rri_triblist.htm#nottely
Bullard, personal communication via comments: 11 September 2015.

Appendix D: Water Quality, Habitat and Biological Condition Metric Modeling

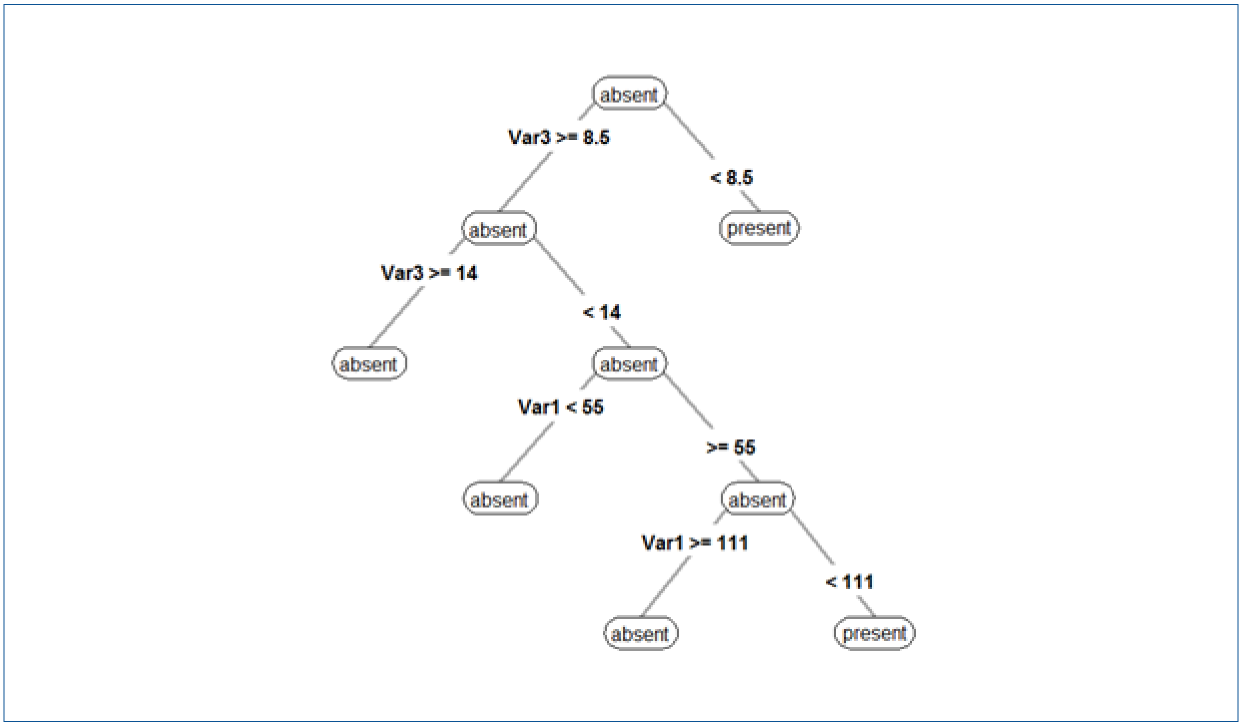
D.1 Introduction

Watershed health metrics characterizing water quality and habitat and biological condition were quantified for each National Hydrography Dataset Plus (NHDPlus) catchment in Tennessee using Boosted Regression Trees (BRTs). This statistical modeling approach was used to relate observed values to landscape- and watershed-scale predictor variables. The fitted statistical models were then used to predict water quality, habitat condition, and biological conditions in catchments without available monitoring data.

D.2 General Modeling Approach

BRTs are a form of tree-based modeling and can be visualized as a series of nodes and branches that represent partitions of the predictor data space into rectangular sections; each binary split partitions the dataset into groups that are more rather than less similar in terms of the response variable (Cutler et al., 2007). This partitioning is *recursive*; each additional split is added to previous splits until all observations are partitioned or until some other stopping criteria is reached. For instance, in **Figure D-1** observations with a 'Var3' value less than 8.5 are partitioned in a terminal node to the right, while observations with a 'Var3' value greater than or equal to 8.5 are directed down the left branch of the tree. Each split represents a predictor variable threshold; a highly influential predictor may be split several times at different nodes.

Figure D-1. Example decision tree output.



BRT incorporates decision tree modeling with additional features to fit both continuous and categorical response variables. BRT is a *stagewise*, *ensemble* modeling approach that utilizes both *stochastic* data selection and *boosting* to improve predictive performance. A BRT model is a collection of hundreds or thousands of individual trees that are combined to obtain the final fitted values, hence *ensemble*. The BRT procedure is *stagewise* because each tree is fitted to the error term of the preceding tree and all trees are retained in their original form. This emphasis on observations that are modeled poorly is a form of *boosting*, which seeks to improve model performance by gradually reducing the overall error of the assembled trees (Elith et al., 2008). Finally, many tree-based modeling approaches adopt a *stochastic*, or random, element to the fitting process to improve overall performance. In this case, a 'bag fraction' specifies the proportion of data that is drawn at each tree fitting step.

BRT models require user input on three settings: bag fraction, learning rate, and tree complexity. Default values for these settings are provided; however, model performance can frequently be improved by calibrating these arguments to each dataset. The bag fraction is the percentage of data that is randomly selected to fit each tree. The learning rate is a measure of how much each individual tree influences the model fitting process; a lower learning rate means that each tree contributes less to the overall model, and more trees are fitted (Elith et al., 2008). Tree complexity sets the number of nodes in the tree; higher tree complexity generally results in fewer, but more complex, trees (Elith et al., 2008).

Tree-based models have been successfully used to characterize and predict a range of ecological and environmental data (see Cutler et al., 2007; De'ath, 2007; De'ath and Fabricius, 2000; Elith et al., 2008; and Maloney et al., 2009). In addition, modern tree-based approaches such as BRT have been designed to improve predictive performance and address the bias issues that sometime arise in tree-based models (Elith et al., 2008).

All water quality and biological BRT models were fit in the statistical software program R using packages {dismo} and {gbm} (Hijmans et al. 2015; Ridgeway 2015). Additional information about R can be found at the Comprehensive R Archive Network (CRAN, https://www.cran.r-project.org/).

D.3 Metrics Methods

Response Variable Management

The following filters were applied to the water quality response variables (total nitrogen [TN], total phosphorus [TP], and specific conductance [SC]):

- The Activity Category field in the Tennessee Department of Environment and Conservation (TDEC) water quality (WQ) database was restricted to 'routine samples.'
- Only river/stream sample sites in the Primary Type field were retained.
- A sample date threshold of 1/1/2000 was applied.

- Observations with quality codes of NULL, below the laboratory detection limit, or between laboratory detection and quantification limit were kept; all other quality codes were discarded.
- Observations with values below the laboratory detection limit or values between the laboratory detection and quantification limit were replaced with values half the detection or quantification limit, respectively.
- Only NHDPlus catchments with five or more post-2000 samples were retained.
- The median parameter value within each NHDPlus catchment was calculated.
- A power transformation was applied as needed to make each response variable approximately normal.

Similar filters were applied to the response variables to assess Habitat Condition and Biologic Condition taken from the TDEC database (Rapid Bioassessment Protocol Score, Benthic BioRecon). Because the nature of the habitat and biology data are different from water quality, and there were fewer samples from which to choose, the filters were, by nature, not as strict:

- Only river/stream sample sites in the Primary Type field were retained.
- A sample date threshold of 1/1/2000 was applied.
- The average parameter value in each NHDPlus catchment was calculated.
- A power transformation was applied as needed to make each response variable approximately normal.
- The largest 5% of NHDPlus catchments (based on cumulative drainage area), by ecoregion, was excluded from the analysis because TDEC sampling protocols for benthos and habitat do not include large rivers.

An even smaller sample size for fish Index of Biological Integrity (IBI) values from the Tennessee Valley Authority (TVA) and Tennessee Wildlife Resources Agency (TWRA) meant that only the “most recent” sample from each site was used, regardless of date; yet the average parameter value in each NHDPlus catchment was calculated and a power transformation was applied if necessary.

D.4 Model Fitting

Initial BRT models were fit to each WQ parameter using all available predictor variables. The appropriateness of the BRT approach for these data was evaluated by examining the following outputs:

- A plot of fitted versus observed values.
- The overall correlation between fitted and observed values for observations used in the fitted model.

- The mean cross-validated correlation, which is calculated within each data subset, or fold, using predicted values for observations that were not used in the fitted model.

- A histogram and density plot of model residuals.

The relative influence value for each predictor variable was then examined. The relative influence of a predictor represents how many times the variable is selected to split a dataset, weighted by the overall improvement in model performance across all fitted trees (Elith et al., 2008). Predictors with lower relative influence scores are not necessarily unimportant; rather, these variables are estimated to have less influence on the response (Elith et al., 2008). All predictor variables with an initial relative influence greater than or equal to 0.5 were retained for further analysis. A Spearman correlation matrix was then computed for this subset of predictor variables and correlation values greater than 0.8 were examined. In cases where highly correlated variables were likely to contain similar information over the same spatial scale (i.e., percent catchment Hydrologically Active Zone [HAZ] high intensity development and percent catchment HAZ impervious cover), one predictor was dropped. However, correlated predictors were retained if the spatial or temporal processes represented by the variables might reasonably be expected to influence the response variable in different ways; for instance, the impact of cumulative riparian forest cover (i.e., natural riparian buffer) is likely to be different than cumulative watershed forest cover (which may or may not be near riparian areas).

The resulting subset of predictor variables was then used to fit a final model for each WQ parameter. Per Elith et al. (2008), a range of BRT settings was evaluated. Bag fraction was tested at values of 0.5, 0.6, and 0.75. Learning rate was tested at 0.005, 0.0075, and 0.01. Tree complexity was evaluated at values of 2, 3, 4, and 5. Model settings were evaluated in terms of cross-validated mean correlation and the number of trees produced by the final model. Because BRT models select subsets of data stochastically (i.e., randomly), evaluating the fit of any single BRT output provides a limited perspective on model performance; fitting the same BRT model two times will produce (slightly) different results. To better characterize BRT performance, an iterative statistical simulation was applied to the model fitting process. Each finalized model was fit to the data 100 times. For each iteration, the training and cross-validated correlation values were retained. In addition, a third goodness of fit (GOF) metric, a training/test correlation, was also calculated. A training/test correlation is a measure of predictive performance, similar to the cross-validated correlation but considered to be more indicative of overall model predictive power (Edith et al., 2008). The training dataset is created by randomly selecting 80% of the data; the BRT model is fit to these data. The resulting model is then used to predict WQ parameter values in the test dataset; for example, the remaining 20% of the data that were not used in the model fitting process. This simulation produced a *distribution* of GOF statistics, from which mean, median, and other percentile values could be extracted to evaluate overall model performance.

The finalized BRT model was then used to make WQ parameter predictions for all NHDPlus catchments in Tennessee. Because habitat and biology data are very much tied to ecoregional differences, separate models were run, where possible, for the following combinations of Level III ecoregions (in some cases, ecoregions were combined to increase the sample size):

- Blue Ridge
- Ridge and Valley
- Southwestern and Central Appalachians
- Interior Plateau
- Southeastern Plains, Mississippi River Alluvial Plain, and Mississippi Valley Loess Plains

D.5 Water Quality Model Results

Median Stream Total Nitrogen Concentrations (mg/L)

Total nitrogen in milligrams per liter (mg/L) was calculated by summing nitrate, nitrite, and total Kjeldahl nitrogen. A power transformation of 0.16 was applied to make the distribution of TN approximately normal. **Table D-1** details sample size and summary statistics for median catchment TN.

