WISCONSIN INTEGRATED ASSESSMENT OF WATERSHED HEALTH

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

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Cover photos courtesy of Wisconsin Department of Natural Resources (Left: Turtle-Flambeau Scenic Waters Area in Iron and Pierce Counties; Upper Right: Devil's Lake in Sauk County; Lower Right: Bad River in Ashland County).

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EXECUTIVE SUMMARY

Healthy waters are a vital part of Wisconsin's identity and economy. The state's high-quality streams, lakes, and wetlands provide a wealth of recreational opportunities, clean drinking water, and other ecosystem services to residents and visitors alike. Their continued function and status as *healthy* aquatic ecosystems depends in large part on the implementation of protection measures to prevent direct impacts and to maintain key watershed features and processes. A more concerted effort to protect high-quality waters by state agencies and other organizations can support the effectiveness of current efforts to restore impaired waters and circumvent the need for costly restoration in the future.

The purpose of the Wisconsin Integrated Assessment of Watershed Health (the Assessment) is to identify healthy watersheds and characterize relative watershed health across the state to guide future protection initiatives. A healthy watershed has the structure and function in place to support healthy aquatic ecosystems. It is characterized as having all or most of these key components: intact and functioning headwaters, wetlands, floodplains, riparian corridors, biotic refugia, instream and lake habitat, and biotic communities; and natural vegetation in the landscape, hydrology (e.g., range of instream flows and lake levels), sediment transport and fluvial geomorphology, and disturbance regimes expected for its location.

The goals of the Assessment were to:

1. Integrate multi-disciplinary data to both identify healthy watersheds and characterize the relative health of watersheds across the state;
2. Make watershed health data and information readily available to a variety of state, federal, and local programs for watershed protection planning; and
3. Encourage inter-agency partnerships and collaboration to build upon previous efforts to assess watershed health and protect healthy watersheds.

This report presents the methods and results of the planning and analysis phases of the Assessment, and outlines proposed next steps and applications. The Assessment applies a *systems 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 is quantified across the state at the catchment (or subwatershed) scale from existing statewide geospatial datasets and from predictive models derived from field monitoring data collected as part of existing statewide assessment programs. This information is synthesized into several indices that describe watershed health and vulnerability to future degradation.

An important facet of the Assessment is that it leverages existing efforts that have been undertaken 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 national scales and/or generate data or tools that facilitate watershed health assessment. This project has forged partnerships among these groups to gather and standardize disparate datasets and provide a more complete picture of watershed health across Wisconsin.

One outcome of the Assessment is a watershed health database that is available through the Wisconsin Department of Natural Resources (WDNR) to 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 have been identified by WDNR.

A second, more enduring, outcome is the integrated assessment framework developed by project partners. This framework reflects our understanding of the interconnected nature of the physical, chemical, and biological condition of aquatic ecosystems; the significance 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. At present, the framework serves as a starting point for agencies and organizations tasked with protecting healthy waters to collaborate and apply a unified approach rather than undertake disjointed efforts. Over the long term, the WDNR envisions that the existing framework will be updated as data gaps are filled and improved methodologies are identified.

1 INTRODUCTION

1.1 Purpose and Intended Use

Over the past several decades, considerable effort has been made to restore the impaired streams, rivers, and lakes of Wisconsin. While some success has been achieved, many miles of streams and acres of lakes remain degraded and new impairments continue to be identified. Degradation of Wisconsin's aquatic ecosystems has important economic and societal consequences. In addition to the large capital expenses associated with restoration, impaired waters often lose their ability to provide valuable ecosystem services to the public, such as recreation and supplies of clean water. Together, these issues call for the expanded use of watershed protection as a tool to preserve ecosystem services and preclude the need for costly restoration.

This report presents the methods, results, next steps, and applications of the Wisconsin Integrated Assessment of Watershed Health (the Assessment). The overarching goal of the Assessment is to characterize the relative health of watersheds across the state for the purpose of guiding future watershed protection initiatives. The Assessment synthesizes disparate datasets to depict current landscape and aquatic ecosystem conditions throughout Wisconsin. It is framed around the recognition that the biological, chemical, and physical health of a water body are fundamentally connected to one another and to the maintenance of natural watershed processes. The Assessment further recognizes that Wisconsin's watersheds are dynamic, ever-changing systems and characterizes the vulnerability of watershed health to future degradation. By integrating information on multiple ecological attributes at several spatial and temporal scales, a systems perspective on watershed health is provided.

Readers are asked to consider the following points regarding the scope of the Assessment as they review methods and interpret results:

- The term *watershed health* can have several connotations. Its use here refers to the holistic condition of *freshwater* ecosystems within a watershed. The condition of terrestrial and coastal ecosystems is not explicitly analyzed and results should not be used to infer the condition of these ecosystem types.
- The Assessment characterizes *relative* watershed health throughout the state 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 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). As noted above, data generated for the Assessment are not intended to be used to determine the absolute condition of aquatic ecosystems (e.g., to assess attainment of designated uses). Further, 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 Initiative

The US Environmental Protection Agency (EPA) launched the Healthy Watersheds Initiative to motivate and support active protection of our nation's remaining healthy watersheds (US EPA, 2012). A cornerstone of the Initiative is the promotion of a strategic, systems approach (Beechie, Sear, & Olden, 2010) to watershed protection planning and implementation. The US EPA has proposed the use of *integrated assessments* of watershed health to assist states and others with identifying healthy watersheds and prioritizing candidate watersheds for protection and restoration. Integrated assessments synthesize information on landscape condition, hydrology, fluvial geomorphology, habitat, water chemistry, and biotic communities. By combining multidisciplinary data from multiple spatial scales, integrated assessments reflect our understanding of 1) the interconnected nature of the physical, chemical, and biological condition of aquatic ecosystems; 2) the significance of landscape and watershed scale processes; and 3) the need to view water bodies as connected parts within a larger system rather than as isolated units.

1.3 Wisconsin Department of Natural Resources

The Wisconsin Department of Natural Resources (WDNR) administers several programs to assess, protect, and restore Wisconsin's aquatic ecosystems. These programs have generated a variety of datasets and tools. The Wisconsin DNR was interested in initiating the Assessment in order to improve its ability to look at these complex datasets from a systems perspective. WDNR is planning to strategically re-evaluate its statewide monitoring and assessment programs in the near future, and the Assessment results may be informative to those efforts. Additionally, WDNR anticipates using the results to better target grant funds for protection and restoration toward watersheds where such projects would generate the most lasting results.

Learn More Online

Visit the US EPA Healthy Watersheds Initiative website and the WDNR aquatic ecosystem management website to review background material and information on related projects:

US EPA Healthy Watersheds Initiative: http://www.epa.gov/healthywatersheds

WDNR Aquatic Ecosystem Management: http://dnr.wi.gov/topic/rivers/management.html

1.4 Overview of Wisconsin's Ecoregions

Wisconsin contains an abundance of streams, lakes, and wetlands whose diversity reflects the convergence of three major biomes (northern boreal forest, eastern deciduous forest, and western prairie) and a rich history of glacial activity. Six Level III Ecoregions lie within the state (Omernik, 1987). Each ecoregion contains a blend of small streams, medium and large river systems, lakes, wetlands, and other aquatic ecosystem types. Below is a brief description of Wisconsin's ecoregions with information adapted from Omernik et al. (2000) and the *Ecological Landscapes of Wisconsin Handbook* (WDNR, 2013):

- **Northern Lakes and Forests** – Covers the northern one-third of the state, with land area in all three of Wisconsin's major drainage basins (Lake Superior, Lake Michigan, and Mississippi River) and the headwaters of the Wisconsin River. Climate is characterized by long, cold winters and short, warm summers. Annual temperatures and precipitation are lower relative to ecoregions of central and southern Wisconsin and growing season length is shorter. Land cover is predominantly mixed conifer-deciduous forest with agriculture less prevalent than other parts of the state due in part to low temperatures and nutrient poor soils. Streams are mostly perennial and typically originate from groundwater-fed springs/lakes. Lakes are high in number and are generally clearer and at a lower trophic state than those in other ecoregions. Forested and shrub-dominated wetlands are also common throughout the region.

- **North Central Hardwoods Forests** – Covers much of central Wisconsin and acts as a transitional area between the forests of the Northern Lakes and Forests ecoregion and agriculture dominated ecoregions to the south. Land cover is a mosaic of forests, wetlands and lakes, cropland, and pasture. Includes headwater streams and several large rivers (e.g., Wolf River, Wisconsin River, Chippewa River). Lake density is lower than in the Northern Lakes and Forests ecoregion, and trophic states are generally higher. Forest, shrub, and herbaceous wetlands are common in various glacial landform features (e.g., moraine depressions and glacial drainage channels).
- **Driftless Area** – Covers the southwest and central west portion of the state and is distinguished by its hilly terrain and carved river valleys. Land cover is a mix of deciduous forest, grassland, and agriculture. Includes the lower reaches of several large rivers (e.g., Wisconsin River, Chippewa River, and Black River) and their confluence with the Mississippi River. Stream density is high and lake and wetland density are low relative to other ecoregions. Coldwater streams are more common than in other areas of southern Wisconsin due to cold groundwater discharge from porous bedrock. Riparian forests and herbaceous wetlands occur throughout the floodplains of the region's several large rivers.
- **Southeastern Wisconsin Till Plains & Central Corn Belt Plains** – Covers southeast and central east Wisconsin. The region's warm climate, gentle topography, and fertile soils have contributed to a high concentration of agricultural cover interspersed with remnant patches of grassland and forest. Also contains urban areas in/around the state's most populous cities, including Milwaukee, Madison, and Green Bay. Aquatic ecosystems throughout these ecoregions have been impacted considerably by human activity. Examples include degradation of water quality in several large rivers and their tributaries (e.g., Fox River, Rock River, and Milwaukee River), and in Lake Winnebago, the state's largest lake. Herbaceous wetlands, once a dominant part of the landscape, have been reduced in extent and colonized by invasive reed canary grass as a result of draining/filling for agriculture and development. Remaining wetlands, such as the 33 square mile Horicon Marsh in Dodge County, provide key habitat for migratory birds and other wildlife and important water quality functions.
- **Western Cornbelt Plains** – Covers a relatively small area of western Wisconsin in St. Croix and Pierce Counties. Climate is similar to the Driftless Area ecoregion and is otherwise distinguished by gentler terrain, higher tall grass prairie cover, and lower forest cover. Much of the native prairie has been converted to cropland due to the region's fertile soils and flat topography. Stream, lake, and wetland density are low relative to other ecoregions though existing waters have experienced degradation due to agricultural activity.

FIGURE 1. LEVEL III ECOREGIONS OF WISCONSIN.

2 METHODS OVERVIEW

2.1 *Healthy Watersheds Assessment Process*

This report is the result of a collaboration between the US EPA and WDNR to assess watershed health throughout Wisconsin. The Assessment was initiated with the formation of an Assessment Team with representation from US EPA, WDNR, and other organizations to develop the assessment methodology, review and communicate results, and implement next steps. The Assessment Team is comprised of members from:

- Participating State Agencies
  - Wisconsin Department of Natural Resources Water Evaluation Section
  - Wisconsin Department of Natural Resources Monitoring Section
  - Wisconsin Department of Natural Resources Lakes and Rivers Section
  - Wisconsin Department of Natural Resources Groundwater Section
  - Wisconsin Department of Natural Resources Runoff Management Section
- Participating Federal Agencies
  - US EPA Office of Water
  - US EPA Region 5
- Other Participating Organizations
  - The Nature Conservancy

The first task undertaken by the Assessment Team was to prepare an inventory of available field monitoring data and geospatial data for assessing current landscape, habitat, hydrological, geomorphological, water quality, and biological condition throughout the state and projected vulnerability to future degradation. From this inventory, a list of candidate watershed health and vulnerability metrics was generated.

The Assessment Team then refined the technical approach to the Assessment, examined and completed the data inventory, and discussed the candidate watershed health and vulnerability metrics. Also discussed were options for communicating results and a preliminary list of uses of the Assessment output. From this step, an Assessment Roadmap (Figure 2) was produced to serve as an outline for assessment planning, analysis, reporting, and implementation.

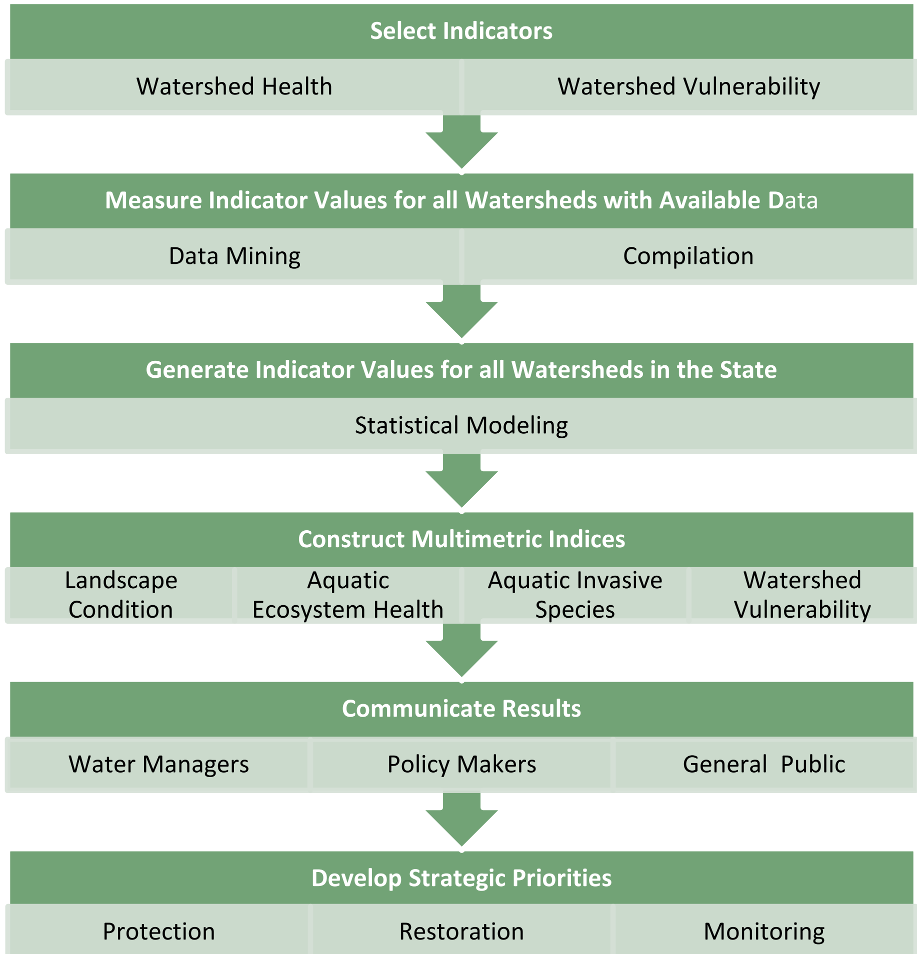

FIGURE 2. ROADMAP FOR THE WISCONSIN INTEGRATED ASSESSMENT OF WATERSHED HEALTH.

2.2 Conceptual Framework

The US EPA defines a healthy watershed as one in which "natural land cover supports dynamic hydrologic and geomorphic processes within their natural range of variation; habitat of sufficient size and connectivity supports native aquatic and riparian species; and water quality supports healthy biological communities" (US EPA, 2012). This definition encompasses six distinct but interrelated attributes of watersheds and the aquatic ecosystems within them: landscape condition; habitat; hydrology; geomorphology; water quality; and biological condition (Figure 3).

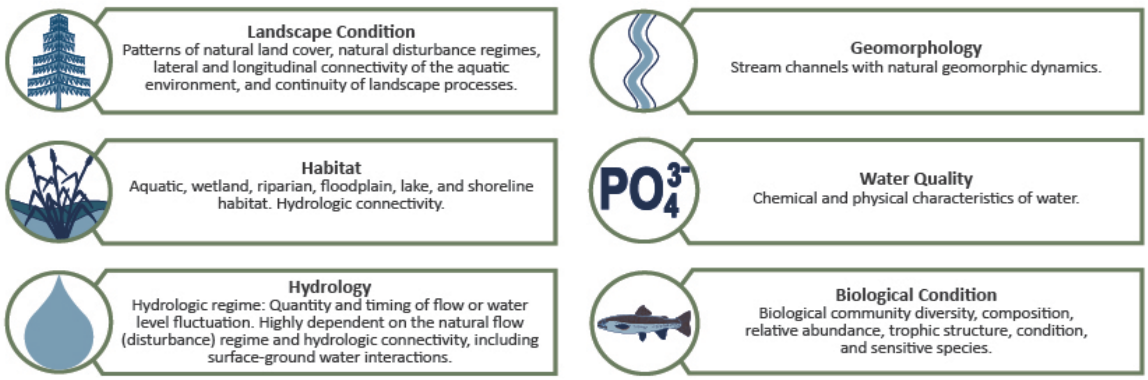

FIGURE 3. SIX ATTRIBUTES OF WATERSHED HEALTH DESCRIBED IN *IDENTIFYING AND PROTECTING HEALTHY WATERSHEDS CONCEPTS, ASSESSMENTS, AND MANAGEMENT APPROACHES* (US EPA, 2012).

An *integrated assessment* of watershed health sets out to evaluate each of these six attributes using a collection of *Watershed Health Metrics*. Watershed health metrics are specific measures of the six attributes that are quantified throughout the entire assessment area based on existing data. For the Wisconsin Integrated Assessment, metrics are broadly grouped as:

a) *Landscape Condition Metrics* – These metrics describe the extent of natural land cover throughout the watershed and in key functional areas, and connectivity between intact natural areas. They characterize the landscape condition attribute of watershed health;

b) *Aquatic Ecosystem Health Metrics* – These metrics focus on instream ecological conditions and characterize the hydrologic, aquatic habitat, geomorphic, water quality, and biological condition attributes of watershed health; and

c) *Aquatic Invasive Species Metrics* – These metrics describe the presence of harmful aquatic invasive species in lakes. They are grouped separately from aquatic ecosystem health metrics because of the limitations of available invasive species data.

Data used to quantify watershed health metrics are selected to depict present 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 degradation. Vulnerability is quantified from a collection of *Watershed Vulnerability Metrics* that characterize potential exposure to future climate, land use, and water use change. Further discussion of metrics and data sources is provided in Sections 2.4, 2.5, and 2.6.

Two approaches are used to calculate metric values for every watershed in Wisconsin. Most metrics are quantified from existing geospatial datasets. These datasets are derived from remote sensing or other data collection methods that provide complete coverage across the state. The remaining metrics are quantified from a group of statistical models that relate instream conditions to landscape characteristics using existing field monitoring data. See Section 2.4, Section 2.5, and Appendix B for details of metric calculation methods.

A total of 26 metrics are used to characterize the relative health and vulnerability of Wisconsin's watersheds. To integrate this information for reporting and application, metrics are aggregated into a collection of multimetric sub-indices and indices. Each index/sub-index combines related metrics into an overall score that ranges from 0 to 100. Methods for developing index and sub-index scores are further discussed in Section 2.9.

2.3 *Spatial Framework*

One objective of the Assessment is to characterize watershed health and vulnerability within a spatial framework that accommodates watershed protection planning across varied spatial scales and planning unit delineations. Toward this end, the geographic units selected for analysis are reach-scale watershed segments of the WDNR 24K hydro geodatabase (WHD) (WDNR, 2009). These watershed segments, termed *catchments* in this report, comprise the direct drainage area of individual hydrographic features (streams, lakes, and reservoirs) in the WHD. The WHD is a high-resolution 1:24,000 scale geospatial representation of water bodies in the state.

WHD catchments are illustrated in Figure 4. A total of 157,103 catchments fall completely within the state or on the border and are included in the Assessment. Average catchment size is approximately 0.4 square miles. WHD catchments therefore provide a finer scale representation of drainage boundaries than the hydrologic units of the national watershed boundary dataset (WBD) maintained by the US Geological Survey (USGS) and US Department of Agriculture Natural Resource Conservation Service (NRCS). For example, dozens of WHD catchments are nested within a given 12-digit hydrologic unit (HUC12), the smallest hydrologic unit of the WBD.

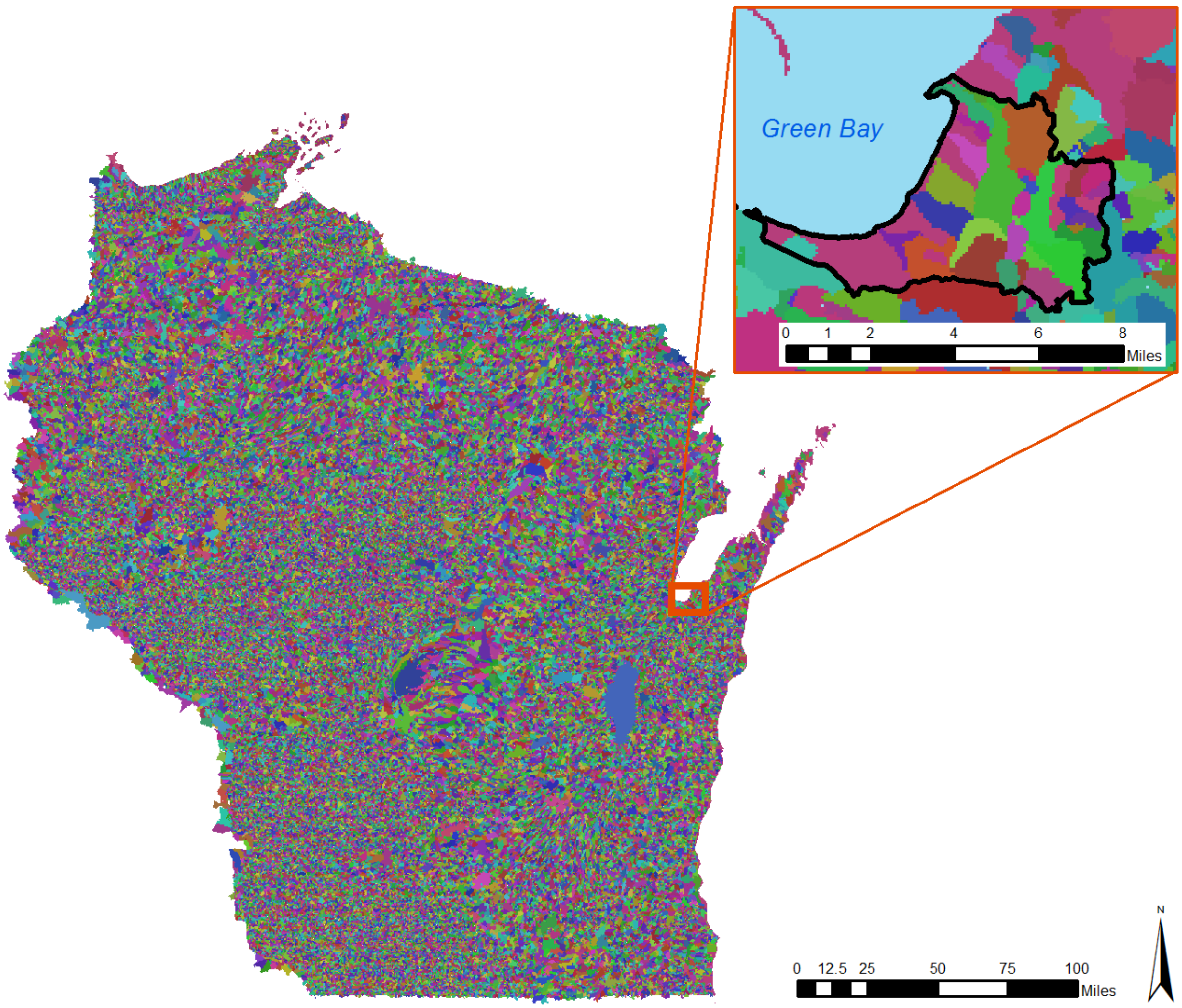

FIGURE 4. CATCHMENTS OF THE WDNR 24K HYDRO GEODATABASE. A VIEW OF CATCHMENTS IN RELATION TO A SINGLE HUC12 (POINT DU SABLE-FRONTAL GREEN BAY; HUC 040302040401) IS SHOWN IN THE INSERT.

Watershed health and vulnerability metrics are quantified for each WHD catchment in the state. Calculation of most metrics involved summarizing existing geospatial datasets to catchment-specific values. Other metrics were quantified from modeled relationships between stream condition and several landscape variables. These landscape variables describe channel, riparian, and watershed-wide characteristics (e.g., riparian forest cover) at both the incremental scale (within catchment boundaries) and cumulative scale (within all upstream catchments) (Figure 5). Cumulative values were included due to the potential for upstream conditions to influence the health of a given stream reach. The WHD supports aggregation of incremental-to-cumulative data by storing a unique numeric identifier for each catchment as well as upstream/downstream catchment IDs.

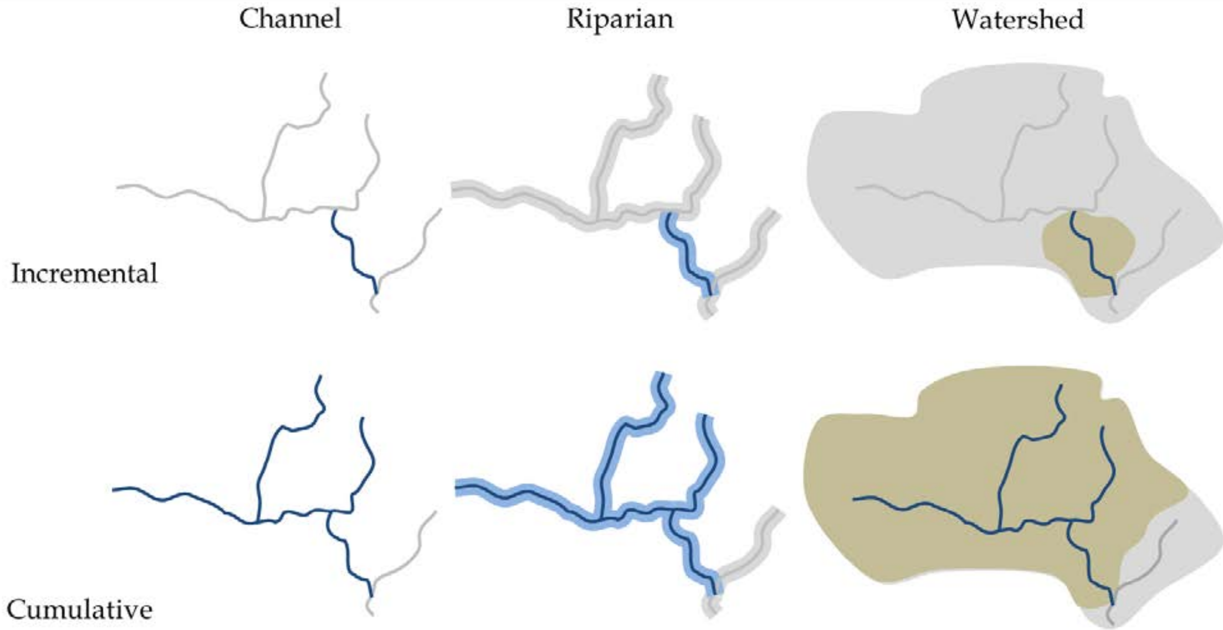

FIGURE 5. DIFFERENCE BETWEEN INCREMENTAL AND CUMULATIVE SCALES FOR QUANTIFYING LANDSCAPE VARIABLES. VARIABLES QUANTIFIED AT THE INCREMENTAL SCALE SUMMARIZE CONDITIONS WITHIN CATCHMENT BOUNDARIES ONLY. VARIABLES QUANTIFIED AT THE CUMULATIVE SCALE ALSO SUMMARIZE CONDITIONS THROUGHOUT ALL UPSTREAM CATCHMENTS.

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 WHD 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.

2.4 Landscape Condition Metrics and Data Sources

Landscape condition is described by the extent and connectivity of natural land cover throughout a watershed and within key functional zones such as floodplains, riparian areas, and wetlands. Landscape condition, as used here, is analogous to the landscape condition attribute of watershed health depicted in Figure 3 and discussed in EPA's *Identifying and Protecting Healthy Watersheds Concepts, Assessments, and Management Approaches* (US EPA, 2012).

The assessment team selected four landscape condition metrics (Figure 6) after considering several potential landscape metrics that are relevant to aquatic ecosystem health in Wisconsin, the availability and quality of data for quantifying metrics, and the objectives of the Assessment. Together, landscape condition metrics describe whether a watershed contains the natural infrastructure necessary to support healthy aquatic ecosystems.

The remainder of this section describes the landscape condition metrics, the reasoning for their selection, the data sources, and the calculation of metric values.

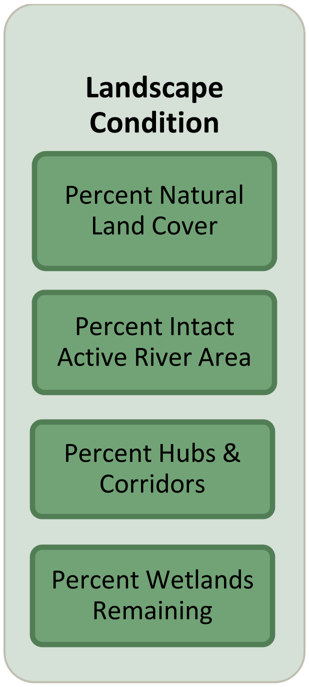

FIGURE 6. LANDSCAPE CONDITION METRICS.

Percent Natural Land Cover

Aquatic ecosystems are connected in the landscape through surface and subsurface drainage. Natural land cover throughout a watershed maintains important natural hydrologic processes such as infiltration, evapotranspiration, and groundwater recharge, and protects aquatic ecosystems from nonpoint sources of pollution, including urban and agricultural runoff. Further, natural land cover in and around the riparian zone, floodplains, and wetlands serves as habitat for aquatic species and supports connectivity between habitat patches. Many aquatic organisms depend on the connections provided by natural corridors to migrate to and among suitable habitats as conditions vary over the short-term and seasonally.

The significance of natural land cover on watershed health is captured in the Assessment with the *Percent Natural Land Cover* metric. Percent natural land cover is calculated from the 2006 National Land Cover Dataset (NLCD) (Fry, et al., 2011) as the area of natural NLCD cover types in a catchment divided by catchment area, multiplied by 100. A list of natural and non-natural NLCD cover types is provided in Table 1.

TABLE 1. CLASSIFICATION OF NATURAL AND NON-NATURAL NLCD COVER TYPES.

Class	NLCD Cover Type & Code[a]
Natural	Open Water (11); Deciduous Forest (41); Evergreen Forest (42); Mixed Forest (43); Shrub/Scrub (52); Grassland/Herbaceous (71); Woody Wetlands (90); Emergent Herbaceous Wetlands (95)
Non-Natural	Developed, Open Space (21); Developed, Low Intensity (22); Developed, Medium Intensity (23); Developed, High Intensity (24); Barren (31)[b]; Pasture/Hay (81); Cultivated Crops (82)

[a] NLCD classification codes are shown in parentheses.

[b] *Barren* is considered a non-natural cover type because mined areas are classified as Barren in the NLCD dataset.

Percent Intact Active River Area

The Active River Area (ARA) has been proposed as a spatially explicit, holistic framework for stream conservation that focuses on portions of a watershed that are most influential to aquatic ecosystem conditions (The Nature Conservancy, 2008). Geographically, the ARA includes:

- Material Contribution Areas – areas that provide the majority of organic and inorganic material input to a stream;
- Meander Belt – the area within which a stream channel migrates over time;
- Floodplains – expansive, low-slope areas adjacent to a channel;
- Terraces – former floodplains created during large landscape forming events such as glacial retreat; and
- Riparian Wetlands – low gradient areas with hydric soils that support wetland dependent species.

The presence of natural land cover in the ARA supports natural flow, sediment, and water temperature regimes, and maintains natural levels of nutrient and organic matter input to streams. *Percent Intact ARA* is included as an metric of watershed condition and was quantified for each catchment by delineating Wisconsin's ARA[1], calculating the area of natural NLCD land cover types in a catchment's ARA, dividing by a catchment's total ARA, and multiplying by 100. See Table 1 for list of natural and non-natural NLCD cover types.

Percent Hubs & Corridors

The size and connectivity of intact vegetative patches are important to the health of a watershed's biological communities. Green infrastructure approaches to land conservation view landscapes as ecological networks

[1] See Appendix C for details of Active River Area delineation.

consisting of linked landscape elements that are broadly classified as hubs (large patches of intact natural areas) and corridors (relatively undisturbed areas that allow for migration between hubs). Green infrastructure provides habitat of sufficient size and connectivity to support both aquatic and aquatic dependent species.

EPA Region 4 has developed the National Ecological Framework (NEF), a geospatial model of the connectivity of natural lands using the hub/corridor approach. The NEF delineates hub locations throughout the nation based on the following:

- Location of Priority Ecological Areas (PEAs). PEAs include first order stream catchments, intact wetland and forest patches, roadless areas, strategic habitat conservation areas of the US Fish and Wildlife Service, protected lands in the USGS Protected Areas Database, and lands within the Nature Conservancy Ecoregional Portfolio Core Data Set;
- Extent of natural land cover in PEAs (based on 2001 NLCD land cover data); and
- Size of PEAs. A minimum hub size of 5,000 acres is used in the NEF.

Corridors are delineated in the NEF by identifying least-disturbed pathways between hubs, based on 2001 NLCD land cover data.

The *Percent Hubs and Corridors* metric is included in the Assessment to account for the role of hubs and corridors as biotic refugia and pathways for migration. It is calculated from NEF data acquired from EPA Region 4 (Gary Davis, personal communication) for each WHD catchment as the area of hubs and corridors within catchment boundaries, divided by catchment area, multiplied by 100.

Percent Wetlands Remaining

Wetlands contribute to the overall health of watersheds in many ways. In addition to providing habitat for wetland dependent biota, wetlands retain sediment and nutrients, have the capacity to store floodwaters, serve as groundwater recharge areas, maintain streamflow during dry periods, and stabilize lake shores and river banks. Despite their ecological and economic value, many of Wisconsin's wetlands have been drained or filled for development.