Table D-1. Summary statistics (minimum, 1st quartile, median, mean, 3rd quartile, and maximum values) and sample count for median total nitrogen (mg/L) in catchments with five or more post-2000 samples.

Count	Minimum	Q1	Median	Mean	Q3	Maximum
1,690	0.0735	0.405	0.7243	0.9177	1.184	8.57

Model results indicate a strong regional influence on TN concentrations (**Figure D-2**). Total forest cover and agriculture, at both the cumulative and HAZ spatial scales, are also important. Surface and bedrock geology and developed areas round out the list of important predictors.

Goodness of fit results for the total nitrogen model are acceptable (**Figure D-3** and **Table D-2**). The high training data correlation values relative to the cross-validated values indicate some overfitting in the modeling process. However, the cross-validated estimates of predictive power fall within the range of the training/test results, which indicates that the cross-validated estimate is a relatively unbiased predictor of predictive performance. The interquartile range (IQR) of the training/test results is narrow (0.77–0.80), which indicates that predictive performance is relatively stable (**Table D-2**).

Figure D-2. Relative influence of predictors in TN model. Note: 'C' indicates cumulative value and HAZ indicates the hydrologically active zone.

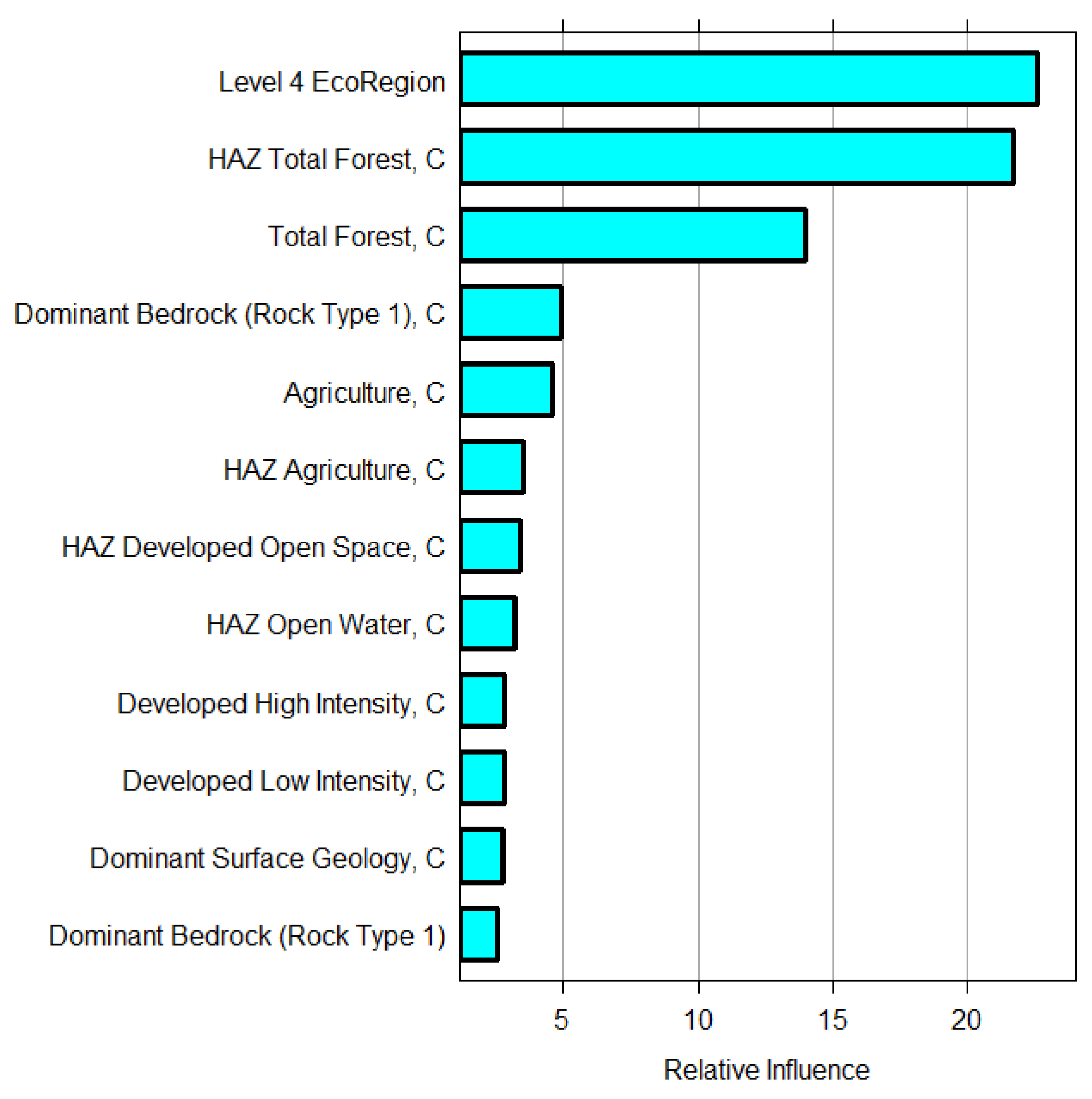


Figure D-3. Simulated distributions of goodness of fit metrics for the TN model.

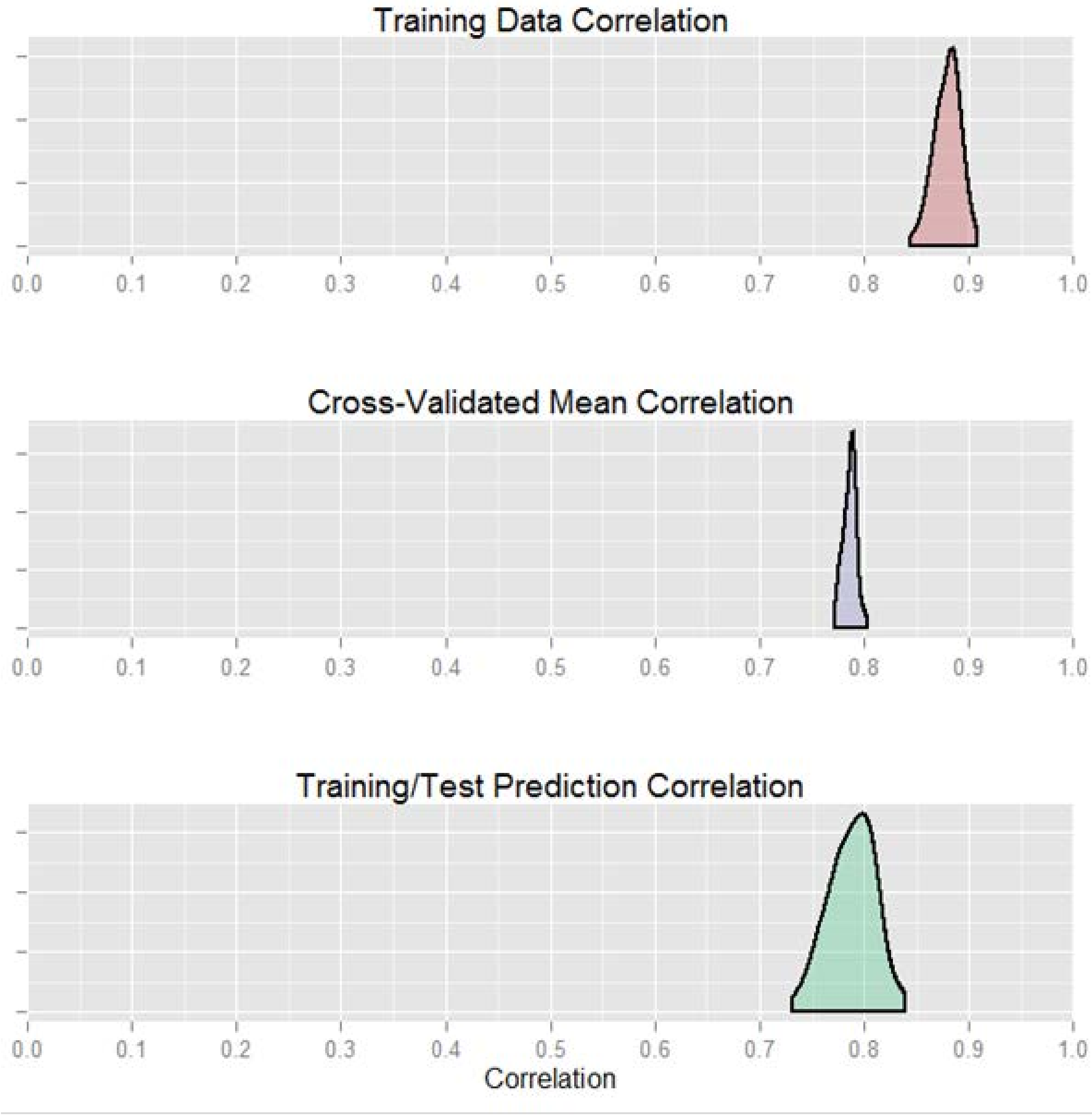


Table D-2. Summary statistics for simulated goodness of fit metrics for median TN model.

Statistic	Minimum	Q1	Median	Mean	Q3	Maximum
Training Correlation	0.84	0.87	0.88	0.88	0.89	0.91
Cross-Validated Mean Correlation	0.77	0.78	0.79	0.79	0.79	0.80
Training/Test Correlation	0.73	0.77	0.79	0.79	0.80	0.84

Median Stream Total Phosphorus Concentrations (mg/L)

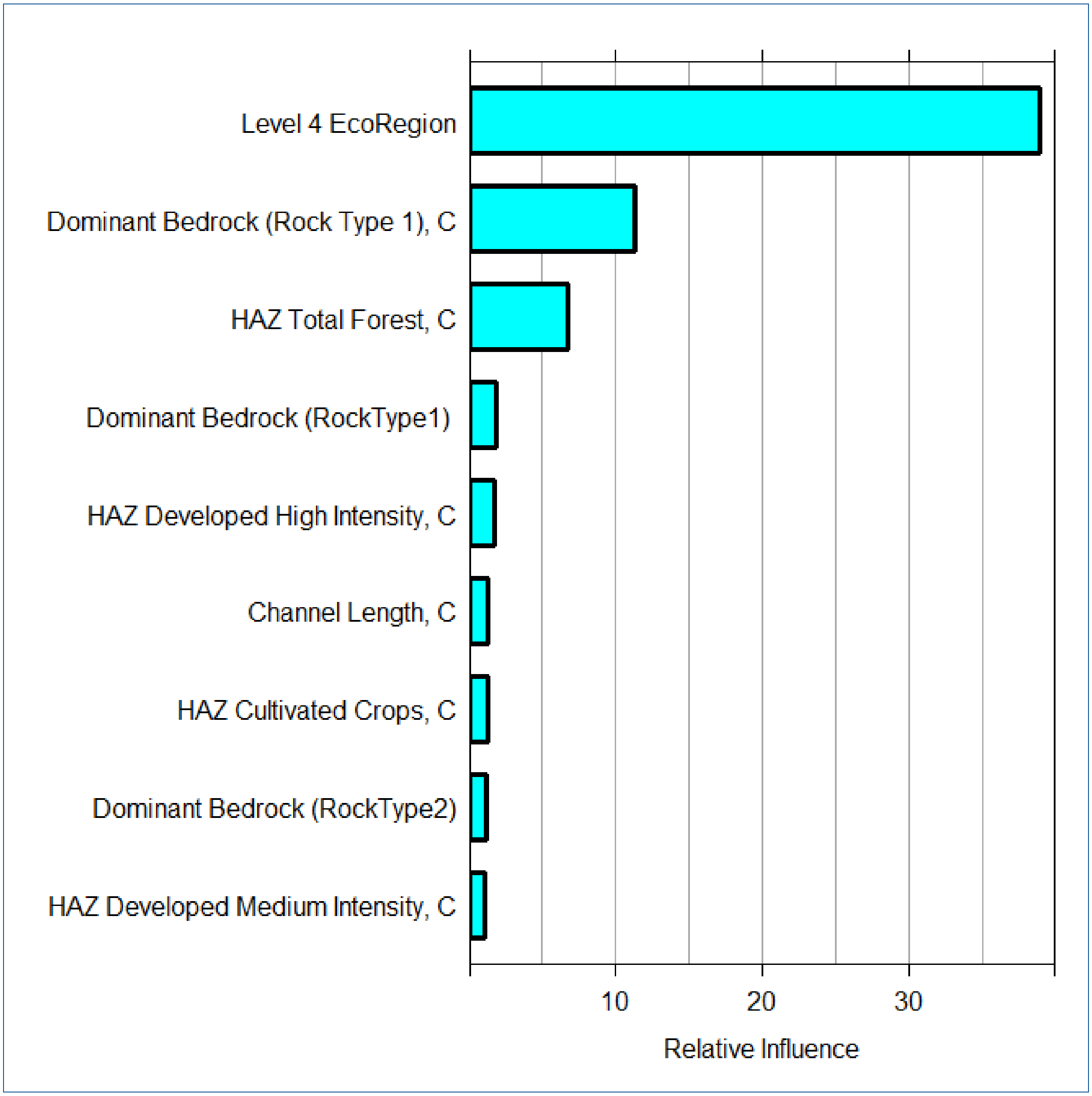
A log transformation was applied to median TP concentrations to make the distribution approximately normal. **Table D-3** details sample size and summary statistics for median catchment TP.

Table D-3. Summary statistics (minimum, 1st quartile, median, mean, 3rd quartile, and maximum values) and sample count for median TP (mg/L) in catchments with five or more post-2000 samples.

Count	Minimum	Q1	Median	Mean	Q3	Maximum
1,828	0.002	0.01	0.02088	0.07135	0.095	0.9

Model results indicate a very strong regional influence, followed by dominant bedrock (**Figure D-4**). Geology is a strong influence on TP values in the state, with geologic weathering contributing phosphate in several regions (USGS, 1967). Geologic factors appear to be more influential on TP at the statewide scale than land use (Figure D-4). However, the percent forest in the HAZ is also important; riparian forest cover can act as a buffer for phosphorus runoff from agricultural and developed land uses. In addition, row crops and developed land uses at various intensities and spatial scales were also influential.

Figure D-4. **Relative influence of predictors in TP model. Note: 'C' indicates cumulative value and HAZ indicates the hydrologically active zone.**



Goodness of fit metrics for the median TP model indicate a good predictive fit (**Figure D-5; Table D-4**). The distribution of training data statistics reveals some overfitting, but the cross-validated and training/test results are aligned. Compared to the TN model, the IQR of the training/test metric is larger, which indicates slightly less stable predictive performance.

Figure D-5. Simulated distributions of goodness of fit metrics for the TP model.

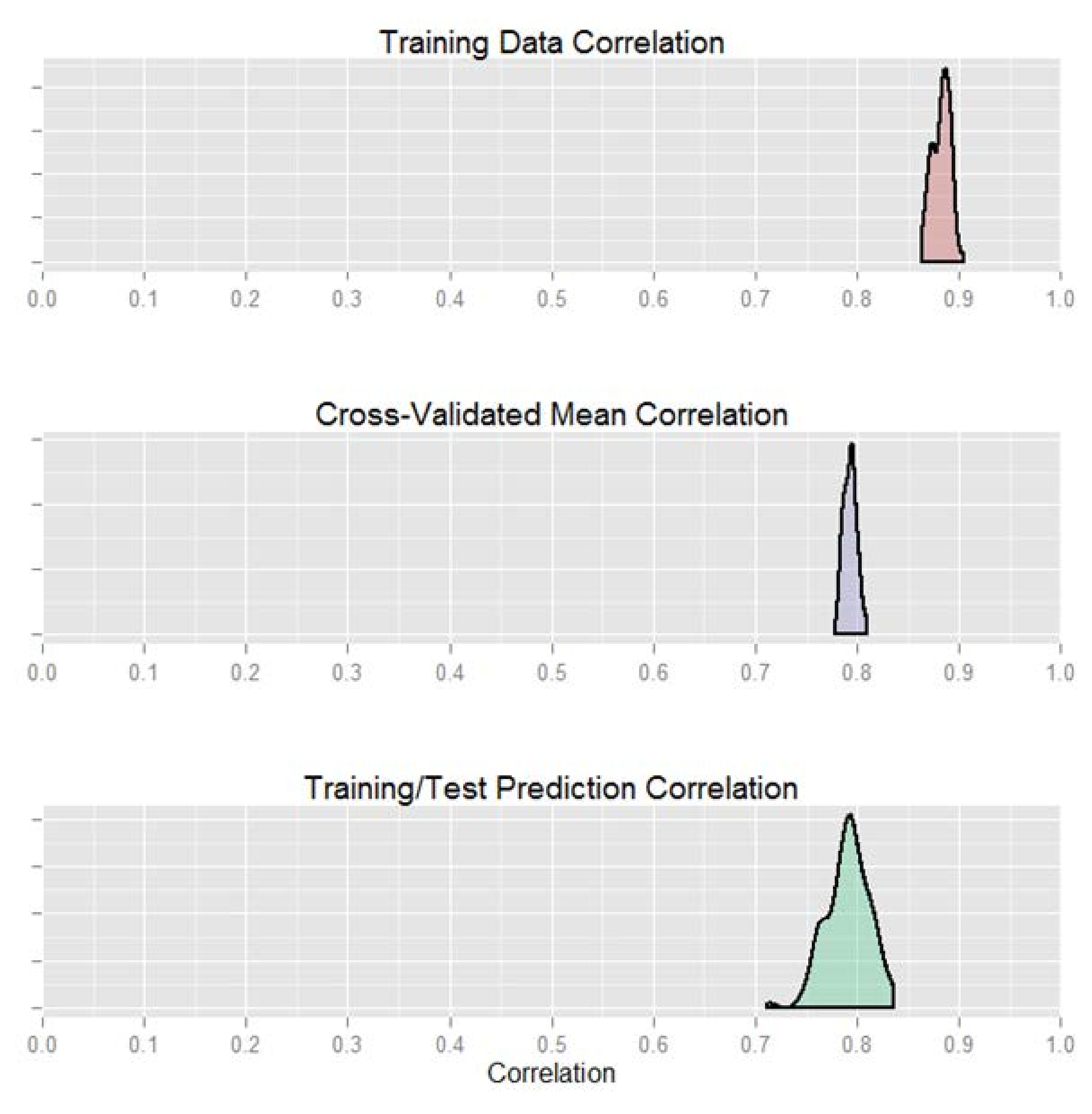


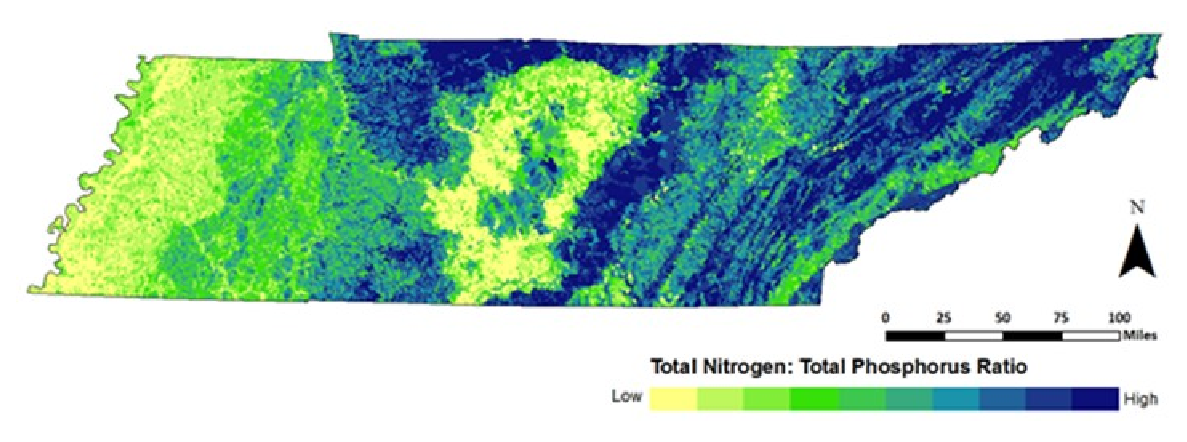
Table D-4. Summary statistics for simulated goodness of fit metrics for the median TP model.

Statistic	Minimum	Q1	Median	Mean	Q3	Maximum
Training Correlation	0.86	0.88	0.88	0.88	0.89	0.90
Cross-Validated Mean Correlation	0.78	0.79	0.79	0.79	0.80	0.81
Training/Test Correlation	0.71	0.78	0.79	0.79	0.81	0.84

TN:TP Ratio (Not Used in Assessment)

In addition to predicted median TN and TP concentrations, the TN:TP ratio was calculated by dividing predicted TN by predicted TP on a catchment by catchment scale (**Figure D-6**). High TN:TP ratio values may indicate relatively undisturbed systems, since natural sources of nitrogen tend to be larger than natural sources of phosphorus. However, considerable natural variation can occur, even in low-nutrient oligotrophic water bodies (Bergström, 2010). Similarly, a low ratio value may indicate eutrophic conditions due to either natural or anthropogenic causes. Ratio values in lotic systems may also be highly determined by hydrologic regime (Green and Finlay, 2010). These uncertainties make ranking TN:TP ratio values difficult; a high ratio value may or may not correspond to a 'healthy' condition. For these reasons, ratio values were not incorporated into the Water Quality Sub-Index. Results are presented in the appendix since the information may be useful from a management perspective.

Figure D-6. Spatial distribution of predicted TN:TP ratios.