The *Percent Wetlands Remaining* metric characterizes the extent of existing wetland areas within a watershed relative to pre-settlement conditions. Existing wetlands acreage is taken from the Wisconsin Wetland Inventory (WWI) digital data and pre-settlement wetland acreage is estimated based on hydric soil areas that are not mapped as wetland on the WWI (Tom Bernthal, personal communication)[2]. In some counties of the state these data do not support calculation of pre-settlement wetland area at the scale of individual WHD catchments. These areas have been mapped as "no data". Where sufficient data exist, percent wetlands remaining is calculated for 12-digit Hydrologic Units (HUC12s) of the USGS/NRCS Watershed Boundary Dataset as the area of existing wetlands within HUC12 boundaries, divided by the area of pre-development wetlands, multiplied by 100. Each WHD catchment is assigned the percent wetlands remaining value that corresponds to the HUC12 to which it belongs.

[2] Wetland inventory data were not available for seven Wisconsin counties: Vilas, Forest, Florence, Dunn, Eau Claire, Jackson, and La Crosse. Percent wetlands remaining is not included as a landscape condition metric for WHD catchments in HUC12s that intersect these counties.

2.5 Aquatic Ecosystem Health Metrics and Data Sources

As used here, aquatic ecosystem health refers to several properties of streams, lakes, and wetlands that describe their structure and function. Because aquatic ecosystem health metrics focus on within-water body conditions, they are discussed separately from landscape condition metrics, which focus on the extent and connectivity of natural land cover throughout a watershed and in key functional zones.

Eleven aquatic ecosystem health metrics were selected by the assessment team (Figure 7) based on data availability, data quality, and the objectives of the Assessment. The selected metrics characterize the hydrology, habitat, geomorphology, water quality, and biological condition attributes of watershed health depicted in Figure 3 and described in EPA's *Identifying and Protecting Healthy Watersheds Concepts, Assessments, and Management Approaches* (US EPA, 2012). For the Assessment, they are grouped as metrics of Hydrologic Condition, Habitat Condition/Geomorphology, Water Quality, and Biological Condition. Note that the habitat and geomorphology attributes of watershed health in the EPA Healthy Watersheds framework are combined for this assessment because selected metrics are relevant to both attributes.

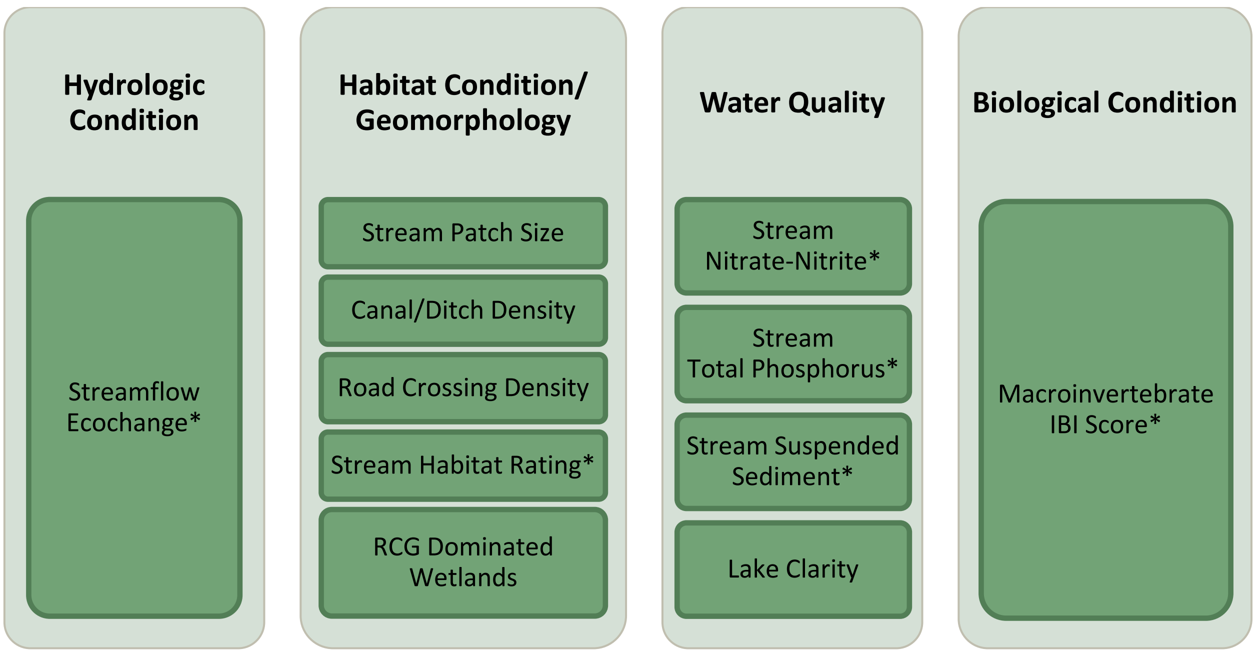

FIGURE 7. AQUATIC ECOSYSTEM HEALTH METRICS. METRICS MARKED WITH AN ASTERISK (*) ARE QUANTIFIED FROM PREDICTIVE STATISTICAL MODELS. THE REMAINING METRICS ARE QUANTIFIED FROM EXISTING GEOSPATIAL DATA.

Two approaches are used to quantify aquatic ecosystem health metrics for all catchments in Wisconsin. Some metrics are quantified by summarizing existing geospatial datasets to produce catchment-specific values. The remaining metrics are quantified from statistical models that relate aquatic ecosystem conditions to landscape characteristics. The underlying sources of data for these modeled metrics are field samples collected across Wisconsin through monitoring programs. A limitation of stream monitoring data for use in the Assessment is that samples are not available for all 157,103 catchments in Wisconsin. For this reason, metrics are not quantified directly from observed values, but rather from a group of statistical models that are developed and validated from field monitoring data.

The statistical models developed for the Assessment are regression models that predict representative values of five aquatic ecosystem health metrics for any WHD catchment using landscape variables as predictors.

Landscape variables describe channel, riparian, and watershed-wide land cover, soils, topography, etc., and are quantified at both the incremental and cumulative scales (see Figure 5). Landscape variables used for statistical modeling are listed in Table 2.

TABLE 2. LANDSCAPE VARIABLES INCLUDED IN PREDICTIVE STATISTICAL MODELS OF AQUATIC ECOSYSTEM HEALTH.

Landscape Variables
Stream Channel Characteristics
Channel Sinuosity; Dominant Surface Geology Class; Dominant Bedrock Geology Class; Dominant Bedrock Depth Class; Centroid Latitude; Centroid Longitude; Flowpath Distance to Large Lake (≥ 500 acres); Flowpath Distance to Medium Lake (50-500 acres); Flowpath Distance to Small Lake (5-50 acres); Downstream Flowpath Distance to Large River (≥1,000 km^2 watershed); Downstream Flowpath Distance to Medium River (100-1,000 km^2 watershed)
Riparian Area Characteristics
Mean Slope; Mean Soil Permeability; Mean Darcy Value; Dominant Surface Geology Class; Dominant Bedrock Geology Class; Dominant Bedrock Depth Class; Percent Natural Land Cover; Percent Agricultural Land Cover; Percent Urban Land Cover
Active River Area Characteristics
Percent Natural Land Cover; Percent Agricultural Land Cover; Percent Urban Land Cover
Watershed-Wide Characteristics
Mean Slope; Mean Soil Permeability; Mean Darcy Value; Dominant Surface Geology Class; Dominant Bedrock Geology Class; Dominant Bedrock Depth Class; Percent Natural Land Cover; Percent Agricultural Land Cover; Percent Urban Land Cover; Percent Wetlands Remaining; Annual Surface Water Withdrawals; Annual Groundwater Withdrawals; Daily Surface Water Well Capacity; Daily Groundwater Well Capacity; Watershed Area

The models developed to predict aquatic ecosystem health metric values are *Boosted Regression Tree* (BRT) models. BRTs are a relatively recent approach to modeling ecological relationships that combine two methods: 1) regression tree modeling; and 2) boosting (see Appendix B for details). BRTs are well-suited for modeling complex ecological relationships (Elith, Leathwick, & Hastie, 2008). Example applications of BRTs for guiding management decisions include the prediction of water chemistry and stream condition scores in West Virginia watersheds (Merovich, Petty, Strager, & Fulton, 2013) and prediction of fish community condition scores and species presence throughout the Midwestern US (Clingerman, et al., 2012).

BRTs were selected for use in the Assessment because they have several advantages over other statistical methods (e.g., multiple linear regression or generalized linear modeling). Specifically, BRTs:

- Can be used to predict several data types (e.g., numeric, categorical, or binary) and can include any combination of data types as predictors;
- Are insensitive to outliers in response and predictor datasets and do not require a pre-processing step to evaluate data distributions and remove outliers;
- Capture interactions between individual predictors in the regression tree structure and do not require the use of "interaction terms" as possible predictor variables (e.g., the product of two predictors that together have an interaction effect);
- Have no assumption of a linear relationship between predictor and response variables and account for nonlinear relationships; and
- Address overfitting without subjective determinations of "significant" predictors.

Refer to Appendix B for details of metric modeling methods and results. The remainder of this section describes aquatic ecosystem health metrics, the reasoning for their selection, data sources, and methods for quantifying metric values.

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. Aquatic organisms have adapted to the range of physical and chemical conditions brought about by natural flow patterns. Alteration of natural flows (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.

The maintenance of the natural flow regime within a catchment is evaluated with the *Streamflow Ecochange* metric. Streamflow ecochange is a measure of the absolute difference between the present-day and pre-development flow duration curve (Figure 8) and is conceptually similar to the "total seasonal ecochange" metric discussed in Gao et al. (2009).

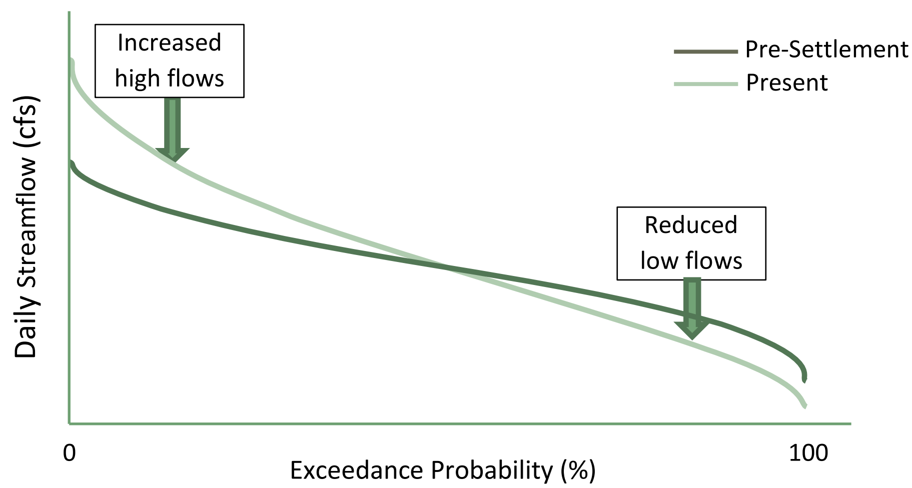

FIGURE 8. EXAMPLE FLOW DURATION CURVES SHOWING POTENTIAL DIFFERENCES BETWEEN THE PRE-SETTLEMENT AND PRESENT-DAY FLOW REGIME FOR A STREAM SEGMENT. STREAMFLOW ECOCHANGE IS A MEASURE OF THE ABSOLUTE DIFFERENCE BETWEEN EACH CURVE.

Streamflow ecochange is quantified from estimated values of present-day and pre-development annual flow duration statistics (5, 10, 25, 50, 75, 90, and 95% exceedance flows) for every catchment in Wisconsin. Flow duration estimates for WHD catchments were acquired for the Assessment from WDNR (Matt Diebel, personal communication). These estimates were generated by WDNR using mixed effects regression models that relate annual flow duration statistics to several climate and landscape variables, including precipitation, soil permeability, wetland area, and area of agricultural cover[3]. Pre-settlement flow statistics were estimated by adjusting several of these variables to simulate land cover conditions before European settlement. The following steps were applied to calculate streamflow ecochange from flow duration estimates:

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[3] Streamflow regression models were developed by WDNR as part of a separate effort described in Diebel et al. (2013). Note that these models differ from the BRT models developed for other aquatic ecosystem health metrics.

1. For each flow duration statistic (e.g., 5% exceedance flow), the absolute value of the percent difference between the present-day flow and pre-settlement flow was calculated as:

$$\left|\frac{Q_{Present} - Q_{Pre-Development}}{Q_{Pre-Development}} * 100\right|$$

2. Streamflow ecochange was calculated as the mean of absolute percent differences for the seven flow duration statistics resulting from step 1.

Habitat Condition/Geomorphology Metrics

The term habitat encompasses a host of physical, chemical, and biological characteristics of aquatic ecosystems and the optimal set of conditions for aquatic life will vary from one species to another. Here, habitat condition is assessed from multi-scale stream and wetland habitat characteristics. Several of these directly or indirectly reflect aspects of fluvial geomorphology, such as channel shape or bed substrate. Selected metrics are therefore grouped as habitat condition *and* geomorphology metrics.

Five metrics are used to describe habitat condition and geomorphology. Metric data sources and calculation methods are summarized below.

Stream Patch Size – Longitudinal connectivity refers to the upstream/downstream connectivity of stream habitats. In natural systems, aquatic species can migrate freely throughout a stream network in search of optimal habitat, with connectivity disrupted by natural dams, waterfalls, or segments with intermittent flow. Man-made dams increase fragmentation of stream networks, resulting in limited migration opportunities for fish and other biota.

Longitudinal connectivity is evaluated in the Assessment with the *Stream Patch Size* metric. It is quantified as the length of stream miles connected to any given segment on the stream network (Figure 9). Values of stream patch size used in the Assessment are those calculated for every catchment in Wisconsin by WDNR (Matt Diebel, personal communication). These values account for the location of man-made dams and consider the length of connected streams along the main stem of the stream network and along any tributary streams. For catchments that do not contain a dam within their boundaries, patch size is quantified as the total stream length between the nearest dam or stream network terminus in both the upstream and downstream directions. For catchments that do contain a dam, two possible stream patch sizes can be quantified: patch size above the dam and patch size below the dam. For these catchments, the minimum of the two patch sizes is used.

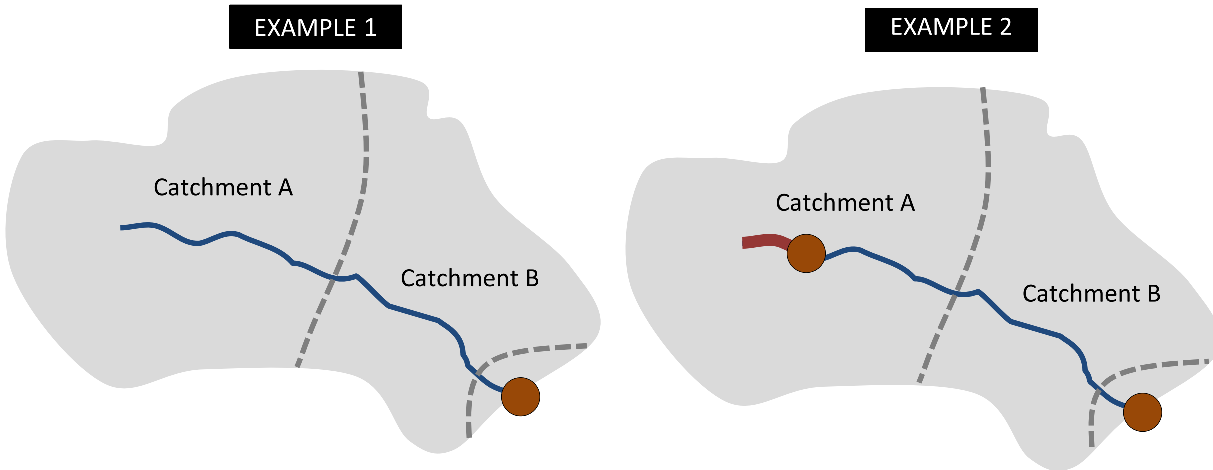

FIGURE 9. ILLUSTRATION OF THE STREAM PATCH SIZE METRIC. IN THE EXAMPLE ON THE LEFT, NO LONGITUDINAL BARRIERS ARE PRESENT IN CATCHMENTS A OR B, AND PATCH SIZE IS EQUAL TO TOTAL BLUE SEGMENT LENGTH FOR BOTH CATCHMENTS. IN THE EXAMPLE ON THE RIGHT, A BARRIER IS PRESENT IN CATCHMENT A, AND PATCH SIZE IS EQUAL TO RED SEGMENT LENGTH FOR CATCHMENT A AND BLUE SEGMENT LENGTH FOR CATCHMENT B.

Road Crossing Density – Like dams, road-stream crossings contribute to highly fragmented stream networks. While culverts generally maintain the flow of water, they are typically not designed to maintain connectivity for aquatic species. To further characterize longitudinal connectivity, *Road Crossing Density* is included as a metric of aquatic ecosystem health. Road crossing density is quantified at the 12-digit Hydrologic Unit (HUC12) scale as the number of road-stream crossings within HUC12 boundaries divided by HUC12 area. Catchments are assigned the road crossing density value that corresponds to the HUC12 to which they belong.