Median Specific Conductance (μS/cm)

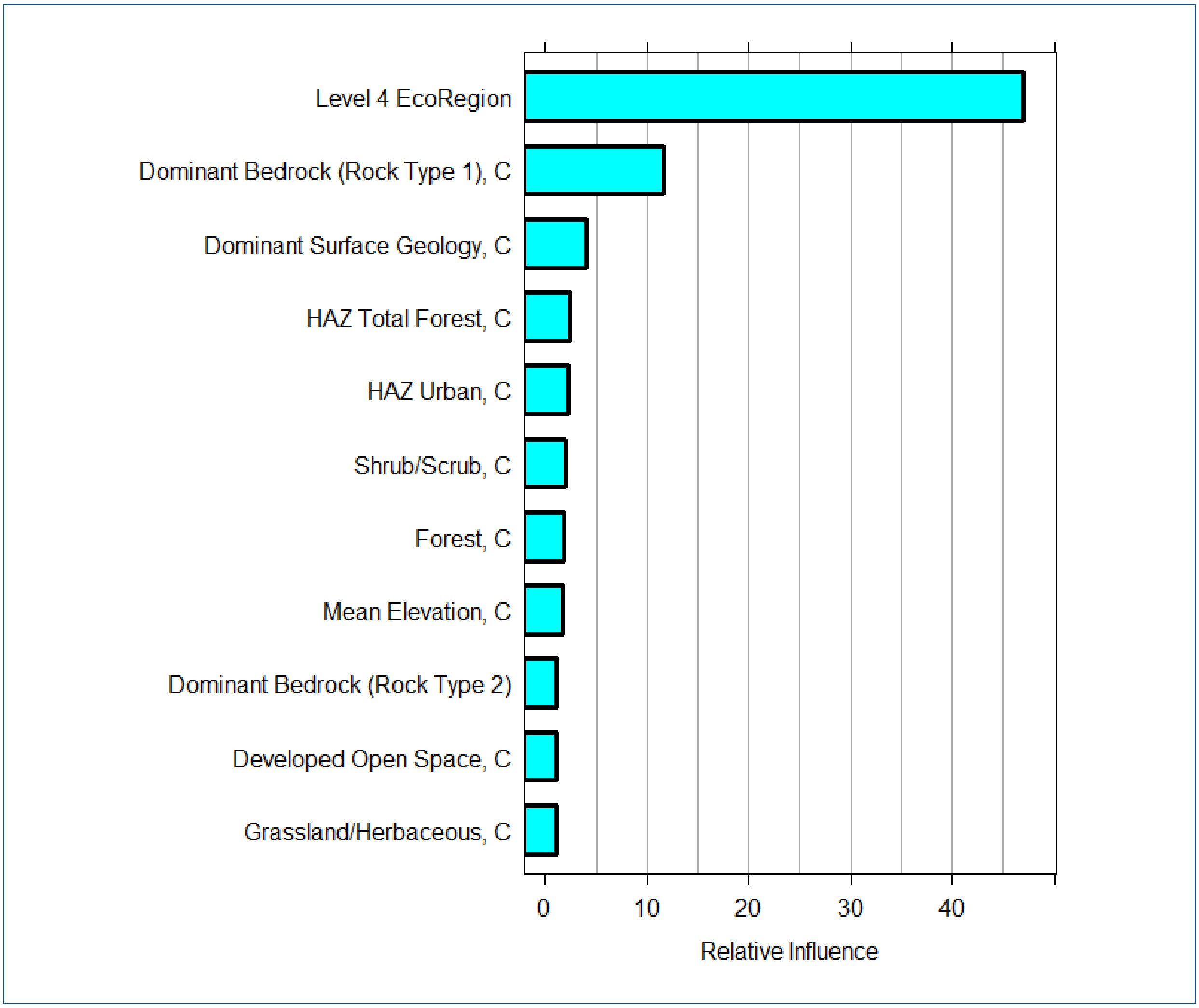
A power transformation of 0.6 was applied to SC values. Sample size and summary statistics for SC are listed in **Table D-5**.

Table D-5. Summary statistics (minimum, 1st quartile, median, mean, 3rd quartile, and maximum values) and sample count for median SC (μS/cm) in catchments with five or more post-2000 samples.

Count	Minimum	Q1	Median	Mean	Q3	Maximum
1,677	8.25	121	252.5	263.4	385.5	1,121

The SC model results again indicate a strong regional influence, followed by bedrock and surface geology (**Figure D-7**). Conductivity is highly influenced by geology; soil and bedrock materials vary tremendously in terms of their ability to ionize. SC is also correlated with dissolved solids and land uses and covers prone to erosion and sediment loss.

Figure D-7. Relative influence of predictors in SC model. Note: 'C' indicates cumulative value and HAZ indicates hydrologically active zone.



The goodness of fit metrics for SC indicate very good predictive performance (**Figure D-8; Table D-7**). While overfitting is again indicated, it is less apparent than in the other WQ parameter models, and the cross-validated and training/test metrics are significantly higher. The training/test IQR is also narrow (0.89–0.91), which indicates stable predictive performance.

Figure D-8. Simulated distributions of goodness of fit metrics for the SC model.

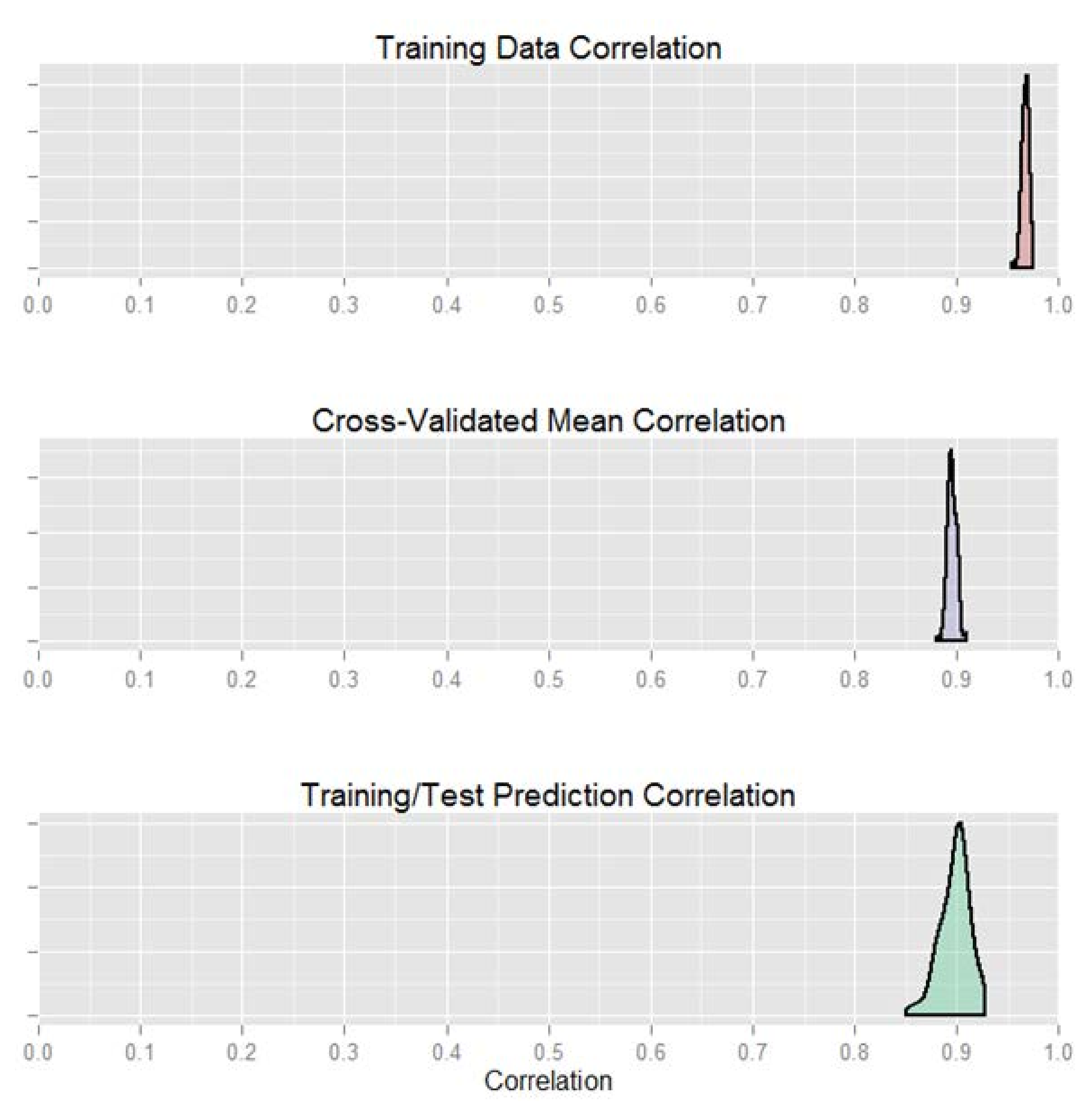


Table D-6. Summary statistics for simulated goodness of fit metrics for median SC model.

Statistic	Minimum	Q1	Median	Mean	Q3	Maximum
Training Correlation	0.95	0.97	0.97	0.97	0.97	0.98
Cross-Validated Mean Correlation	0.88	0.89	0.90	0.90	0.90	0.91
Training/Test Correlation	0.85	0.89	0.90	0.90	0.91	0.93

D.6 Habitat Model Results

Rapid Bioassessment Protocol Scores

Separate models were run for each ecoregion or group of ecoregions for the Rapid Bioassessment Protocol (RBP) score. RBP scores range from 0-200. **Table D-7** details sample size and summary statistics for the RBP score.

Table D-7. Summary statistics (minimum, 1st quartile, median, mean, 3rd quartile, and maximum values) and sample count for the RBP score, by ecoregion.

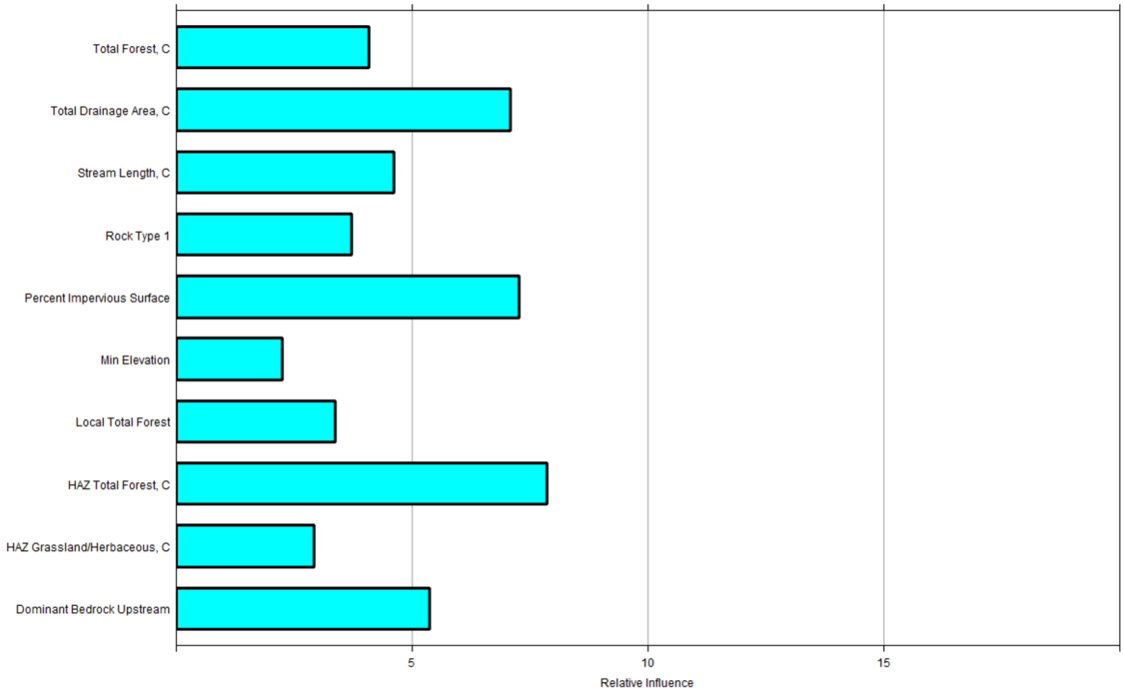
Ecoregion	Count	Minimum	Q1	Median	Mean	Q3	Maximum
Blue Ridge	284	73	132	152	150.43	172	196
Ridge and Valley	939	38	106	126	124.59	145	184.5
Central/SE Appalachians	473	40	132	151	147.72	166.75	200
Interior Plateau	1,597	52	118	130	130.07	143.5	188
SE/Mississippi Loess Plains	877	31	81	97.5	100.20	115.27	191

Model results vary by ecoregion, but indicate a strong influence of the land use in the HAZ on the RBP metric (**Figure D-9**). Distance to bedrock is the strongest driver for the model in the Interior Plateau region of the state.

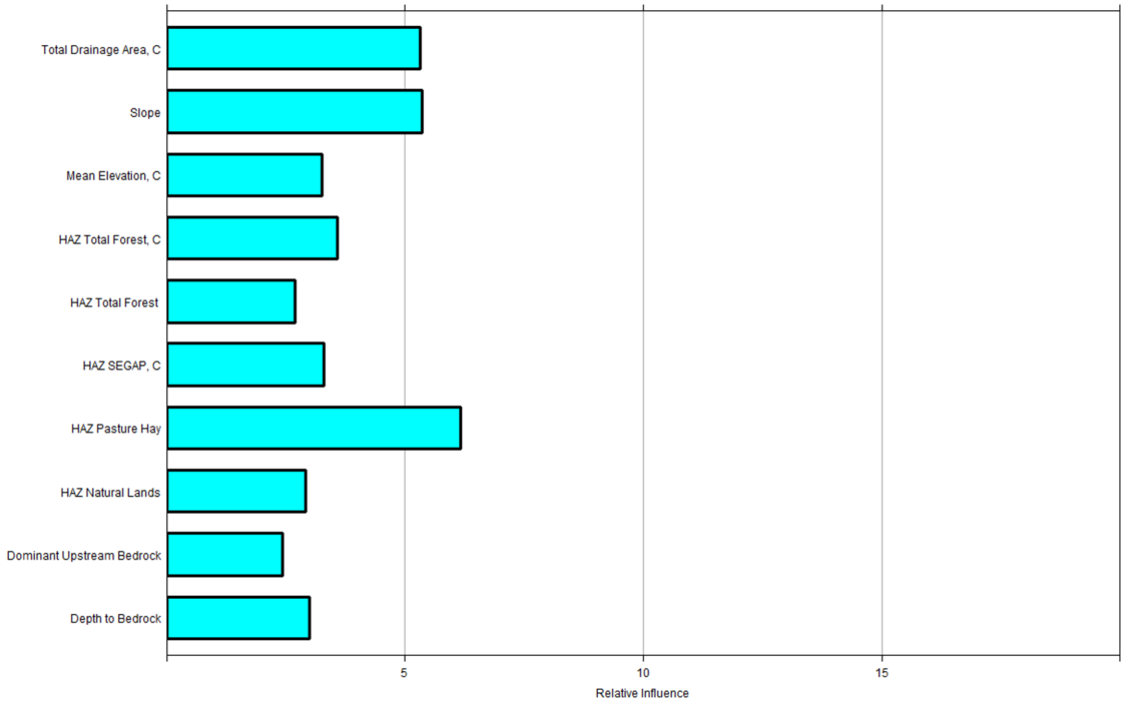
The goodness of fit metrics indicate very good predictive performance in all ecoregions (**Table D-8**).

Figure D-9. **Relative influence of predictors for RBP. Note: “C” indicates a cumulative value and HAZ indicates hydrologically active zone.**

Blue Ridge

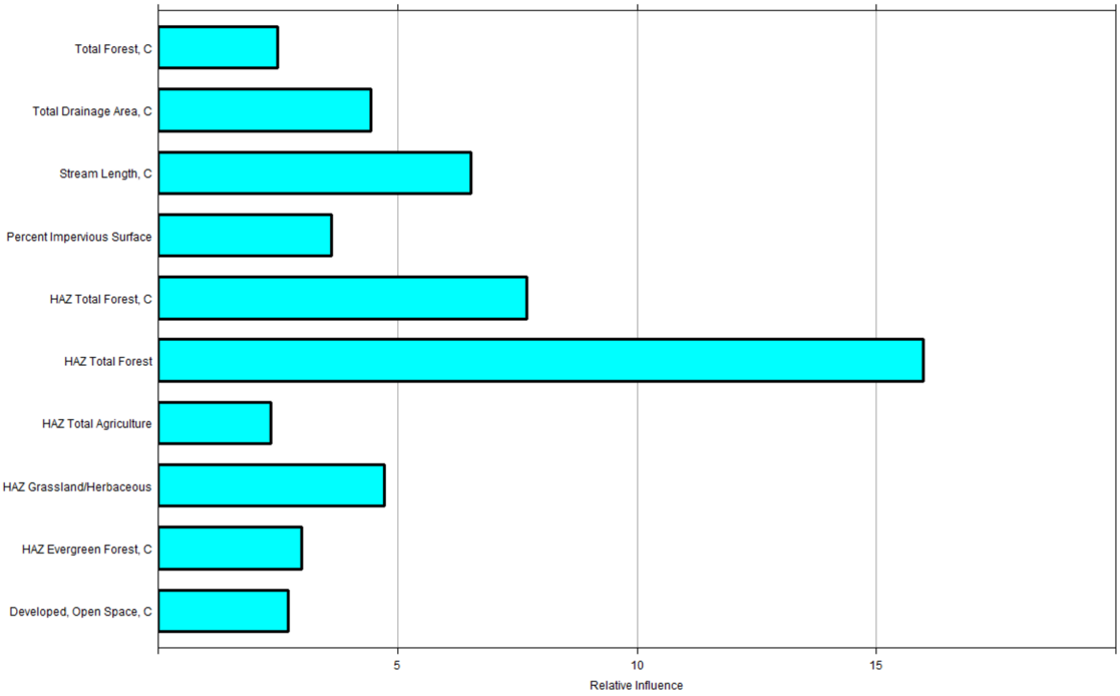


Ridge and Valley

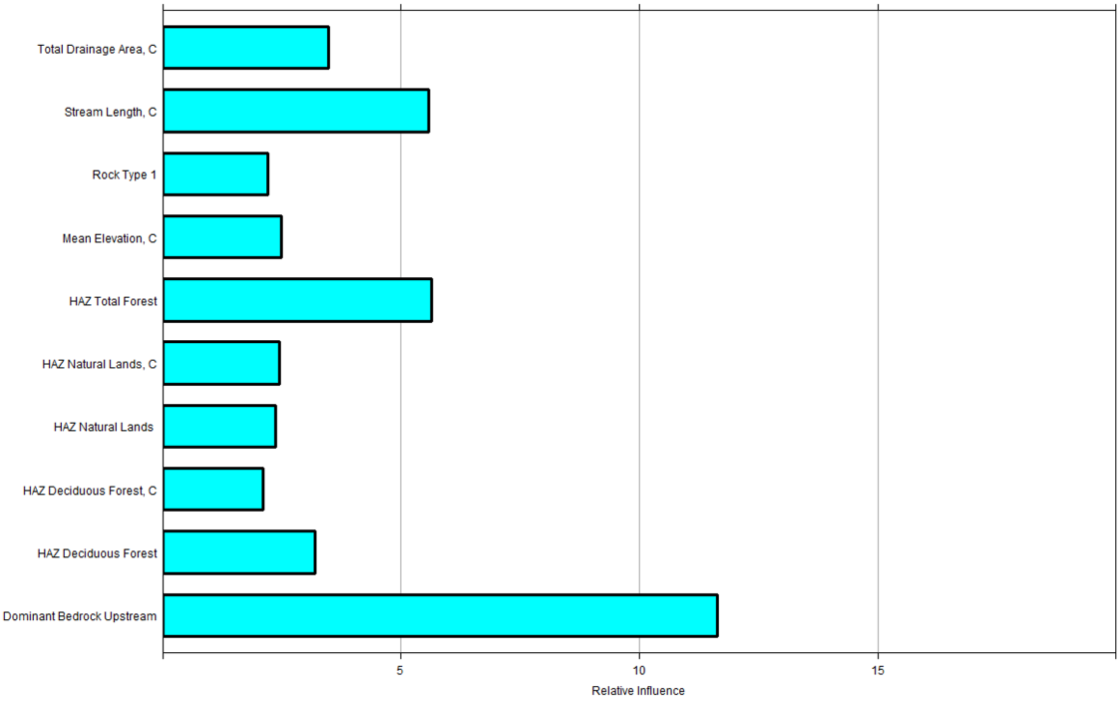


(continued)

Figure D-9. Relative influence of predictors for RBP. Note: “C” indicates a cumulative value and HAZ indicates hydrologically active zone. (continued)



Central/SE Appalachians



Interior Plateau

(continued)

Figure D-9. Relative influence of predictors for RBP. Note: "C" indicates a cumulative value and HAZ indicates hydrologically active zone. (continued)

SE/Mississippi Loess Plains

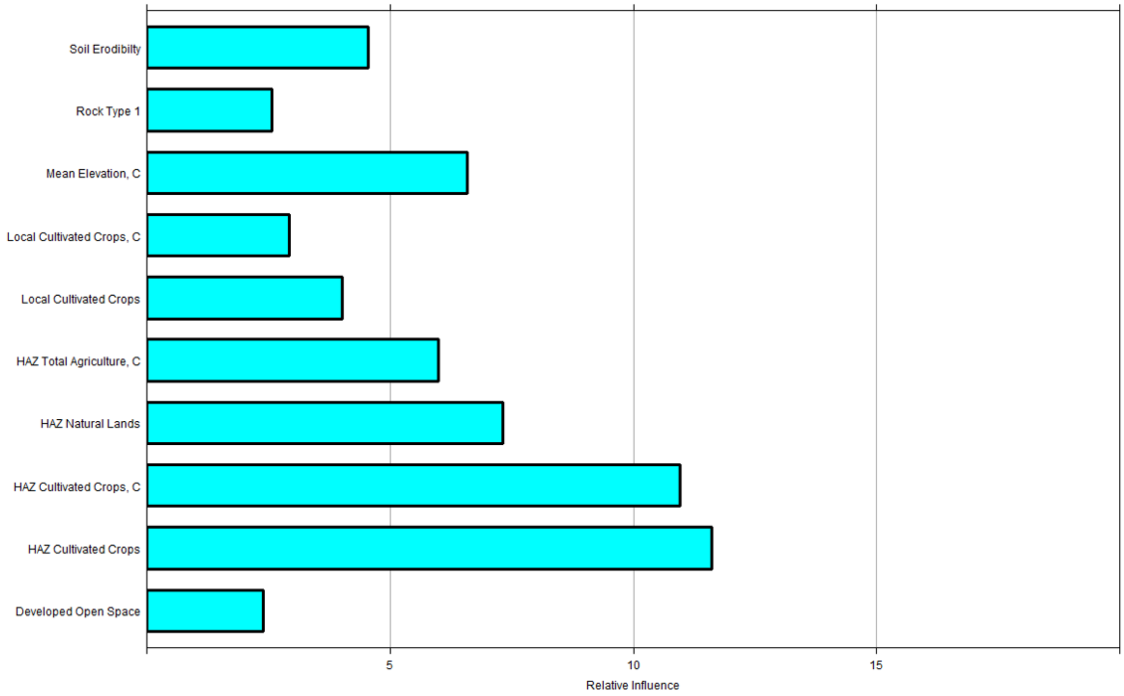


Table D-8. Summary statistics for simulated goodness of fit metrics for RBP model.