Canal/Ditch Density – The construction of artificial canals/ditches and channelization of naturally sinuous streams can contribute to degraded stream habitat through alteration of flow magnitude, velocity, and sediment dynamics. *Canal/Ditch Density* is therefore included as a metric of aquatic ecosystem health and is quantified from information on the location of canals, ditches, and channelized streams stored in the WHD. Canal/ditch density is calculated for each WHD catchment as the length of WHD flowlines classified as canals or ditches in catchment boundaries, divided by total flowline length, multiplied by 100.

Stream Habitat Rating – WDNR monitors several habitat and geomorphic variables in streams throughout the state as part of reach-scale habitat assessments. Monitored variables include the extent of pools, riffles, and bends, channel dimensions, amount of fish cover, riparian buffer width, severity of bank erosion, and substrate properties. These variables are combined into an overall stream habitat score and rating (Excellent, Good, Fair, or Poor).

Stream Habitat Rating is included as an integrated metric of stream habitat condition and geomorphology. Stream habitat data compiled for the Assessment were acquired from the WDNR Surface Water Integrated Monitoring System (SWIMS) and were processed to produce a single representative habitat rating for each monitored catchment.

Stream habitat ratings were available for 3,445 WHD catchments throughout Wisconsin. Observed ratings were used to develop a BRT regression model to predict a representative stream habitat rating for every catchment in the state. Landscape variables listed in Table 2 were included as potential predictors of stream habitat rating. Refer to Appendix B for details of habitat monitoring data, modeling methods, and model results.

Reed Canary Grass Dominated Wetlands – Reed canary grass (RCG) is an aggressive invasive species whose presence in wetlands signals declining ecosystem health. Once established, it forms dense monotypic stands that have reduced value as wildlife habitat relative to native plant communities. The absence of RCG establishment in wetlands is considered to be a trait of healthy watersheds and is accounted for in the Assessment with the *RCG Dominated Wetlands* metric.

RCG dominated wetlands is quantified from geospatial data generated by a past WDNR effort to map RCG prevalence throughout the state using satellite imagery (WDNR, 2008). A grid depicting the location of wetlands dominated by RCG and wetlands dominated by other species was acquired from WDNR (Tom Bernthal, personal communication) and was used to calculate the area of RCG dominated wetlands in each WHD catchment relative to total wetland area. Calculated percentages of RCG dominated wetlands were converted to ratings using the following thresholds:

- Low = 0-7% RCG Dominated Wetlands
- Medium = 8-28% RCG Dominated Wetlands
- High = 29-100% RCG Dominated Wetlands

Thresholds were selected according to the distribution of catchment values. Note that this metric is not quantified for catchments that do not contain any wetland area.

Water Quality Metrics

Under natural conditions, stream and lake water chemistry varies within a characteristic range. For example, reference concentrations of total phosphorus have been reported to average 30-40 µg/L in Wisconsin's nonwadeable streams (Robertson, et al., 2006). Aquatic biota have adapted to such conditions, and the presence of water quality parameters in their natural range is a key feature of healthy streams.

Stream and lake water quality is monitored by several agencies and organizations in Wisconsin, with dozens of parameters sampled. For this Assessment, the focus is on parameters that represent natural water quality characteristics. Based on this objective and data availability, *Stream Total Phosphorus*, *Stream Nitrate-Nitrite*, *Stream Suspended Sediment*, and *Lake Water Clarity* are included as water quality metrics.

A statewide water quality database was compiled for stream nitrate-nitrite and suspended sediment concentrations from data stored in WDNR SWIMS, for stream total phosphorus concentrations from data reported in Robertson et al. (2006), and for lake water clarity from WDNR's statewide lake clarity map (Jennifer Filbert, personal communication).

Water quality data were processed to generate representative values of each parameter for monitored catchments. Processing steps for nitrate-nitrite, total phosphorus, and suspended sediment concentrations are described in Appendix B. For lake water clarity, WDNR'S gridded lake clarity dataset was used to calculate mean lake clarity in each WHD catchment.

Table 3 lists the number of catchments with observed values of each water quality parameter. Note that lake water clarity data are derived from satellite imagery and provide a comprehensive estimate of water clarity in lakes greater than 5 acres in area throughout the state. Because observations of stream parameters are relatively limited, BRT models were developed to predict median total phosphorus, nitrate-nitrite, and suspended sediment concentrations for every catchment in the state. Landscape variables listed in Table 2 were included as potential predictors of stream water quality. Refer to Appendix B for details of monitoring data, modeling methods, and model results.

TABLE 3. NUMBER OF WHD CATCHMENTS WITH WATER QUALITY MONITORING DATA.

Water Quality Metric	No. of Catchments
Stream Nitrate-Nitrite Concentration (Annual Median)	2,022
Stream Total Phosphorus Concentration (Annual Median)	239
Stream Suspended Sediment Concentration (Annual Median)	332
Lake Water Clarity	12,322

Biological Condition Metrics

A stream's biological condition can be described by the abundance, diversity, and functional organization of fish, invertebrates, and other aquatic fauna. A healthy biotic community demonstrates a natural balance of native species that are integrated across trophic and functional levels and are able to adapt to short- and long-term variation in ecosystem conditions. Healthy watersheds support biotic communities with these characteristics due to hydrologic, geomorphic, and water quality regimes that provide habitat of sufficient size, variety, and connectivity.

The biological characteristics of aquatic ecosystems considered in this assessment are macroinvertebrate community variables monitored in wadeable streams by WDNR. WDNR samples the number and proportion of several taxonomic and functional macroinvertebrate groups in streams throughout the state. For each monitored site, macroinvertebrate variables are combined into an overall *Macroinvertebrate Index of Biotic Integrity (MIBI) Score* that is used as the metric of stream biological condition for the Assessment.

Observed MIBI scores were acquired from WDNR SWIMS and processed to produce a single representative score for each monitored catchment. Observed MIBI scores were available for 3,483 catchments and were used to develop a BRT model to predict a representative MIBI score for every WHD catchment in the state. Landscape variables listed in Table 2 were included as potential predictors of MIBI scores. Refer to Appendix B for details of monitoring data, modeling methods, and modeling results.

WDNR also monitors several fish community variables in wadeable streams throughout the state and combines fish variables into an overall Fish Index of Biotic Integrity (FIBI) score. FIBI was included as a preliminary indicator of biological condition but was omitted from the Assessment due to concerns over the accuracy of modeled FIBI data. Further discussion of FIBI data and model results is provided in Appendix B.

2.6 Aquatic Invasive Species Metrics and Data Sources

Wisconsin's native aquatic species have adapted to the range of natural environmental conditions throughout the state to create a complex web of primary producers, herbivores, predators, and detritivores. The introduction and establishment of invasive aquatic species can alter the physical habitat and water chemistry properties of a water body, disrupt food webs, and degrade native fisheries.

The assessment team selected aquatic invasive species metrics (Figure 10) to characterize the potential for altered aquatic communities due to the establishment of non-native species with aggressive growth habits and other traits that drive a shift from natural ecosystem conditions. Selected metrics describe the presence of four key invasive species in lakes: *Eurasian Watermilfoil, Curly Leaf Pondweed, Spiny Waterflea, and Zebra Mussel.*

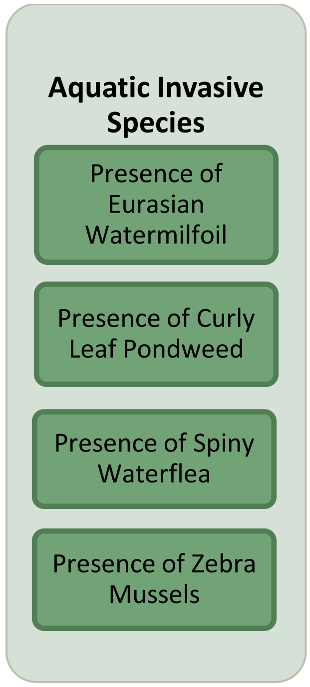

FIGURE 10. AQUATIC INVASIVE SPECIES METRICS.

Species presence/absence records for each of the four aquatic invasive metrics were acquired from WDNR (Jennifer Filbert, personal communication). These data denote whether each species is presently established in nearly 1,300 lakes throughout the state. For each species, data were summarized by WHD catchment, with catchments assigned a value of 1 if the species was reported to be present and a value of 0 is the species was reported to be absent.

Note that while records were available for nearly 1,300 lakes, invasive species presence/absence is undetermined for over 80% of Wisconsin lakes greater than 5 acres. Because a complete, statewide invasive species dataset was not available, and because invasive species presence/absence data are not appropriate for landscape predictive modeling, invasive species metrics are grouped separately from aquatic ecosystem health metrics despite their relevance to the biological condition attribute of EPA's Healthy Watersheds framework.

2.7 Watershed Vulnerability Metrics and Data Sources

Watershed vulnerability is defined as the potential for future degradation of watershed processes and aquatic ecosystem health. Vulnerability can be driven by a variety of factors. Here, three vulnerability attributes are considered: Climate Change Vulnerability; Land Use Vulnerability; and Water Use Vulnerability.

The assessment team selected watershed vulnerability metrics (Figure 11) based on the data availability, data quality, and the objectives of the Assessment. This section describes the watershed vulnerability metrics, the reasoning for their selection, data sources, and methods applied to calculate metric values.

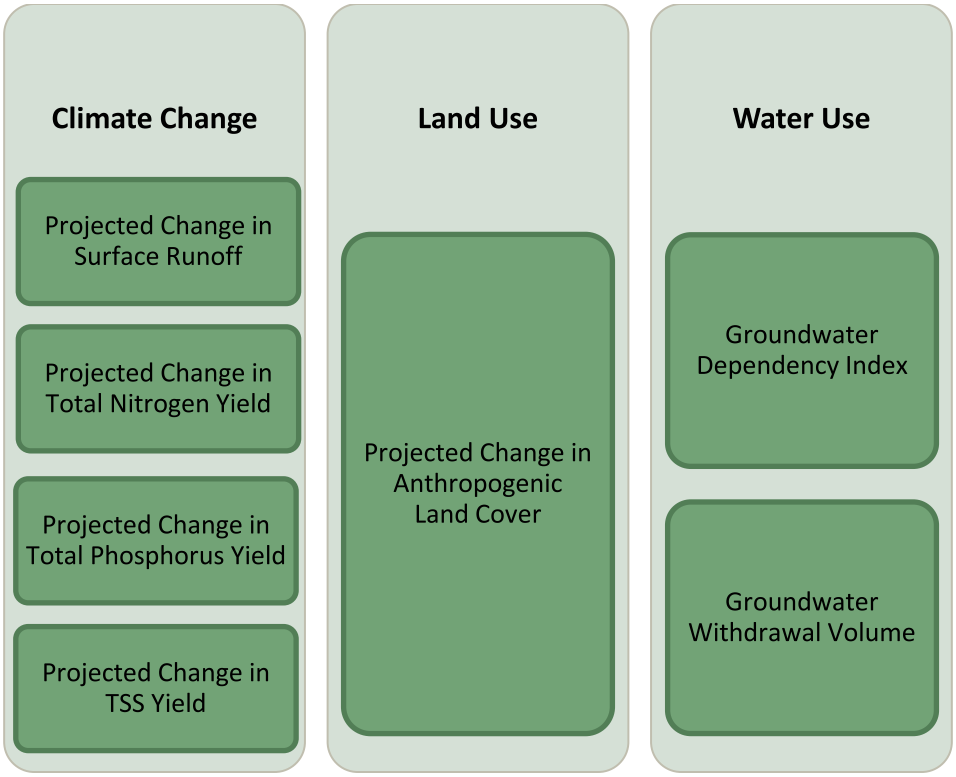

FIGURE 11. WATERSHED VULNERABILITY METRICS.

Climate Change Vulnerability Metrics

Changes in climate translate to a shift in material and energy inputs to aquatic ecosystems. The impact of climate-driven changes to aquatic ecosystem health can be significant and in line with those posed by large-scale landscape disturbance by humans.

With the availability of downscaled global climate model data, projected changes in temperature and precipitation can be evaluated for watersheds across a large region or state. These projections, however, do not explicitly portray impacts to watershed processes or aquatic ecosystem health. With this goal in mind, WDNR recently modeled hydrologic response to projected climate change in Wisconsin using the Long-Term Hydrologic Impact Assessment (L-THIA) model (Mednick, Nelson, & Watermolen, 2012). This assessment incorporates projections of future hydrology based on "middle-of-the-road" climate change projections to characterize the vulnerability of Wisconsin's watersheds to climate change. Four climate change vulnerability metrics are used:

- *Projected Change in Surface Runoff (2010 – 2050)*
- *Projected Change in Total Nitrogen (TN) Yield (2010 – 2050)*
- *Projected Change in Total Phosphorus (TP) Yield (2010 – 2050)*
- *Projected Change in Total Suspended Solids (TSS) Yield (2010 – 2050)*

Climate change metrics are quantified from runoff and pollutant load projections acquired from WDNR (Theresa Nelson, personal communication). Gridded projections were obtained for the years 2010 and 2050 for mean growing season (May-September) surface runoff, TN load, TP load, and TSS load.

Runoff grids were averaged by 10-digit hydrologic units (HUC10s) of the USGS/NRCS Watershed Boundary Dataset, and each HUC10's projected change in surface runoff was calculated as the absolute value of the difference between 2050 and 2010 values. WHD catchments were assigned the projected runoff change value of their corresponding HUC10.

A similar approach was used for calculating projected changes in TN, TP, and TSS yields. Grids for each pollutant were summed by HUC10, and total loads were divided by HUC10 area to determine yields. Projected changes in pollutant yields were calculated as the difference between 2050 and 2010 values[4], and WHD catchments were assigned the projected change in TN, TP, and TSS yield of their corresponding HUC10.

Land Use Vulnerability Metrics

As described in Section 2.4, natural land cover maintains hydrologic processes within a watershed, protects aquatic ecosystems from nonpoint sources of pollution, provides habitat for aquatic biota, and supports connectivity between habitat patches. Future changes in land cover will occur with the expansion of urban and agricultural lands. *Projected Change in Anthropogenic Land Cover* is therefore included as a metric of watershed vulnerability.

Future land cover projections from the Land Transformation Model (Pijanowski, 2006) served as the source of data for the projected land cover change metric. Gridded land cover projections for the years 2010 and 2030 were acquired from the Illinois, Wisconsin, Michigan (ILWIMI) Land Transformation Model Data Portal (http://ltm.agriculture.purdue.edu/ilwimi/). Grids display the projected cover type (urban, agriculture, forest, wetland, barren, or open water) for each grid cell based on land cover data from the 1990s and simulations of urban growth and afforestation (agricultural expansion was not simulated). Grids were used to calculate the percent area of anthropogenic land cover (urban, agricultural, and barren) in 2010 and 2030 in each WHD catchment. *Projected Change in Anthropogenic Land Cover* was calculated as the difference between 2030 and 2010 anthropogenic cover percentages[5].

Water Use Vulnerability Metrics

Surface and groundwater withdrawals can greatly alter a watershed's natural hydrologic regime, and thus, the health of aquatic ecosystems. Future water demand will increase beyond current levels with population growth and expansion of agriculture, industry, and mining. Projections of future water use are not presently available for Wisconsin at a scale that is compatible with the Assessment. For this reason, current *Groundwater Withdrawal Volume* is used as a metric of water use vulnerability under the assumption that future patterns of water use will follow patterns of the present day.

Because groundwater depletions have a greater impact on ecosystems that have formed around points of groundwater discharge, *Groundwater Dependency Index* is also included as a vulnerability metric. The

[4] The *absolute value* of catchment runoff change (without regard to sign) is calculated while a simple difference is used to express changes in pollutant yields. This is because of the potential for increased or decreased runoff to negatively impact aquatic ecosystems. Conversely, only an increase in pollutant yield is assumed to negatively impact aquatic ecosystems.

[5] Land cover projections for some catchments pointed to a loss of anthropogenic cover due to future afforestation. For these catchments, projected land cover change was set to zero for rank-normalization and index calculations (described in Sections 2.8 and 2.9).

Groundwater Dependency Index is a measure of the prevalence of groundwater dependent ecosystems within a watershed relative to other watersheds in the state.

Annual groundwater withdrawal volume was quantified for each WHD catchment using geospatial data acquired from the WDNR Water Use Registration Program (Robert Smail, personal communication). This data set includes estimated 2011 withdrawal volume and location for withdrawals having a permitted daily capacity greater than 100,000 gallons. Catchment values were calculated as the sum of estimated annual withdrawal volumes for all permits within catchment boundaries.

Groundwater Dependency Index scores were quantified for WHD catchments using methods developed by The Nature Conservancy for mapping groundwater dependent ecosystems in California (Howard & Merrifield, 2010). The following steps were applied to calculate Groundwater Dependency Index scores:

1. Calculate the density of springs in each catchment (number of springs per unit area) using geospatial data on spring locations acquired from the Wisconsin Geological and Natural History Survey (Macholl, 2007). Spring density was then weighted by reported flow volume. Flow-weighted spring densities were then normalized to a 0 to 1 scale.
2. Calculate average wetland water table depth in each catchment using geospatial data on water table depth from the USDA Soil Survey Geographic Database (SSURGO) and wetland locations from the Wisconsin Wetlands Inventory. Average wetland water table depths were then normalized to a 0 to 1 scale.
3. Estimate groundwater discharge in each catchment using mean Darcy flow values reported in the WHD. Darcy flow is the velocity of water flow through a saturated porous media, as expressed by Darcy's Law (see Baker et al. (2003) for further details). Mean Darcy flow values reported in the WHD were normalized to a 0 to 1 scale.
4. Calculate the percent area of seepage lakes and springs for each catchment using water body locations and types reported in the WHD. Percentages of seepage lakes/springs were then normalize to a 0 to 1 scale.
5. Calculate the Groundwater Dependency Index for each catchment as the average of normalized flow-weighted spring density, wetland water table depth, mean Darcy flow, and the percent area of seepage lakes/springs.

2.8 Metric Rank-Normalization

Watershed health and vulnerability metrics are *rank-normalized* for reporting and for index calculations (discussed in Section 2.9). Normalization provides a dataset that is both unitless and on a shared scale, typically 0 to 100. Normalizing by rank (rank-normalization) provides a dataset with uniform scale *and* uniform distribution (Figure 12). The benefits of standardizing metric distributions are discussed further in Section 2.9.

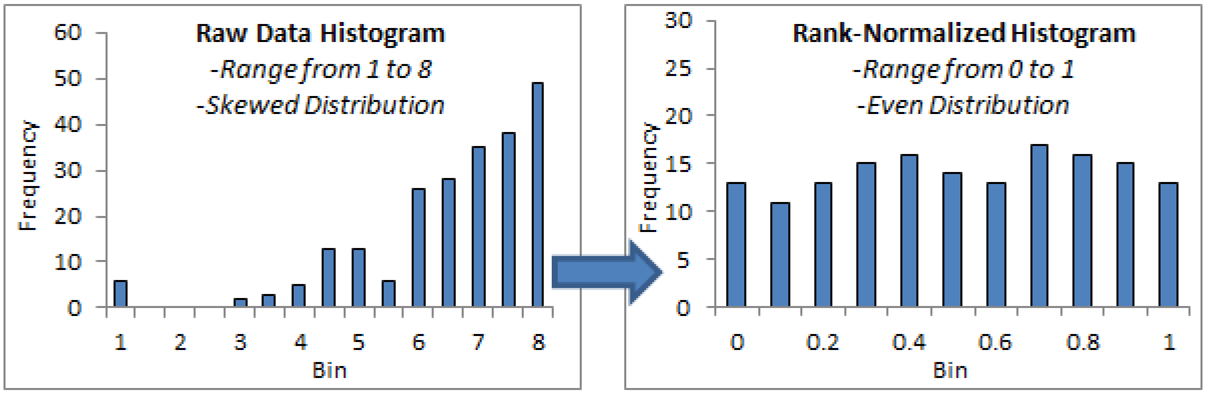

FIGURE 12. EXAMPLE HISTOGRAMS FOR RAW (LEFT) AND RANK-NORMALIZED (RIGHT) DATA. NOTE THAT RANK-NORMALIZATION STANDARDIZES BOTH THE SCALE AND DISTRIBUTION OF COMPONENT METRIC DATA.

Here, rank normalization is performed by:

1. Ranking catchments on the basis of raw metric values.
    - Catchments are ranked in ascending order if higher metric values correspond to higher watershed health or vulnerability.
    - Catchments are ranked in descending order if higher metric values correspond to lower watershed health or vulnerability.
2. Applying the following formula to calculate a catchment's rank normalized score:

$$Rank\ Normalized\ Score = \frac{Catchment\ Rank - 1}{Maximum\ Rank - 1} * 100$$

Rank-normalization provides metric scores ranging from 0 to 100 with consistent *directionality*. Directionality refers to the relationship between metric scores and watershed health or vulnerability (i.e., whether high scores correspond to higher or lower watershed health). Table 4 lists the original directionality of watershed health and vulnerability metrics. Rank-normalized scores are directionally aligned so that:

- Higher scores for landscape condition metrics correspond to higher landscape condition;
- Higher scores for aquatic ecosystem health metrics correspond to higher aquatic ecosystem health;
- Higher scores for watershed vulnerability metrics correspond to higher watershed vulnerability.

The above steps were applied to all landscape condition metrics, aquatic ecosystem health metrics, and watershed vulnerability metrics. Rank-normalization was not required for aquatic invasive species metrics since only two values were possible (1 for species presence, 0 for species absence). For consistency, these metrics were "normalized" to a 0 to 100 scale by multiplying by 100.

TABLE 4. ORIGINAL DIRECTIONALITY OF WATERSHED HEALTH AND VULNERABILITY METRICS. RANK-NORMALIZED METRIC SCORES RANGE FROM 0 TO 100 AND ARE DIRECTIONALLY ALIGNED SO THAT HIGHER SCORES CORRESPOND TO HIGHER LANDSCAPE CONDITION, AQUATIC ECOSYSTEM HEALTH, AQUATIC INVASIVE SPECIES PREVALENCE, OR WATERSHED VULNERABILITY.

Metric Category	Metric Name	Original Directionality
Landscape Condition	Percent Natural Land Cover Percent Intact Active River Area Percent Wetlands Remaining Percent Hubs & Corridors	Higher Value = Higher Landscape Condition
Aquatic Ecosystem Health	Stream Patch Size Stream Habitat Rating Lake Clarity Macroinvertebrate IBI Score	Higher Value = Higher Aquatic Ecosystem Health
	Streamflow Ecochange Canal/Ditch Density Road Crossing Density Reed Canary Grass Dominated Wetlands Stream Nitrate-Nitrite Concentration Stream Total Phosphorus Concentration Stream Suspended Sediment Concentration	Higher Value = Lower Aquatic Ecosystem Health
Aquatic Invasive Species	Presence of Eurasian Watermilfoil Presence of Curly Leaf Pondweed Presence of Spiny Waterflea Presence of Zebra Mussel	0 = Absence 1 = Presence
Watershed Vulnerability	Projected Absolute Change in Surface Runoff Projected Change in Total Nitrogen Yield Projected Change in Total Phosphorus Yield Projected Change in Total Suspended Solids Yield Projected Change in Anthropogenic Land Cover Groundwater Dependency Index Groundwater Withdrawal Volume	Higher Value = Higher Watershed Vulnerability

2.9 Index Development

Twenty-six metrics are used to characterize the relative health and vulnerability of Wisconsin's watersheds. To integrate this information for reporting and application, metrics are aggregated into several *multimetric indices* describing landscape condition, aquatic ecosystem health, aquatic invasive species prevalence, and watershed vulnerability. A multimetric index synthesizes information from several *component metrics* into a single composite value. For example, the Assessment includes a *Landscape Condition Index* that combines the four metrics selected to characterize landscape condition in order to provide an integrated view of the condition of a watershed's natural infrastructure.

Two "levels" of multimetric indices are distinguished for aquatic ecosystem health and for watershed vulnerability. Metrics are first combined into a set of *sub-indices* based on groupings depicted in Figure 7 and Figure 11. Sub-indices describe each aquatic ecosystem health attribute (hydrologic condition, water quality, etc.) and each watershed vulnerability attribute (climate change, land use change, and water use change). Sub-indices are then combined into an overall *Aquatic Ecosystem Health Index* and an overall *Watershed Vulnerability Index*.

The purpose of the sub-index/index hierarchy is to balance the influence of each aquatic ecosystem health attribute on Aquatic Ecosystem Health Index scores (or, for the Watershed Vulnerability Index, to balance the influence of each watershed vulnerability attribute). Without this step, index scores can be biased toward attributes that have the highest number of metrics. For example, the Assessment uses four metrics to characterize water quality in aquatic ecosystems, while a single metric is used to characterize biological condition. Without an intermediate step to calculate a *Water Quality Sub-Index* and a *Biological Condition Sub-Index,* Aquatic Ecosystem Health Index scores would be more reflective of water quality than biological condition.

The multimetric indices generated for the Assessment include:

- Landscape Condition Index
- Aquatic Ecosystem Health Index
    - Hydrologic Condition Sub-Index
    - Habitat Condition/Geomorphology Sub-Index
    - Water Quality Sub-Index
    - Biological Condition Sub-Index
- Aquatic Invasive Species Index
- Watershed Vulnerability Index
    - Climate Change Vulnerability Sub-Index
    - Land Use Vulnerability Sub-Index
    - Water Use Vulnerability Sub-Index

A list of component metrics for each index/sub-index is provided in Table 5.

TABLE 5. LIST OF COMPONENT METRICS FOR EACH MULTIMETRIC INDEX OF LANDSCAPE CONDITION, AQUATIC ECOSYSTEM HEALTH, AQUATIC INVASIVE SPECIES, AND WATERSHED VULNERABILITY.

Index	Sub-Index	Component Metrics
Landscape Condition	*None*	Percent Natural Land Cover Percent Intact ARA Percent Wetlands Remaining Percent Hubs & Corridors
Aquatic Ecosystem Health	Hydrologic Condition Sub-Index	Streamflow Ecochange
	Habitat Condition/ Geomorphology Sub-Index	Stream Patch Size Canal/Ditch Density Road Crossing Density Stream Habitat Rating Reed Canary Grass Dominated Wetlands
	Water Quality Sub-Index	Stream Nitrate-Nitrite Concentration Stream Total Phosphorus Concentration Stream Suspended Sediment Concentration Lake Clarity
	Biological Condition Sub-Index	Macroinvertebrate IBI Score
Aquatic Invasive Species	*None*	Presence of Eurasian Watermilfoil Presence of Curly Leaf Pondweed Presence of Spiny Waterflea Presence of Zebra Mussel
Watershed Vulnerability	Climate Change Vulnerability Sub-Index	Projected Change in Surface Runoff Projected Change in Total Nitrogen Yield Projected Change in Total Phosphorus Yield Projected Change in Total Suspended Solids Yield
	Land Use Vulnerability Sub-Index	Projected Change in Anthropogenic Land Cover
	Water Use Vulnerability Sub-Index	Groundwater Dependency Index Groundwater Withdrawal Volume

Index/sub-index scores range from 0 to 100 and are calculated as the average of rank-normalized component metrics[6]. Normalization is a customary step in multimetric index development that standardizes the scale of component metrics. Rank-normalization also standardizes component metric distributions (see Section 2.8). This eliminates the potential for one single component metric to dominate index scores due to varied scales and distributions. However, the effects of standardizing data scales and distributions are not always positive, particularly when values for a given metric are predominantly “good” or predominantly “poor”. Rank-normalization can also be problematic when a large number of catchments share the same value of a given metric.

The rank-normalization methodology described in Section 2.8 provides scores that are directionally aligned (i.e., higher rank-normalized scores correspond to higher watershed condition, aquatic ecosystem health, or watershed vulnerability). Index/sub-index scores follow the same directionality:

- High landscape condition index scores correspond to high landscape condition;

[6] Values of some metrics were not quantified for all Wisconsin catchments (see Section 2.4 through Section 2.7). For catchments with “missing” metric values, index/sub-index scores are the average of quantified metrics only.

- High aquatic ecosystem health index/sub-index scores correspond to high aquatic ecosystem health;
- High aquatic invasive species index scores correspond to the presence of multiple aquatic invasive species;
- High watershed vulnerability index/sub-index scores correspond to high watershed vulnerability.

Raw index scores calculated from rank-normalized component metrics are subsequently rank-normalized for reporting. This ensures that scores for each index range from 0 to 100. Further, rank-normalization eases interpretation by providing index/sub-index scores that correspond to percentiles. For example:

- A Landscape Condition Index score of 0 corresponds to the lowest condition in the state;
- A Landscape Condition Index score of 25 corresponds to the 25th percentile condition;
- A Landscape Condition Index score of 50 corresponds to the 50th percentile condition;
- A Landscape Condition Index score of 75 corresponds to the 75th percentile condition;
- A Landscape Condition Index score of 100 corresponds to the highest condition in the state.

For the Aquatic Invasive Species Index, five values are possible (corresponding to 0 to 4 aquatic invasive species present). For consistency, these also range from 0 to 100:

- An Aquatic Invasive Species Index score of 0 corresponds to an absence of all four aquatic invasive species considered for the Assessment.
- An Aquatic Invasive Species Index score of 25 corresponds to the presence of one of four aquatic invasive species considered for the Assessment.
- An Aquatic Invasive Species Index score of 50 corresponds to the presence of two of four aquatic invasive species considered for the Assessment.
- An Aquatic Invasive Species Index score of 75 corresponds to the presence of three of four aquatic invasive species considered for the Assessment.
- An Aquatic Invasive Species Index score of 100 corresponds to the presence of all four aquatic invasive species considered for the Assessment.

3 RESULTS & DISCUSSION

This section presents maps illustrating scores for the 11 indices and sub-indices of landscape condition, aquatic ecosystem health, and watershed vulnerability listed in Table 5 (full page maps of all indices and metrics are provided in Appendix A). When reviewing index maps, recall that scores depict relative conditions across the state for the purpose of screening priority areas for protection and restoration planning. The following discussion of Assessment results is centered on regional patterns of index scores and the relevance of each index to watershed planning.

3.1 Landscape Condition

Landscape Condition Index scores for Wisconsin catchments are displayed in Figure 13. Regional patterns include:

- High Landscape Condition Index scores are concentrated in the northern one-third of the state, where forest cover dominates and urban/agricultural development is low.
- Large patches of high scores are also found in the Central Sands region (Eau Claire, Clark, and Jackson Counties) and along floodplains of the lower Wisconsin River, Black River, and Chippewa River in the Driftless Area of western Wisconsin.
- Low scores occur throughout most of southern and eastern Wisconsin, though some mid to high scoring areas are evident along the Kettle Moraine belt from Walworth to Sheboygan Counties.

Although Landscape Condition Index scores are in line with patterns of human activity across the state, the index provides information tailored to watershed protection planning that is not offered by a simple map of land cover or human population. By incorporating metrics on land cover configuration and resource connectivity, the index presents a view of locations where ecological infrastructure is intact and able to support healthy aquatic ecosystems.

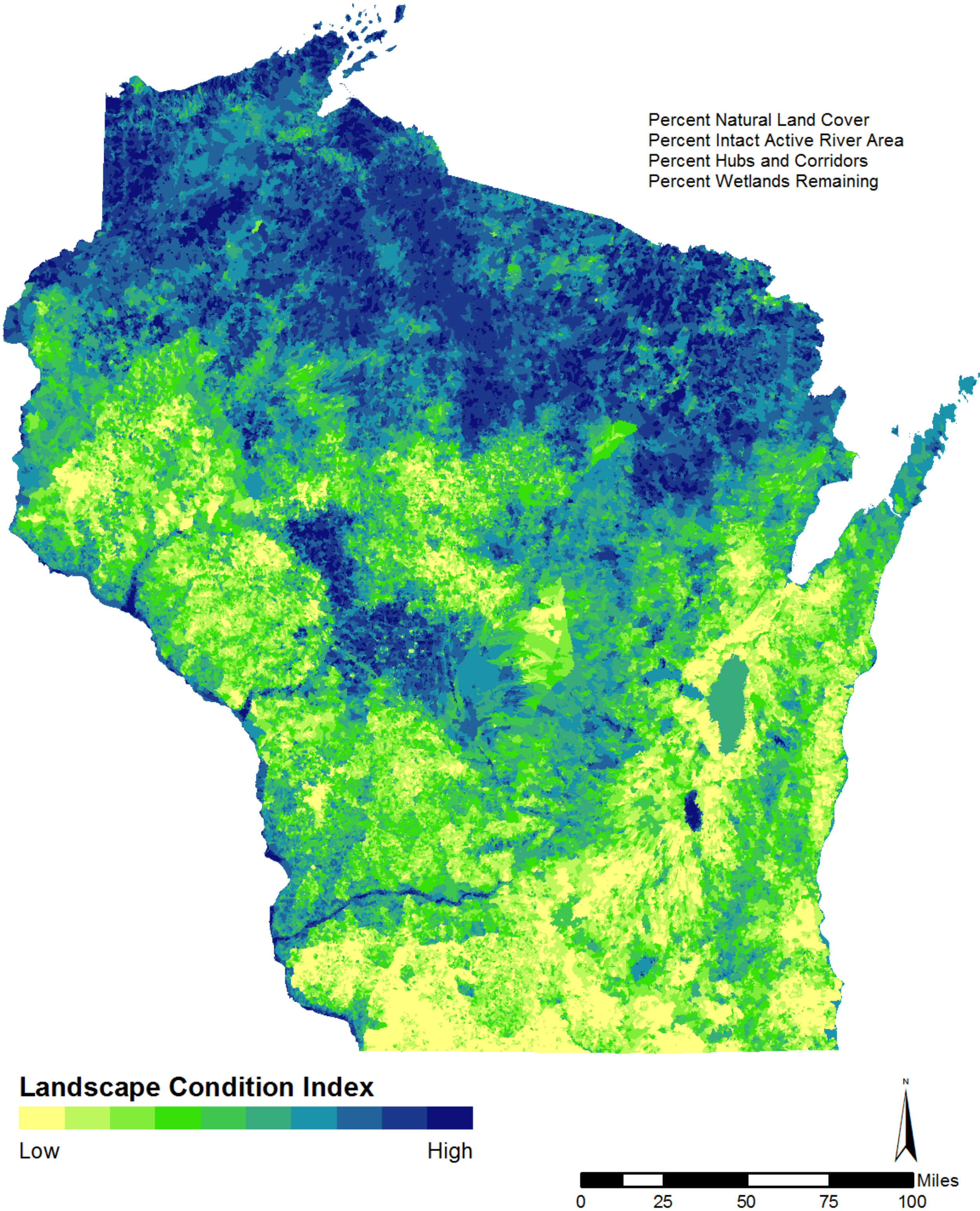

FIGURE 13. LANDSCAPE CONDITION INDEX SCORES.