Ecoregion	Minimum	Q1	Median	Mean	Q3	Maximum
Ridge and Valley						
Training Correlation	0.74	0.78	0.81	0.80	0.84	0.84
Cross-Validated Mean Correlation	0.52	0.54	0.55	0.55	0.57	0.57
Training/Test Correlation	0.47	0.52	0.53	0.54	0.56	0.61
Blue Ridge						
Training Correlation	0.83	0.85	0.86	0.86	0.88	0.90
Cross-Validated Mean Correlation	0.54	0.58	0.59	0.59	0.61	0.64
Training/Test Correlation	0.48	0.57	0.58	0.59	0.65	0.68
Central/SE Appalachians						
Training Correlation	0.71	0.73	0.75	0.75	0.78	0.79
Cross-Validated Mean Correlation	0.44	0.50	0.51	0.51	0.54	0.55
Training/Test Correlation	0.42	0.45	0.49	0.50	0.58	0.61
SE/Mississippi Loess Plains						
Training Correlation	0.79	0.79	0.80	0.81	0.83	0.86
Cross-Validated Mean Correlation	0.67	0.69	0.69	0.69	0.70	0.71
Training/Test Correlation	0.65	0.67	0.68	0.69	0.70	0.75
Interior Plateau						
Training Correlation	0.71	0.73	0.75	0.75	0.76	0.80
Cross-Validated Mean Correlation	0.51	0.53	0.55	0.54	0.55	0.57
Training/Test Correlation	0.47	0.54	0.56	0.56	0.58	0.64

Habitat Suitability Ranking

Data provided by The Nature Conservancy (TNC)/TWRA already included a prioritization of NHDPlus catchments in Tennessee from a low probability of encountering greatest conservation need (GCN) species to a very high probability. For the purposes of this Assessment, the ranking for only the High and Very High catchments was used in order to increase the Habitat Condition Sub-Index scores for those watersheds.

D.7 Biology Model Results

Benthic Macroinvertebrate Score

Separate models were run for each ecoregion or group of ecoregions for the Benthic BioRecon score. **Table D-9** details sample size and summary statistics for the Benthic BioRecon score.

Table D-9. Summary statistics (minimum, 1st quartile, median, mean, 3rd quartile, and maximum values) and sample count for the Benthic Macroinvertebrate Metric, by ecoregion.

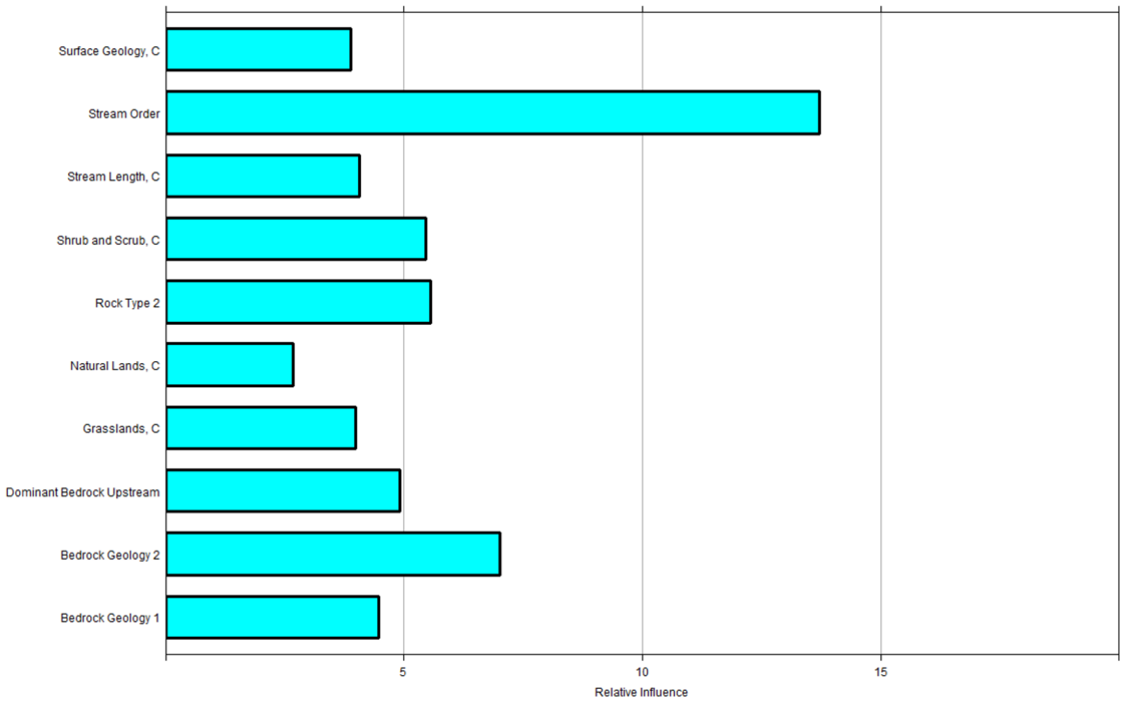
Ecoregion	COMID Count	Minimum	Q1	Median	Mean	Q3	Maximum
Blue Ridge	197	3	9	11	10.65	14	15
Ridge and Valley	586	3	6	9	9.49	13	15
Central/SE Appalachians	250	3	9	12	10.98	14.33	15
Interior Plateau	1,289	3	9.67	13	11.75	15	15
SE/Mississippi Loess Plains	648	3	6	10	9.78	13	15

Model results vary by ecoregion, but indicate a strong influence of cumulative upstream land use on the benthic macroinvertebrate community (**Figure D-10**). Stream size and elevation also influence the biology of the watershed, especially in the more mountainous Appalachian and Blue Ridge ecoregion.

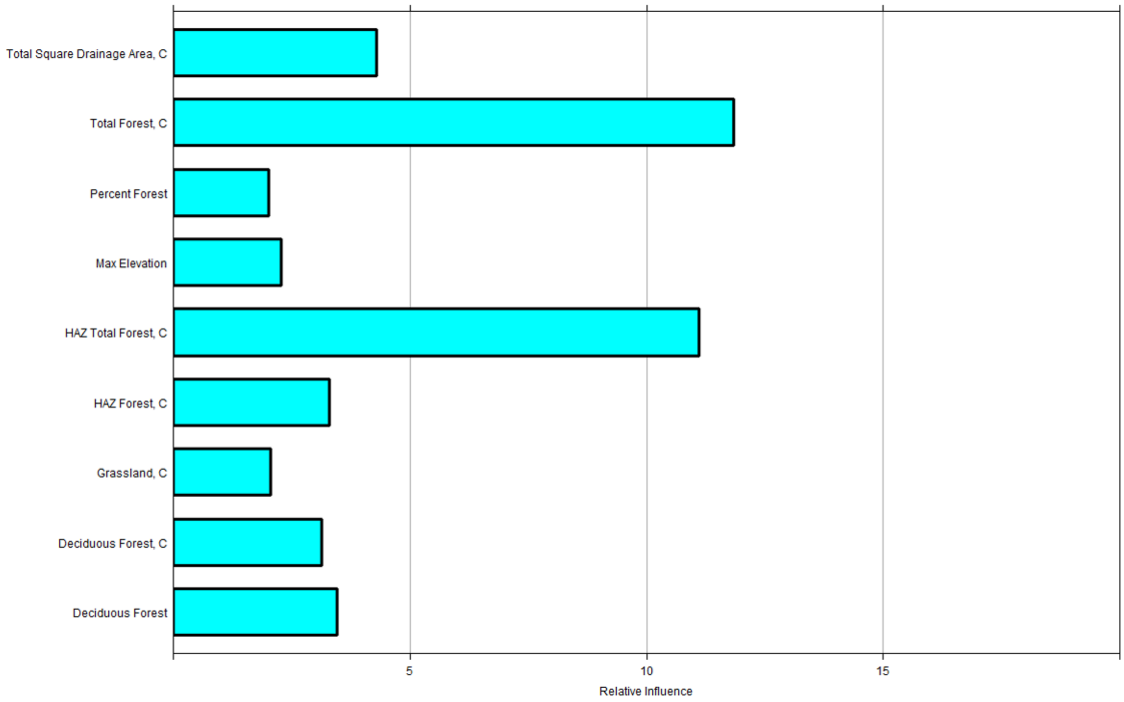
The goodness of fit metrics indicate relatively good predictive performance in most ecoregions (**Table D-10**). Performance was best in the Blue Ridge and Central/SE Appalachians. The weakest performing model was in the Ridge and Valley ecoregion.

Figure D-10. Relative influence of predictors for the benthic macroinvertebrate scores. Note: "C" indicates a Cumulative value and HAZ indicates hydrologically active zone.