3.2 Aquatic Ecosystem Health

Aquatic Ecosystem Health Index scores for Wisconsin catchments are displayed in Figure 14. Regional patterns include:

- High Aquatic Ecosystem Health Index scores occur across much of northern Wisconsin.
- Low index scores predominate in the southern and eastern portions of the state, though scattered patches of moderate to high aquatic ecosystem health are evident in these areas.
- Index scores are highly variable through central Wisconsin and the western Driftless Area, with large patches of high scoring areas interspersed with large patches of low scoring areas.

Aquatic Ecosystem Health Index scores are based on the estimated condition of several physical, chemical, and biological characteristics of Wisconsin's streams, lakes, and wetlands. Scores are quantified from measured values of aquatic ecosystem health metrics and from statistical models that relate metric values to landscape variables. Landscape variables with the largest influence on aquatic ecosystem health vary by metric and characterize both natural and non-natural watershed features (refer to Appendix B for details of influential predictors). Aquatic Ecosystem Health Index scores therefore reflect ecological gradients shaped by 1) natural variation in soils, topography, geology, hydrology, etc.; 2) anthropogenic stressors that have influenced measured metric values; and 3) anthropogenic stressors that have been determined to be relevant to ecosystem 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.

Figure 14 also presents scores for the four aquatic ecosystem health sub-indices: Hydrologic Condition Sub-Index, Habitat Condition/Geomorphology Sub-Index, Water Quality Sub-Index, and Biological Condition Sub-Index. Scores for the four sub-indices are generally consistent with one another and with the overall Aquatic Ecosystem Health Index. However, differences in sub-index scores are apparent in some areas. For example, in northwest Wisconsin, Habitat Condition/Geomorphology Sub-Index scores are lower than those of other sub-indices. The opposite is the case in southwest Wisconsin, where Habitat Condition/Geomorphology Sub-Index scores and Biological Condition Sub-Index scores are relatively high compared to Water Quality Sub-Index and Hydrology Sub-Index scores for the region. Such differences underscore the importance of integrating physical, chemical, and biological metrics to assess aquatic ecosystem health rather than focusing on a single metric type.

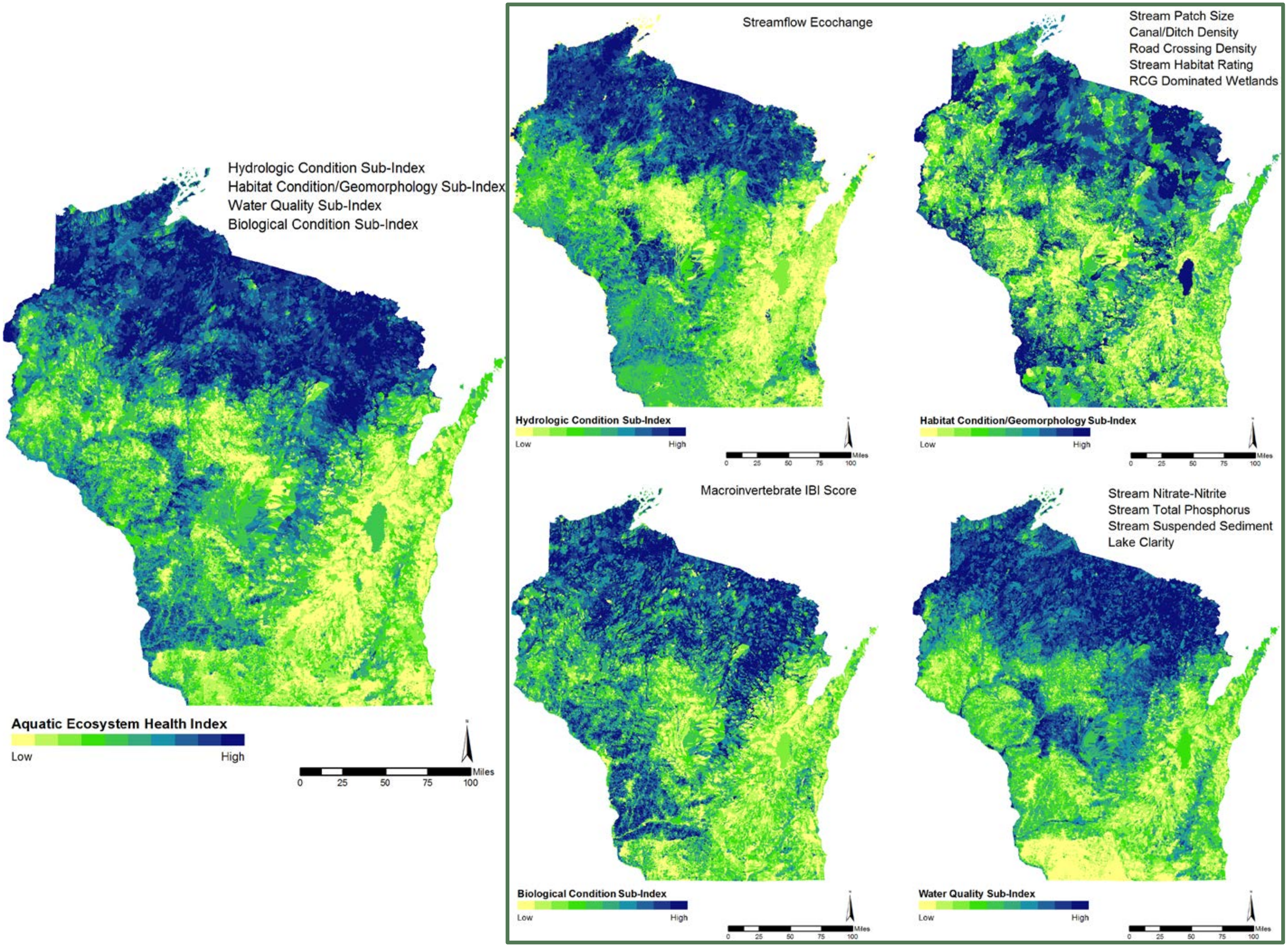

FIGURE 14. AQUATIC ECOSYSTEM HEALTH INDEX AND SUB-INDEX MAPS.

3.3 Aquatic Invasive Species

Aquatic Invasive Species Index scores for Wisconsin catchments with species presence/absence records for lakes are displayed in Figure 15. Scores are generally higher in southwest Wisconsin relative to the northern half of the state. This parallels patterns of Aquatic Ecosystem Health Index scores (Figure 14) and points to a link between degraded aquatic ecosystem health and the introduction/establishment of invasive species.

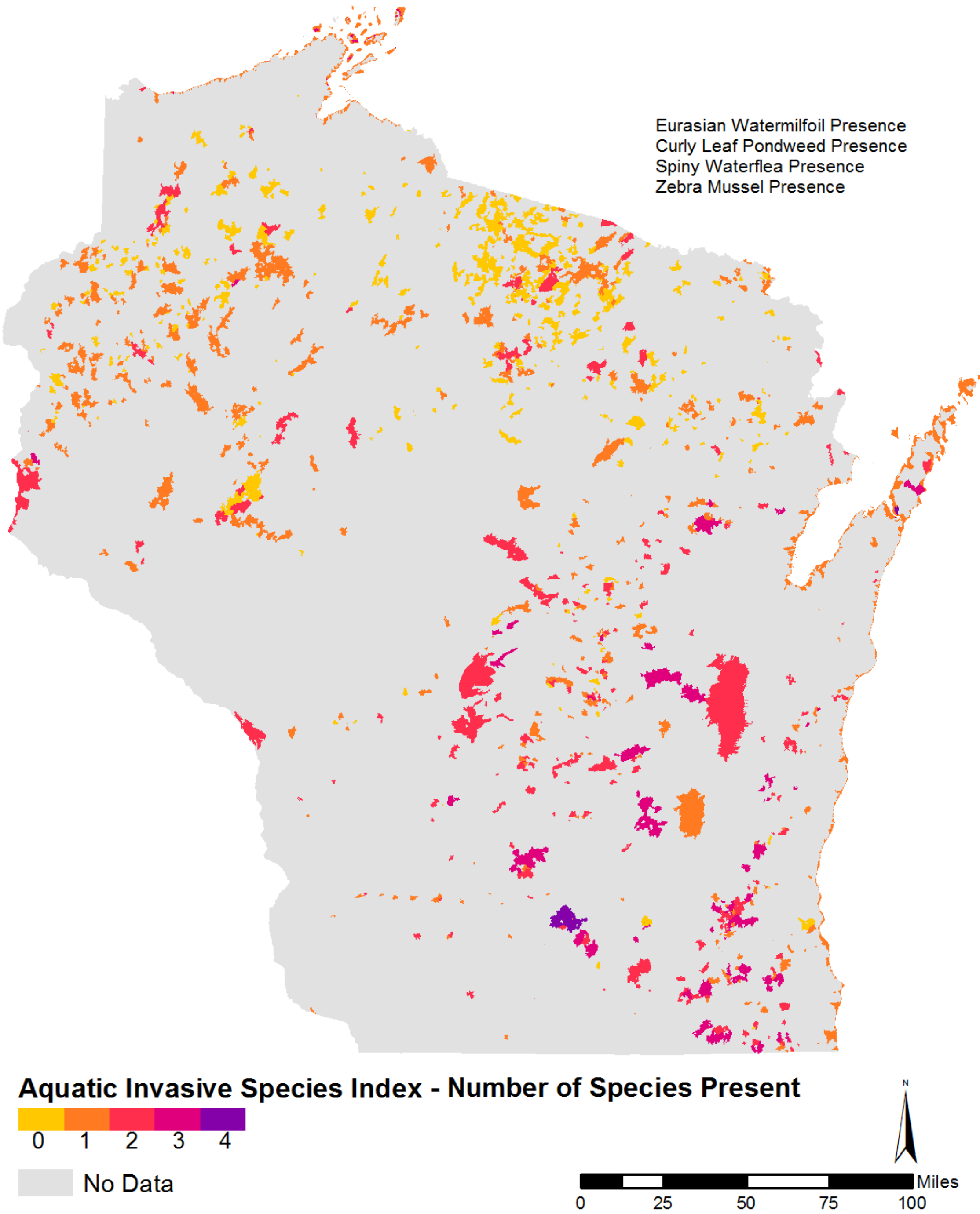

FIGURE 15. AQUATIC INVASIVE SPECIES INDEX SCORES.

3.4 Watershed Vulnerability

Watershed Vulnerability Index scores for Wisconsin catchments are displayed in Figure 16. Regional patterns include:

- High vulnerability scores are concentrated in the southeastern half of Wisconsin. Large patches of high vulnerability scores also occur throughout the central portion of the state.
- Low scores predominate throughout northern Wisconsin and the Driftless Area.

Scores for watershed vulnerability sub-indices (Climate Change, Land Use, and Water Use) are also shown in Figure 16. Regional patterns vary considerably among sub-indices due to thematic differences:

- Climate Change Vulnerability Sub-Index scores are high throughout much of southern and eastern Wisconsin. These patterns reflect estimated changes in runoff and pollutant yields as a result of projected changes in the state's precipitation regime.
- Land Use Vulnerability Sub-Index scores are high in the Milwaukee/Madison metro areas and in scattered patches in the north and west and reflect expected growth patterns of human populations.
- Water Use Vulnerability Sub-Index scores are highly variable throughout the state. The largest concentration of high scores occurs in the Central Sands region in central Wisconsin. This area is subject to intensive groundwater pumping and also contains many groundwater dependent springs, wetlands, and seepage lakes.

Watershed Vulnerability Index scores represent an approximation of the potential for future degradation of aquatic ecosystem health. They depict projected changes in natural and anthropogenic watershed characteristics that are related to aquatic ecosystem health rather than explicit changes to the physical, chemical, and biological makeup of a stream, lake, or wetland. The index is most valuable when used in conjunction with information on watershed health, such as Landscape Condition Index scores and/or Aquatic Ecosystem Health Index scores.

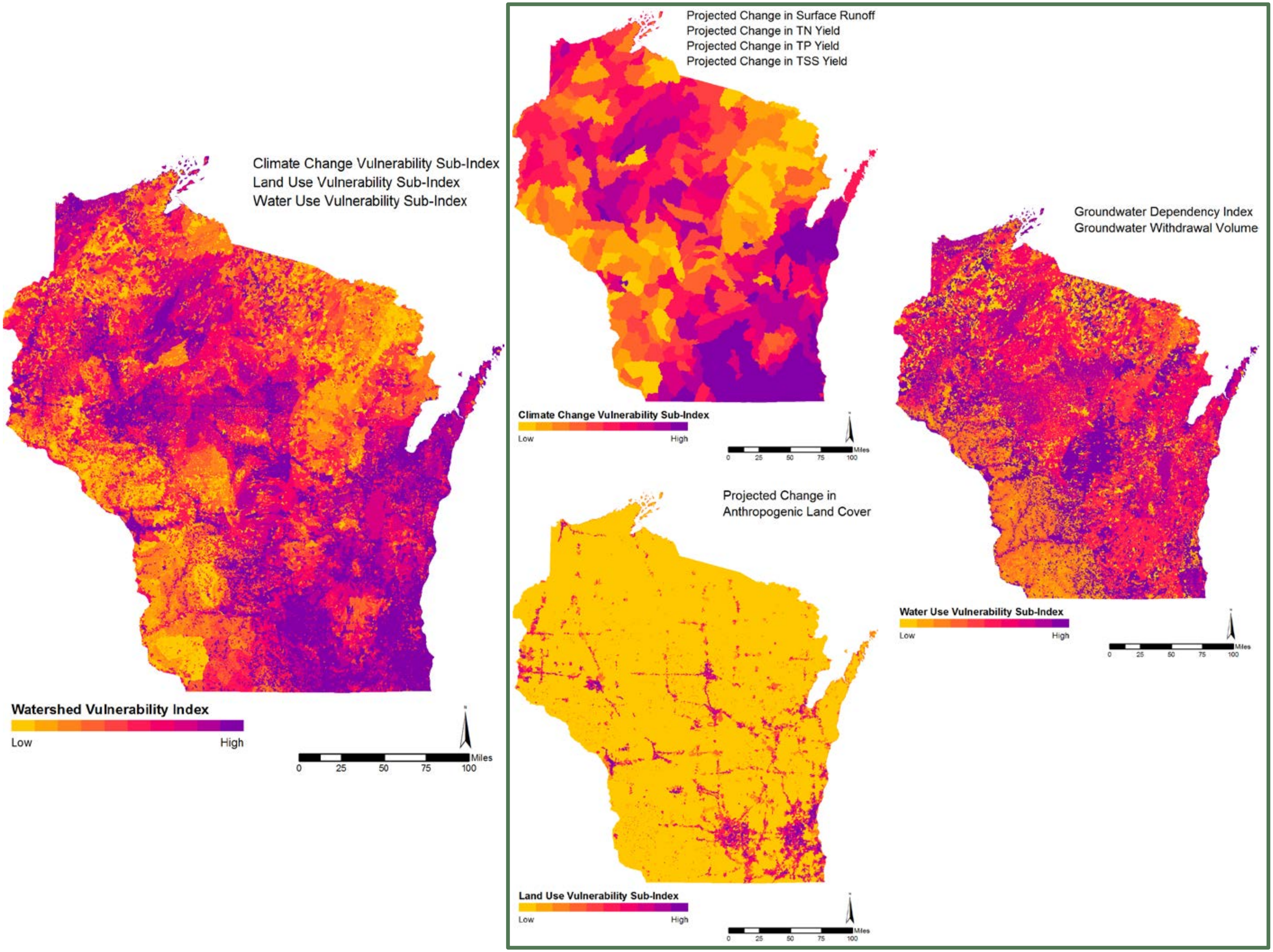

FIGURE 16. WATERSHED VULNERABILITY INDEX AND SUB-INDEX MAPS.

3.5 Assumptions & Limitations

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

➢ **Spatial Framework**

- The WHD is a high resolution (1:24,000) representation of water body locations in Wisconsin. While the accuracy of the WHD stream network and catchment delineations were not verified as part of this project, they were determined to be sufficient for statewide and regional screening of watershed protection priorities.
- Metric and index scores describe overall or average conditions within a given WHD catchment. Assessment results do not supply information at a resolution finer than the catchment scale.

➢ **Landscape Condition Metrics and Index**

- Landscape condition metrics were selected on the basis of data availability, data quality, and expert judgment of relevance to watershed health. Index scores do not account for aspects of landscape condition beyond those represented by selected metrics.
- Landscape Condition Index scores may not reflect the condition of aquatic ecosystems within a given watershed due to upstream influences and factors not represented by landscape condition metrics.
- The *Percent Wetlands Remaining* metric was quantified at the HUC12 scale rather than the catchment scale due to data limitations. Further, data were not available to calculate metric values in seven Wisconsin counties: Vilas, Forest, Florence, Dunn, Eau Claire, Jackson, and La Crosse. Wetland loss is therefore not explicitly accounted for in Landscape Condition Index scores for catchments in these counties. Metric and index values should be updated as more complete, higher-resolution wetlands data become available.
- 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 biased index scores.

➢ **Aquatic Ecosystem Health Metrics and Indices**

- Aquatic ecosystem health metrics were selected on the basis of data availability, data quality, and expert judgment of relevance to watershed health. Index scores do not account for aspects of aquatic ecosystem health beyond those represented by selected metrics.
- Several aquatic ecosystem health metrics are quantified from statistical models that relate aquatic ecosystem condition to landscape variables. Error and uncertainty in model predictions can result from error/uncertainty in both model structure and predictor data. Model predictive error was reviewed through two validation methods (k-fold cross-validation and independent validation; see Appendix B). However, a detailed error and uncertainty analysis was not undertaken as part of this effort (e.g., calculation of prediction intervals or quantification of uncertainty). The suitability of modeled metrics for use in statewide and regional screening of watershed protection priorities was determined from model performance statistics, predictor-response relationships, and expert judgment of model predictions.

- Recommendations for improving the accuracy of predictive models of aquatic ecosystem health include refining response variable data by evaluating and accounting for sampling bias, expanding predictor data to account for factors not represented by the present set of predictors, and refining predictor data by selecting among correlated predictors.
- The condition of fish communities in Wisconsin's streams was intended to be represented in the Assessment from predicted fish Index of Biotic Integrity (IBI) ratings. However, fish IBI was omitted from the Assessment due to concerns over predictive model performance (see Appendix B).
- 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 biased index scores.

➢ **Aquatic Invasive Species Metrics and Index**

- Invasive species presence/absence records were available for a limited number of Wisconsin lakes. Metric and index values were quantified for catchments with reported presence/absence data only. Because data were not available for every waterbody in the state, index scores do not provide a statewide view of aquatic invasive species prevalence.

➢ **Watershed Vulnerability Metrics and Indices**

- Watershed vulnerability metrics were selected on the basis of data availability, data quality, and expert judgment of relevance to watershed vulnerability. Index scores do not account for aspects of watershed vulnerability beyond those represented by selected metrics.
- Climate change vulnerability metrics were quantified at the HUC10 scale rather than the catchment scale due to data limitations. Climate change metrics also reflect the projections of a single Global Climate Model (GCM) that provided "middle-of-the-road" projections of hydrologic response (Mednick, Nelson, & Watermolen, 2012). Metric and index scores should be updated as more refined climate and hydrology projections become available.
- Values of the "Projected Change in Anthropogenic Land Cover" metric reflect estimated changes in land use due to urban expansion and afforestation only. Land use changes resulting from agricultural expansion are not accounted for in the Assessment due to a lack of data.
- "Percent Protected Lands" was initially included as a land use vulnerability metric to characterize the extent of lands that are presently under protection (state parks, land trust holdings, etc.). The metric contributed to high Land Use Vulnerability Sub-Index scores in rural lands throughout the state and was omitted from the Assessment to make the Land Use Vulnerability Sub-Index more reflective of vulnerability to urban expansion. For reference, a map of Percent Protected Lands is provided in Appendix A.
- The Water Use Vulnerability Index characterizes the vulnerability of groundwater dependent ecosystems due to groundwater use. Although surface water use was quantified for the Assessment, it was not included as a vulnerability metric due to the relatively low number of surface water withdrawals in Wisconsin. For reference, a map of surface water withdrawals is provided in Appendix A.

- 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 biased index scores.

4 NEXT STEPS & APPLICATIONS

The results of the Assessment can be used to inform the prioritization and targeting of efforts to protect healthy watersheds in Wisconsin. The following is a summary of potential applications of Assessment results by WDNR and their partners, as well as recommendations for future updates to the Assessment.

4.1 Assessment Applications

Watershed Planning – Each year, watershed plans are developed for certain HUC10 watersheds throughout the state. The Assessment results can be used to prioritize watersheds that may benefit from having a plan conducted in the near-term. Results can also be used in conjunction with field observations of aquatic ecosystem conditions to identify healthy subwatersheds within HUC10s and determine appropriate management actions.

Monitoring and Assessment – The WDNR water monitoring program has already used the Assessment results to identify a subset of healthy but vulnerable watersheds to be monitored during the 2014 sampling season as part of the Targeted Watershed Assessment baseline monitoring program. Because only a small number of sites around the state can be sampled each year, this tool will help to target monitoring efforts for the purpose of validating Assessment results and, where validated, establish baseline conditions for analyzing changes in watershed health over time. Field monitoring data from healthy watersheds may also support the designation of Outstanding or Exceptional Resource Waters (ORW/ERW). ORW/ERW waters receive higher levels of protection under the antidegradation principles outlined in the Clean Water Act and in Wisconsin Administrative Code.

In addition to targeting healthy but vulnerable watersheds for monitoring, Assessment results can be used to target watersheds with low health scores. Field monitoring data from these watersheds can be used to confirm watershed health issues, pinpoint causes of degradation, and inform biennial assessment and listing decisions.

Wetlands – WDNR's Wetlands program is planning to incorporate the Assessment results as part of their Wetlands Rapid Assessment Methodologies (WRAM). The WRAM includes questions to be answered within the context of a wetland's watershed, and Assessment data may provide answers to those questions. Watershed health data may also be used to inform land acquisition decisions for purposes of wetland protection. Additionally, the program may evaluate whether Assessment results can be used in conjunction with other information to identify preferred locations for future wetland mitigation banks.

Lakes – Assessment results can be used as part of efforts to inform and educate lake groups, the public, and counties on the general condition of their watersheds relative to other watersheds in the state, and to encourage action to protect or improve their watersheds (through protective zoning at the county/local level, for example). The Assessment may also guide planning for lake management. For instance, the presence of an impaired lake in a healthy watershed may indicate that the lake is a good candidate for restoration as it may be supported by an otherwise healthy watershed. The lakes program is already working on incorporating Assessment data and models into its new lake health classification schema for 2014.

Streams/Rivers – Results can be used to inform the type of monitoring needed in specific catchments. For instance, in watersheds where biology is known or suspected to be poor, the Assessment predictions could be used as a screen for stressor identification. In such a case, the results might indicate whether habitat or water quality stressors are most likely, and appropriate monitoring plans can be developed accordingly. In the future, if new reference sites or long-term trend monitoring sites are needed, Assessment results could be used to help identify potential locations for such sites.

Great Lakes – WDNR's Office of the Great Lakes (OGL) is charged with implementing a comprehensive program to protect the lakes, which includes leading efforts to assess, protect, and restore natural resources within the Great Lakes basins. Assessment results may be useful for supporting the development of Lakewide Action Management Plans, by providing information on threats and candidate catchments for protection/restoration in the basins, and helping to set management priorities. Great Lakes Grants direct funds toward priority needs for both restoration and protection, and Assessment results may be useful for guiding the decision-making process. Another major focus of the OGL is restoration of the Great Lakes Areas of Concern (AOC). Assessment results may be used to prioritize AOC-related restoration efforts, and changes in watershed health metrics over time may be useful for determining whether management actions have been successful.

Runoff Management – A key anticipated use of the Assessment results is as a component of the grant scoring process for WDNR's runoff management grants. These grants fund BMP implementation and are targeted toward both urban and agricultural projects. One of the grant scoring components is "Water Quality Need," which may be revised to factor in Assessment results for protection-based projects. The intent of the grants has always been to include protection projects as well as restoration projects, but tools to determine where protection is most needed have been lacking; the Assessment will help to fill that need. The Runoff Management program may also use the Assessment results to track improvements in watersheds where BMP projects have been implemented.

Total Maximum Daily Load (TMDL) Analyses and Water Discharge Permits – Total Maximum Daily Load development in Wisconsin focuses primarily on large-scale basins (e.g., HUC 8 and larger). Assessment results may be useful for understanding the relative health of watersheds within these basins, and for targeting BMP implementation efforts. If watershed-wide permitting is adopted in the Wisconsin Pollutant Discharge Elimination System (WPDES) Permitting program, Assessment results may be useful in prioritizing which watersheds to address in the near-term.

Lands/Wildlife – WDNR anticipates that Assessment results will be useful in the Master Planning Process, which is conducted for all state-owned properties. Knowing that a watershed is healthy but vulnerable can trigger the prioritization of protective practices for that area. Additionally, Assessment results may aid in determining where to invest funds in land acquisition. WDNR always aims to target these purchases strategically, to help ensure the best protection while making the most efficient use of taxpayer dollars. The Assessment results may serve as a valuable tool in this planning process.

Partner Groups – It is expected that the Assessment will be useful to a variety of external partner groups within the state. Watershed health rankings could be used to provide partner groups with help in prioritizing where to locate BMPs, develop ordinances, fund restoration, etc. WDNR should work with County Land Conservation Departments and Regional Planning Commissions to determine where the Assessment results might contribute to their future conservation efforts.

The Nature Conservancy (TNC) – TNC's Wisconsin chapter was a partner in developing Wisconsin's Assessment. TNC plans to iteratively develop strategies for biodiversity conservation at state, regional, and ecoregional scales. The Assessment results may be used to inform these strategies. TNC may use the Assessment results to target funding for water quality and wildlife protection for priority watersheds in the state and to help other conservation agencies and organizations in similar endeavors. Additionally, TNC is applying "Watershed Approach" methods for regulatory and non-regulatory preservation and protection of wetlands, and may use the Assessment results to help prioritize areas of the state to focus such efforts.

4.2 Recommendations for Future Updates

The WDNR plans to update the Assessment every five years. This allows for incorporation of new methods and additional data, and allows the state to evaluate trends over time. For future updates, WNDR will consider recommendations coming out of any peer reviews and improvements to methodologies identified from other similar state assessments. It is important to note that revised methods/data may prohibit analysis of changes in watershed health over time.

Potential updates to the Assessment include the addition of new watershed health and vulnerability metrics, incorporation of additional and new data for existing metrics, and refinement of predictive statistical models of aquatic ecosystem health.

Addition of new watershed health and vulnerability metrics – Additional metrics for lake biology and lake water quality should be included as data and tools become available. Macrophyte assessment metrics are under development and may be complete for the next iteration of the Assessment. A fish Index of Biotic Integrity (IBI) for lakes would be an important addition, as would additional lake eutrophication metrics (phosphorus and chlorophyll a). A new lake health classification schema is projected to be completed in 2014, elements of which may be of use for future iterations of the Assessment.

The incorporation of additional metrics to characterize stream and wetland biology would contribute to a more robust assessment of the condition of aquatic biota throughout the state. Potential biological metrics include the Hilsenhoff Biotic Index (HBI) for macroinvertebrates and metrics derived from the Wisconsin Frog and Toad Survey, a citizen-based monitoring program coordinated by WDNR to determine the status, distribution, and long-term population trends of Wisconsin's twelve frog and toad species.

Additional watershed vulnerability metrics should also be considered for future iterations of the Assessment. For example, a metric characterizing a watershed's vulnerability to aquatic invasive species establishment could be quantified according to its proximity to existing aquatic invasive populations and other watershed characteristics. Climate change vulnerability metrics that characterize biological responses to climate change could also be developed from a current WDNR effort to project fish distributions under altered climate regimes.

Incorporation of updated data for existing metrics – Existing metrics can be re-calculated as updated data become available. For example, data used for calculating the *Percent Wetlands Remaining* metric were unavailable for seven Wisconsin counties and should be updated when the Wisconsin Wetlands Index is completed for the entire state. Additionally, calculated values of climate change vulnerability metrics could be refined from: 1) the use of updated downscaled climate projections from the University of Wisconsin in hydrologic response models; and 2) an evaluation of the range of hydrologic responses from multiple global climate model (GCM) outputs (metrics are currently based on a single "middle-of-the-road" GCM projection only).

Refinement of predictive statistical models – Predictive models of aquatic ecosystem health metrics can be refined in a number of ways, including the use of alternative statistical modeling techniques, the use of improved monitoring data, and the inclusion of additional predictor variables.

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APPENDIX A MAP ATLAS

This Appendix contains full page maps for all metrics, indices, and sub-indices of watershed health and vulnerability.

The following guidelines were used for map development:

- Maps display rank-normalized metric or index scores and therefore depict relative conditions. For reference, summary statistics for watershed health and vulnerability metrics are provided in Table 6;
- Maps were created using 10 equal-interval color classes. Because scores are rank-normalized, these classes generally correspond to deciles;
- To ease interpretation, maps display metrics in their original directionality (see Table 4) rather than directionally aligned scores used for index calculations. For example, areas labeled as having "high" road crossing density scores in Figure 24 correspond to areas with a high density of road crossings. The inverse of these scores (1-x) were used to calculate the Aquatic Ecosystem Health Index so that a higher road crossing density contributed to a lower Aquatic Ecosystem Health Index score.

TABLE 6. SUMMARY STATISTICS FOR WATERSHED HEALTH AND VULNERABILITY METRICS.

Metric Name	Minimum	Mean	Median	Maximum
Percent Natural Land Cover	0%	56%	58%	100%
Percent Intact Active River Area	0%	59%	68%	100%
Percent Hubs & Corridors	0%	28%	0%	100%
Percent Wetlands Remaining	0%	70%	76%	100%
Streamflow Ecochange	0%	11%	9%	60%
Stream Patch Size (meters)	0	1,198,902	378,163	7,630,500
Canal/Ditch Density	0%	3%	0%	100%
Road Crossing Density (#/mi^2)	0	6E-04[1]	6E-04[1]	0.02
Stream Total Phosphorus Concentration (mg/L)	0.012	0.092	0.074	1.641
Stream Nitrate-Nitrite Concentration (mg/L)	1E-11[2]	1.3	0.5	24.9
Stream Suspended Sediment Concentration (mg/L)	2.0	12.7	8.8	372
Lake Water Clarity (ft)	0.1	5.7	5.5	26.8
Projected Absolute Change in Surface Runoff (mm)	5E-04[3]	0.029	0.0	12.5
Projected Change in Total Phosphorus Yield (lbs/mi^2)	-6.3	11.8	9.7	59.8
Projected Change in Total Nitrogen Yield (lbs/mi^2)	-110.1	174.4	151.1	832.6
Projected Change in Total Suspended Solids Yield (lbs/mi^2)	-1,079.9	3,948.6	3,164.1	19,763.6
Projected Change in Anthropogenic Land Cover	0%	0.2%	0%	69%
Percent Protected Lands	0%	15%	0%	100%
Groundwater Dependency Index	0	0.2	0.2	0.7
Groundwater Withdrawal Volume (thousands of gallons)	530	49,291	22,294	2,071,729
Surface Water Withdrawal Volume (thousands of gallons)	402	1,212,506	172,767	90,532,646

[1] 6E-04 = 6×10^{-4} [2] 1E-11 = 1×10^{-11} [3] 5E-04 = 5×10^{-4}

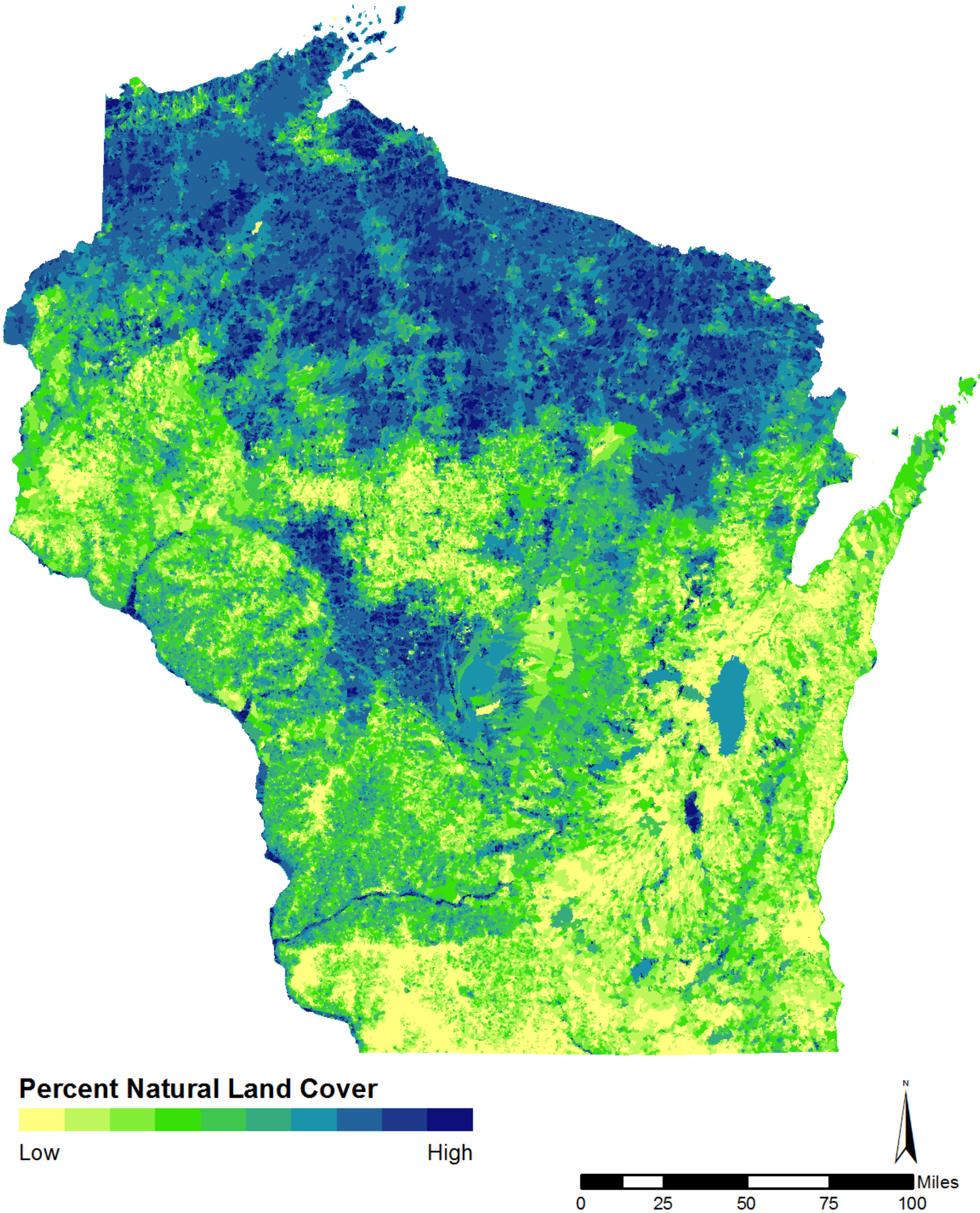

FIGURE 17. PERCENT NATURAL LAND COVER SCORES.