Blue Ridge



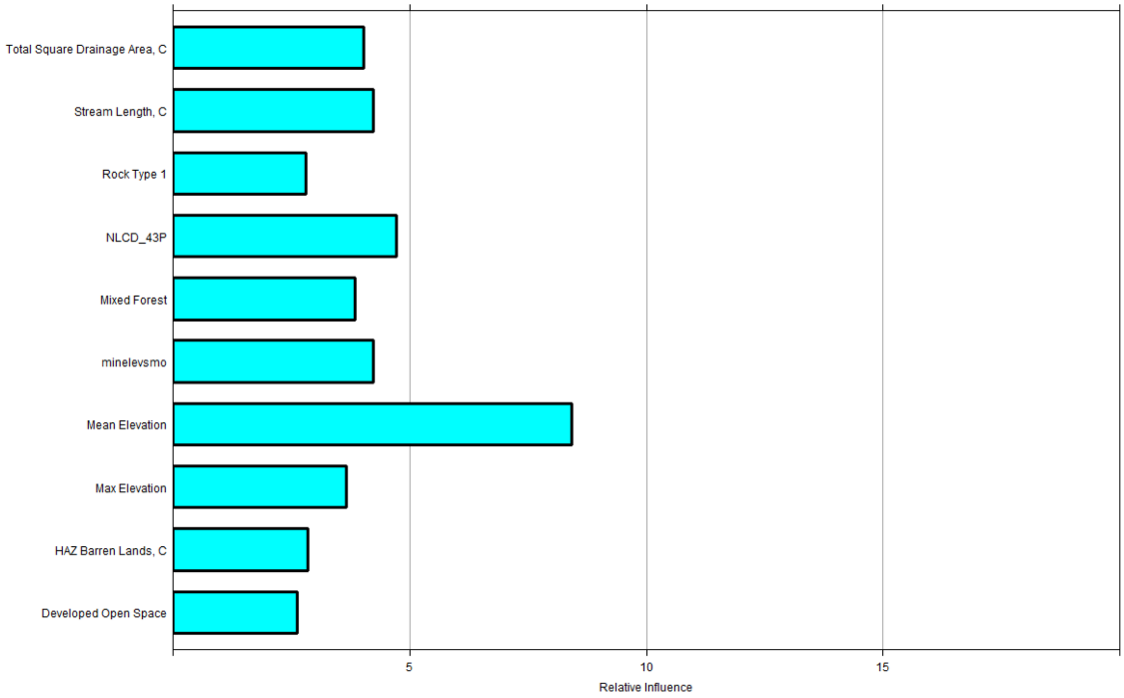
Ridge and Valley



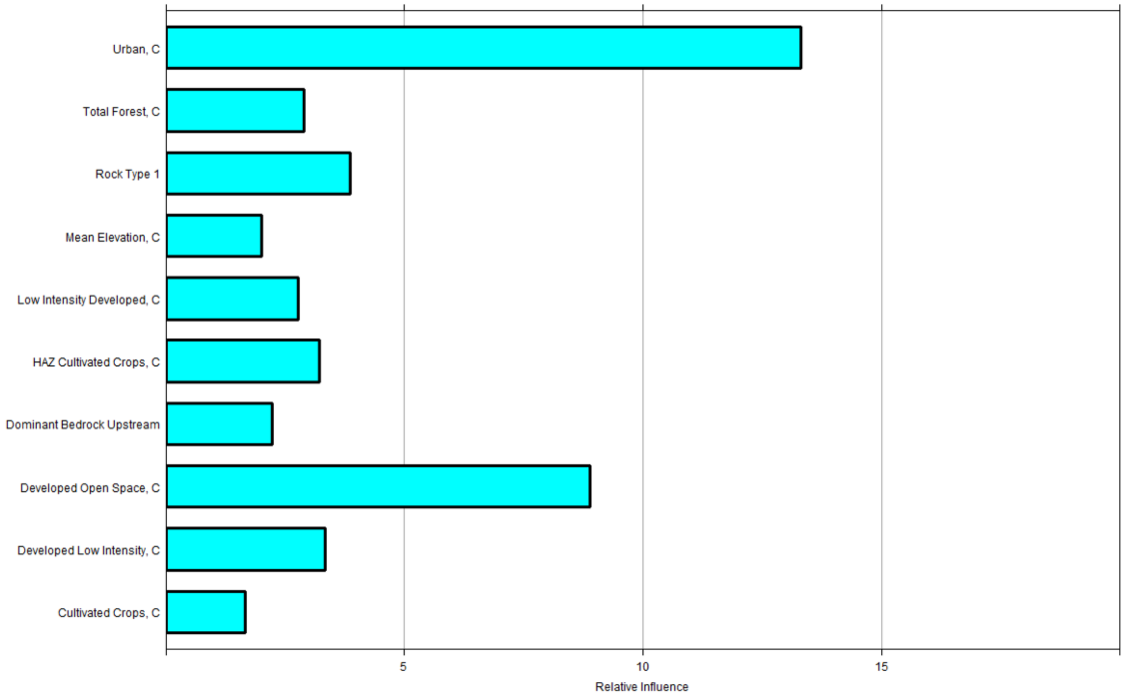
(continued)

Figure D-10. Relative influence of predictors for benthic macroinvertebrate scores. Note: "C" indicates a Cumulative value and HAZ indicates hydrologically active zone. (continued)

Central/SE Appalachians



Interior Plateau



(continued)

Figure D-10. Relative influence of predictors for benthic macroinvertebrate scores. Note: "C" indicates a Cumulative value and HAZ indicates hydrologically active zone. (continued)

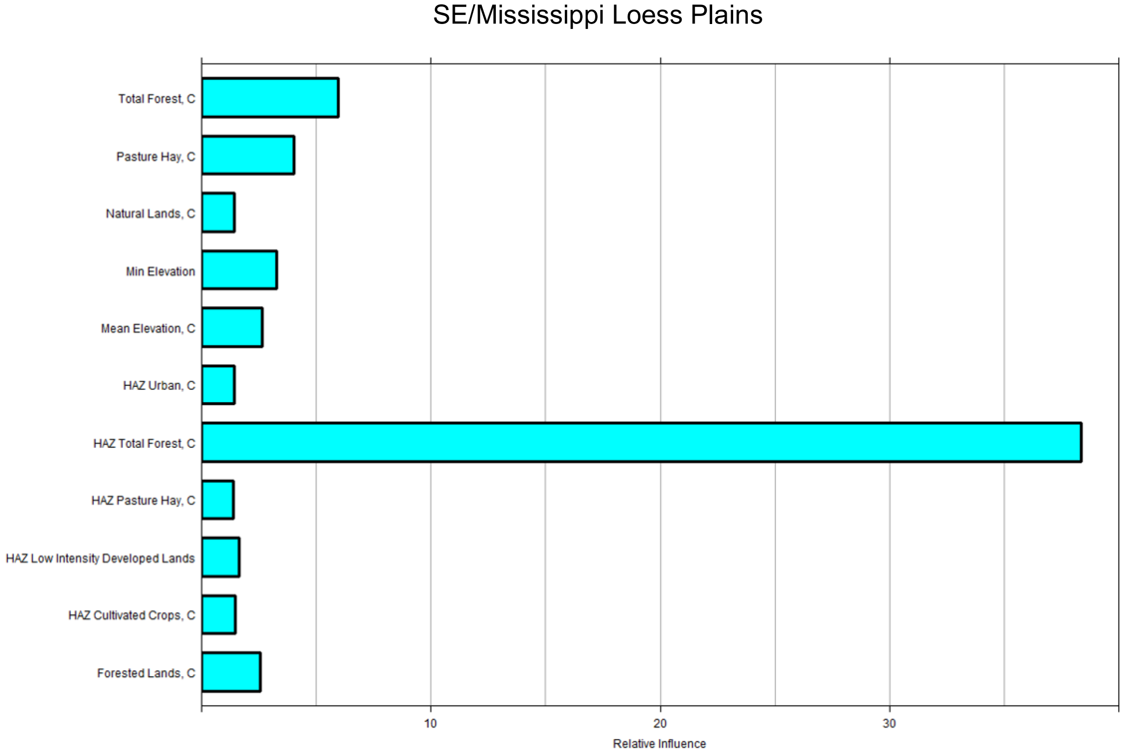


Table D-10. Summary statistics for simulated goodness of fit metrics for benthic macroinvertebrate model.

Ecoregion	Minimum	Q1	Median	Mean	Q3	Maximum
Ridge and Valley						
Training Correlation	0.63	0.65	0.69	0.68	0.71	0.72
Cross-Validated Mean Correlation	0.42	0.45	0.47	0.47	0.49	0.51
Training/Test Correlation	0.31	0.42	0.48	0.47	0.54	0.58
Blue Ridge						
Training Correlation	0.77	0.82	0.88	0.87	0.90	0.98
Cross-Validated Mean Correlation	0.36	0.42	0.47	0.47	0.52	0.57
Training/Test Correlation	0.29	0.36	0.42	0.45	0.50	0.76
Central/SE Appalachians						
Training Correlation	0.80	0.82	0.83	0.84	0.85	0.97
Cross-Validated Mean Correlation	0.39	0.43	0.46	0.46	0.48	0.56
Training/Test Correlation	0.17	0.36	0.47	0.44	0.51	0.61
SE Plains/Mississippi Loess Plains						
Training Correlation	0.76	0.78	0.80	0.81	0.83	0.88
Cross-Validated Mean Correlation	0.63	0.65	0.67	0.67	0.68	0.68
Training/Test Correlation	0.56	0.59	0.64	0.65	0.69	0.75
Interior Plateau						
Training Correlation	0.73	0.75	0.77	0.77	0.79	0.81
Cross-Validated Mean Correlation	0.57	0.59	0.60	0.60	0.61	0.63
Training/Test Correlation	0.55	0.57	0.62	0.61	0.65	0.73

Fish IBI

Fish IBIs were only available for a limited portion of the state, so the models were not run separately by ecoregion. **Table D-11** details sample size and summary statistics for the fish IBI.

Table D-11 Summary statistics (minimum, 1st quartile, median, mean, 3rd quartile, and maximum values) and sample count for the fish IBI score.

COMID Count	Minimum	Q1	Median	Mean	Q3	Maximum
102	18	33.5	38	38.92	46	56

Model results show a strong influence of cumulative land use, especially in the HAZ, on the quality of the fish community in Tennessee (**Figure D-11**).

The goodness of fit metrics indicate very good predictive performance (**Table D-12**).

Figure D-11. Relative influence of predictors for fish IBI. Note: “C” indicates a cumulative value and HAZ indicates hydrologically active zone.

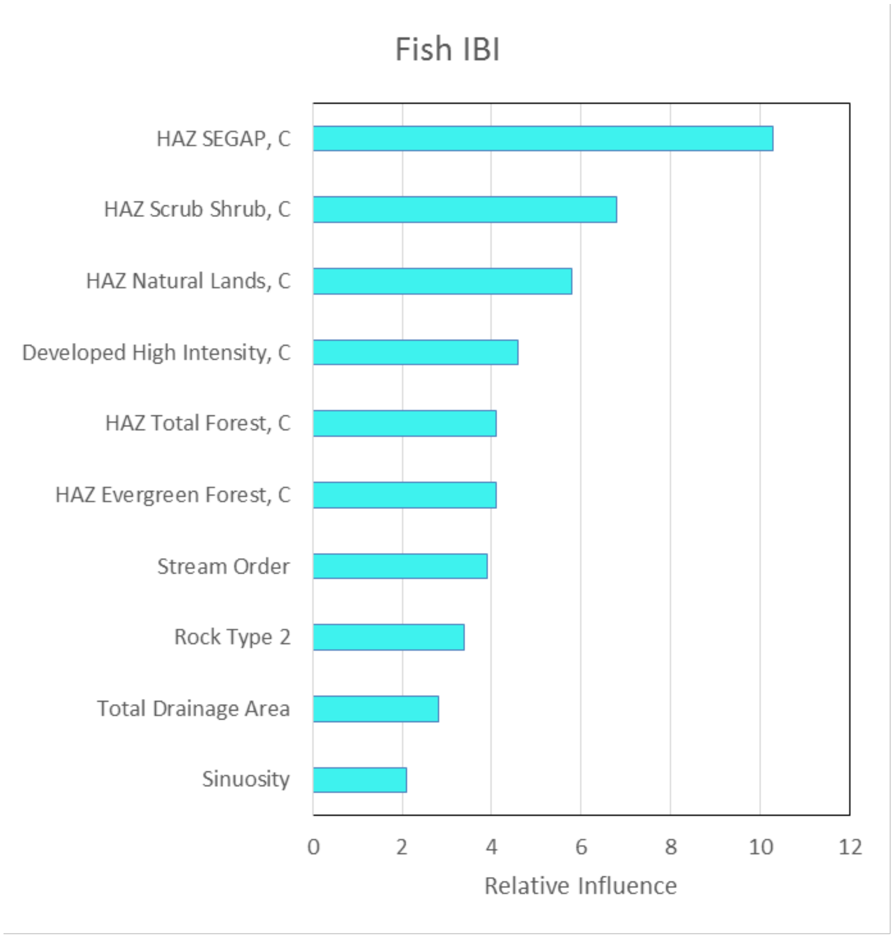


Table D-12. Summary statistics for simulated goodness of fit metrics for the Fish IBI.

Statistic	Minimum	Q1	Median	Mean	Q3	Maximum
Training Correlation	0.86	0.86	0.87	0.89	0.94	0.99
Cross-Validated Mean Correlation	0.38	0.41	0.44	0.46	0.52	0.56
Training/Test Correlation	0.35	0.39	0.58	0.54	0.67	0.69

D.8 References

Bergström, A-K. 2010. The use of TN:TP and DIN:TP ratios as indicators for phytoplankton nutrient limitation in oligotrophic lakes affected by N deposition. *Aquatic Sciences* 72(3), 277-281.

Cutler, D., T.C. Edwards Jr., K.H. Beard, A. Cutler, K.T. Hess, J. Gibson, and J.J. Lawler. 2007. Random forests for classification in ecology. *Ecology* 88: 2783-2792.

De'ath, G. 2007. Boosted trees for ecological modeling and prediction. *Ecology* 88(1): 243-251.

De'ath, G., and K. Fabricius. 2000. Classification and regression trees: A powerful yet simple technique for ecological data analysis. *Ecology* 88(11): 3178-3192.

Elith, J., J.R. Leathwick, and T. Hastle. 2008. A working guide to boosted regression trees. *Journal of Animal Ecology* 77: 802-813.

Green, M., and J. Finlay. 2010. Patterns of hydrologic control over stream water total nitrogen to total phosphorus ratios. *Biogeochemistry* 99, 15-30.

Hijmans, R., S. Phillips, J. Leathwick, and J. Elith. 2015. *dismo: Species Distribution Modeling*. R package version 1.0-12. Available at http://CRAN.R-project.org/package=dismo

Maloney, K., D. Weller, M. Russel, and T. Hothorn. 2009. Classifying the biological condition of small streams: an example using benthic macroinvertebrates. *Journal of the North American Benthological Society* 28(4): 869-884.

Ridgeway, G. 2015. *gbm: Generalized Boosted Regression Models*. R package version 2.1.1. http://CRAN.R-project.org/package=gbm.

United States Geological Survey (USGS). 1967. *Phosphate deposits: A summary of salient features of the geology of phosphate deposits, their origin, and distribution*. Geological Survey Bulletin 1252-D. Available at http://pubs.usgs.gov/bul/1252d/report.pdf

Appendix E: Data Analyses Methods and Correlation Results

E.1. Background

Data transformations, including normalization, standardization, centering, and scaling, are often required to complete analyses of environmental and ecological data. This is because the results may be biased if data are not transformed prior to analysis. However, the selection of the transformation method is guided by project goals and end user considerations, such as:

- Need to combine/integrate multiple variables that occur on different scales so that results are not biased towards any single attribute.
- Need to directly compare catchments on a relative basis.
- Need to provide the end-user with a useable tool that is amenable to further development in a format that does not report too many ‘significant digits.’

Based on these goals and considerations, rank normalization was selected as the transformation method for this Assessment. Rank normalization transforms one or more variables to a uniform distribution and scale, typically from 0 to 100; this common scale allows for comparisons between variables that may exhibit different units and scales. Rank normalization is also insensitive to outlier or extreme values, which can overly compress a normalized distribution when other normalization methodologies are applied (Mitchell, 2012).

However, the effects of standardizing the scale and distributing component metrics are not always positive, particularly when the values of a metric are predominantly in a range considered to be “good” or predominantly “poor.” It is also important that rank-normalized scores with lower index and sub-index scores should not be considered impaired or degraded; rather, the condition is lower in score relative to other catchments in the Assessment area. If all the catchments in a basin are considered “good” for a given metric, catchments with the lower metric scores will be considered the “least” healthy. Rank normalization can also be problematic when a large number of catchments share the same value of a given metric. The risk of these undesirable outcomes was minimized by choosing component parameters in consultation with the Tennessee Healthy Watershed Initiative Technical Team as well as examining the observed variability of candidate variables; if a parameter was not judged to be indicative of watershed health or vulnerability or exhibited very low variability, the variable was not included in the Assessment.

E.2. Rank Normalization of Metrics

Metrics of watershed health and vulnerability were rank normalized for reporting the metric, sub-index, and final index calculations. Rank normalization provides metric scores ranging from 0 to 100 with consistent directionality. Rank normalizing the watershed health metrics involved the following steps:

- Rank all catchments on the basis of raw metric scores:

  - Catchments were ranked in ascending order if higher metric scores corresponded to higher watershed health (i.e., higher percent natural lands).
  - Catchments were ranked in descending order if lower metric scores corresponded to higher watershed health (i.e., low total nitrogen concentrations).
- Apply the following formula to calculate the catchment's rank-normalized score:

$$Rank\ Normalization = \frac{Catchment\ Rank - Minimum\ Rank}{Maximum\ Rank - Minimum\ Rank} \times 100$$

For this Assessment, the minimum rank was always 1 and the maximum rank was 61,859 (the total number of NHDPlus catchments in Tennessee). The catchment rank was based on the order of the raw metric scores.

Rank-normalized scores are directionally aligned so that higher scores for watershed health metrics and sub-indices correspond to higher watershed health (**Table E-1**). The results of each metric and sub-index are displayed in the Map Atlas (**Appendix A**) using colors to depict the final score of each catchment; cool (blue) colors represent better condition and warm (yellow) colors represent lower condition.

As noted above, rank normalization was not applied to the Hydrologic Condition metrics. Instead, only the final Hydrologic Condition Sub-Index was rank normalized based on the sum of the absolute percentage change for all the component metrics. Lower scores correspond to the largest total percentage change, and higher scores correspond to the smallest total percentage change across the watershed.

E.3 Multi-metric Index Development

Multi-metric indices are a powerful tool for reporting aggregate conditions for ecosystems, including healthy watersheds. At the same time, care is required to ensure that multi-metric indices remain transparent and are not confounded with redundant or spurious information.

Index scores were aggregated at two levels: the sub-indices (six for watershed health and three for vulnerability) and the Watershed Health and Vulnerability Indices. Metrics were first combined into a set of sub-indices based on the groupings depicted in **Figure 7**. Each sub-index describes one attribute or component of watershed health (Landscape Condition Sub-Index, Geomorphic Condition Sub-Index, Hydrologic Condition Sub-Index, Water Quality Sub-Index, Habitat Condition Sub-Index and Biological Condition Sub-Index) or vulnerability (Land Use Vulnerability Sub-Index, Water Vulnerability Sub-Index, and Climate Change Vulnerability Sub-Index). The purpose of scoring the sub-indices before calculating the Watershed Health and Vulnerability Indices was to balance the influence of each metric on the overall index scores. Without this step, index scores could be biased toward attributes with the higher number of metrics (e.g., Hydrologic Condition).

Table E-1. Original directionality of watershed health and vulnerability metrics.

	Metric	Original Directionality
Watershed Health	Percent Natural Land Cover	Higher values = Higher watershed health
	Percent Natural Lands in HAZ	
	Resistance Score	
	Rapid Bioassessment Protocol (RBP)	
	Species Habitat Suitable Score	
	Benthic Macroinvertebrate Score	
	Fish IBI	
	Erosion Score	Lower value = Higher watershed health
	Deviation from Streamflow Characteristics Reference Condition	
	Dam Storage Ratio	
	Stream Total Nitrogen Concentration	
	Stream Total Phosphorus Concentrations	
	Stream Specific Conductance	
Watershed Vulnerability	Projected Impervious Cover Change	Higher value = Higher Watershed Vulnerability
	Potential for Energy Development	
	Projected Change in Water Consumption	
	Projected Change in Water Withdrawal	
	Projected Increase in Drought	
	Projected Increase in Heavy Precipitation Events	

The rank-normalization methodology provides metric scores that are directionally aligned (i.e., higher rank-normalized scores correspond to higher watershed health). Index scores follow the same directionality such that High Watershed Health Index scores correspond to high watershed health and high Vulnerability Index scores corresponds with watersheds that are the most like to be negatively impacted by future projected changes in land use, water use, and climate. Rank normalization eased interpretation by providing scores that correspond to percentiles. For example, a Watershed Health Index score of 75 corresponds to the 75th percentile of condition.

E.4 Correlation Analyses

A correlation analysis between all possible pairings of the watershed health sub-indices was conducted to determine whether there is any relationship between these calculated measures that would ultimately prohibit combining the sub-indices into the Watershed Health Index without redundancy. The potential for correlation exists due to some commonalities in the underlying data used to calculate the metrics used for each sub-index. Component metrics for Geomorphic Condition, Hydrologic Condition, Biological Condition, Habitat Condition, and Water Quality were quantified from statistical models that relate stream health observations to several landscape variables, including those that describe the amount and distribution of natural land cover in a catchment. Because these same properties are captured in Landscape Condition, there is potential for redundancy between the Landscape Condition Sub-Index and sub-indices derived from modeled metrics, as well as between the sub-indices themselves.

Table E-2 presents the Pearson correlation coefficients among each combination of sub-indices. Values range from 0.008 to 0.485. A weak correlation exists between the Geomorphology and Habitat Condition Sub-Indices ($R^2 = 0.485$); however, this correlation does not violate the redundancy limits used in other studies of biological multi-metric index development (Emery et al., 2003; Hering et al., 2006; Stoddard et al., 2008). These correlation results support the use of all sub-indices in the calculation of the Watershed Health Index without concerns of redundancy.

Table E-2. Pearson correlation coefficients (R-squared values) between each pairing of sub-indices available to calculate the Watershed Health Index.

Metric	Geomorphology	Hydrology	Water Quality	Habitat	Biology
Landscape	0.287	0.008	0.362	0.253	0.157
Geomorphology		0.044	0.267	0.485	0.088
Hydrology			0.016	0.040	0.039
Water Quality				0.217	0.226
Habitat					0.146

E.5 References

Emery, E.B., T.P. Simon, F.H. McCormick, P.L. Angermeier, J.E. Deshon, C.O. Yoder, R.E. Sanders, W.D. Pearson, G.D. Hickman, R.J. Reash, and J.A. Thomas. 2003. Development of a multimetric index for assessing the biological condition of the Ohio River. *Transactions of the American Fisheries Society* 132(4): 791–808.

Hering, D., C.K. Feld, O. Moog, and T. Ofenbock. (2006). Cook book for the development of a Multimetric Index for biological condition of aquatic ecosystems: experiences from the European AQEM and STAR projects and related initiatives. *Hydrobiologia* 566(1): 311–324.

Mitchell, H.B. 2012. *Data Fusion: Concepts and Ideas*. Springer, 2nd edition. 346 pages.

Stoddard, J.L., A.T. Herlihy, D.V. Peck, R.M. Hughes, T.R. Whittier, and E. Tarquinio. 2008. A process for creating multimetric indices for large-scale aquatic surveys. *Journal of the North American Benthological Society* 27(4): 878–891.