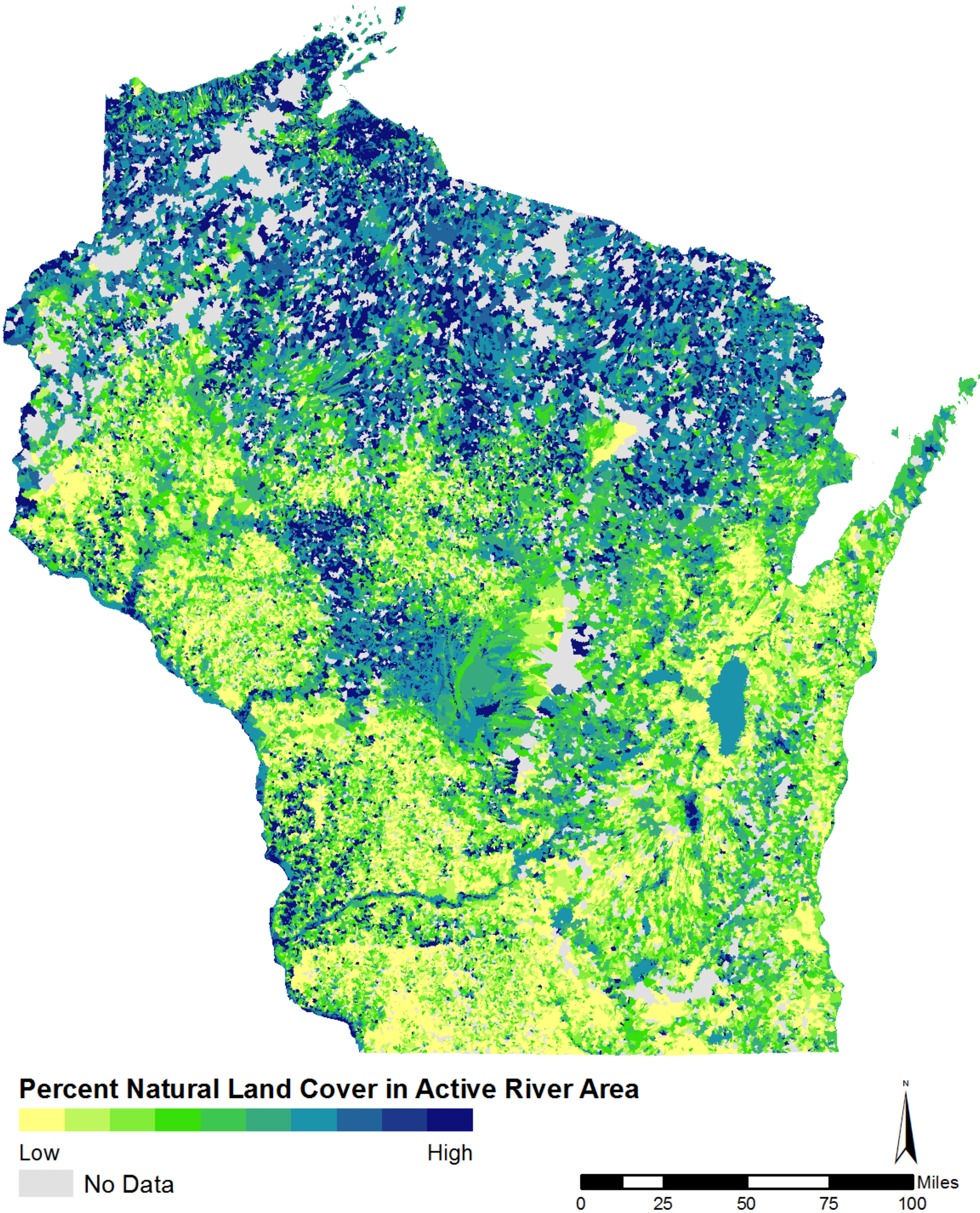

Figure 18. Percent Natural Land Cover in Active River Area scores. Catchments with "No Data" had no Active River Area delineated because they lack flowline features in the WHD.

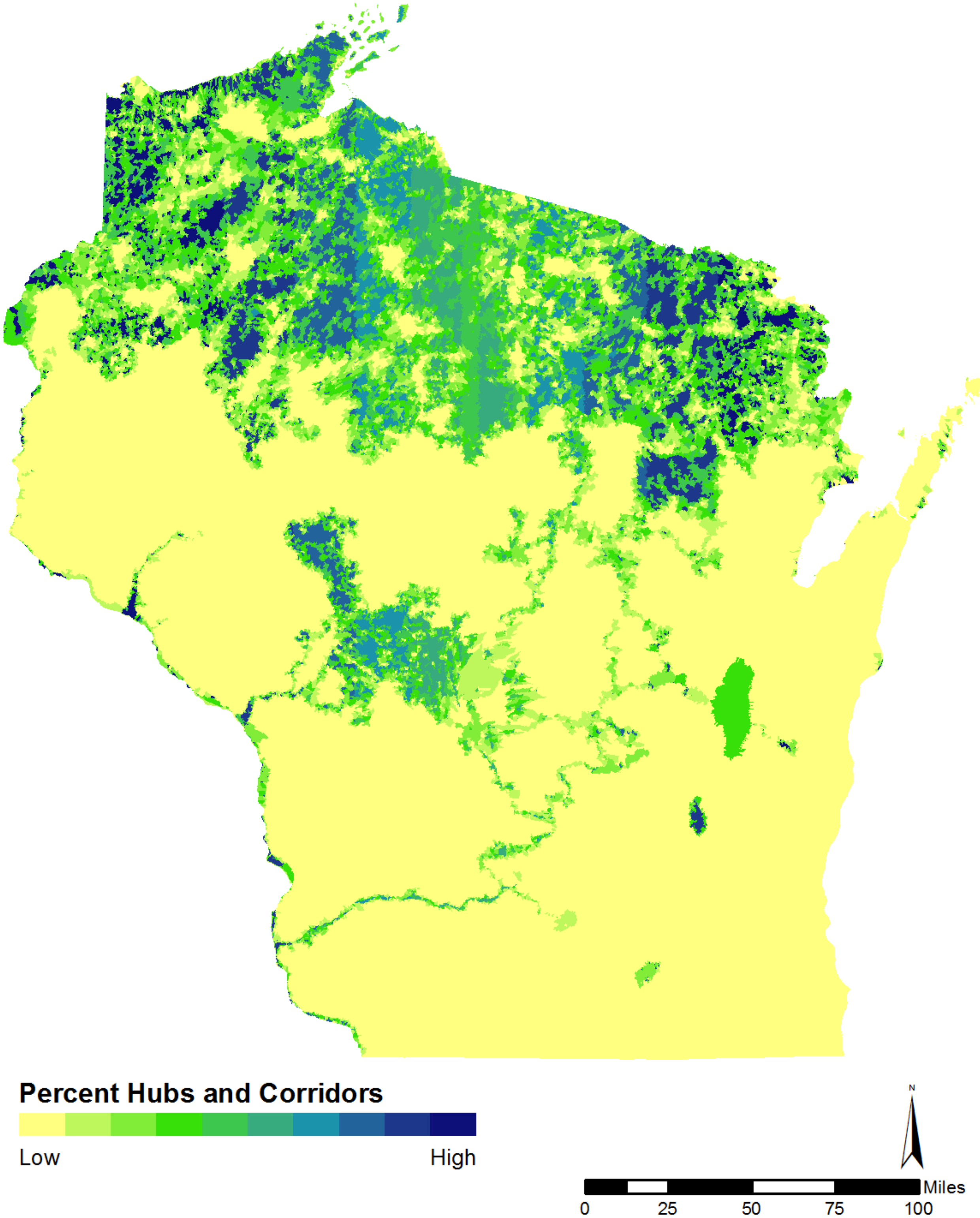

FIGURE 19. PERCENT HUBS AND CORRIDORS SCORES.

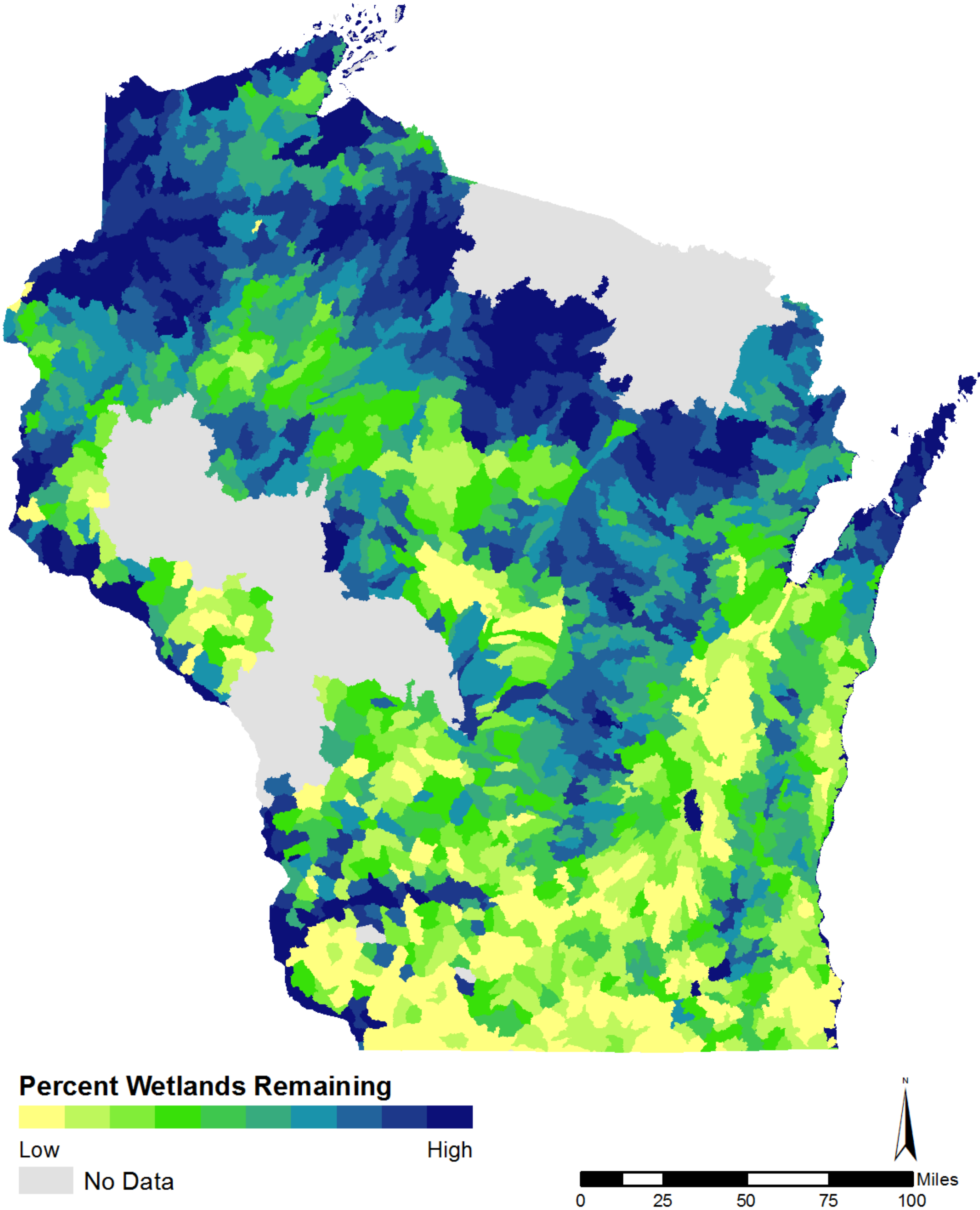

FIGURE 20. PERCENT WETLANDS REMAINING SCORES. CATCHMENTS WITH "NO DATA" DID NOT HAVE DATA AVAILABLE FOR QUANTIFYING METRIC SCORES.

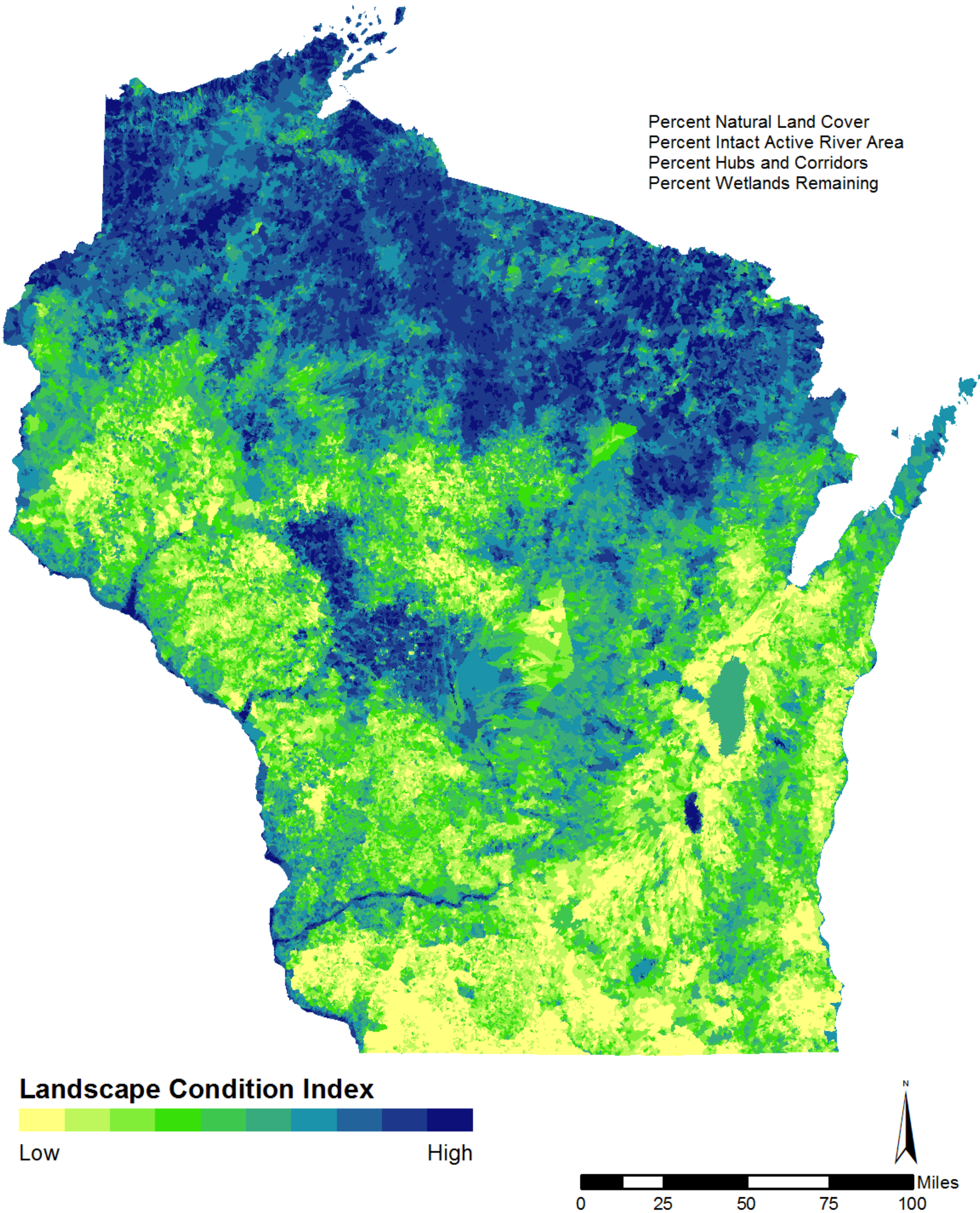

FIGURE 21. LANDSCAPE CONDITION INDEX SCORES.

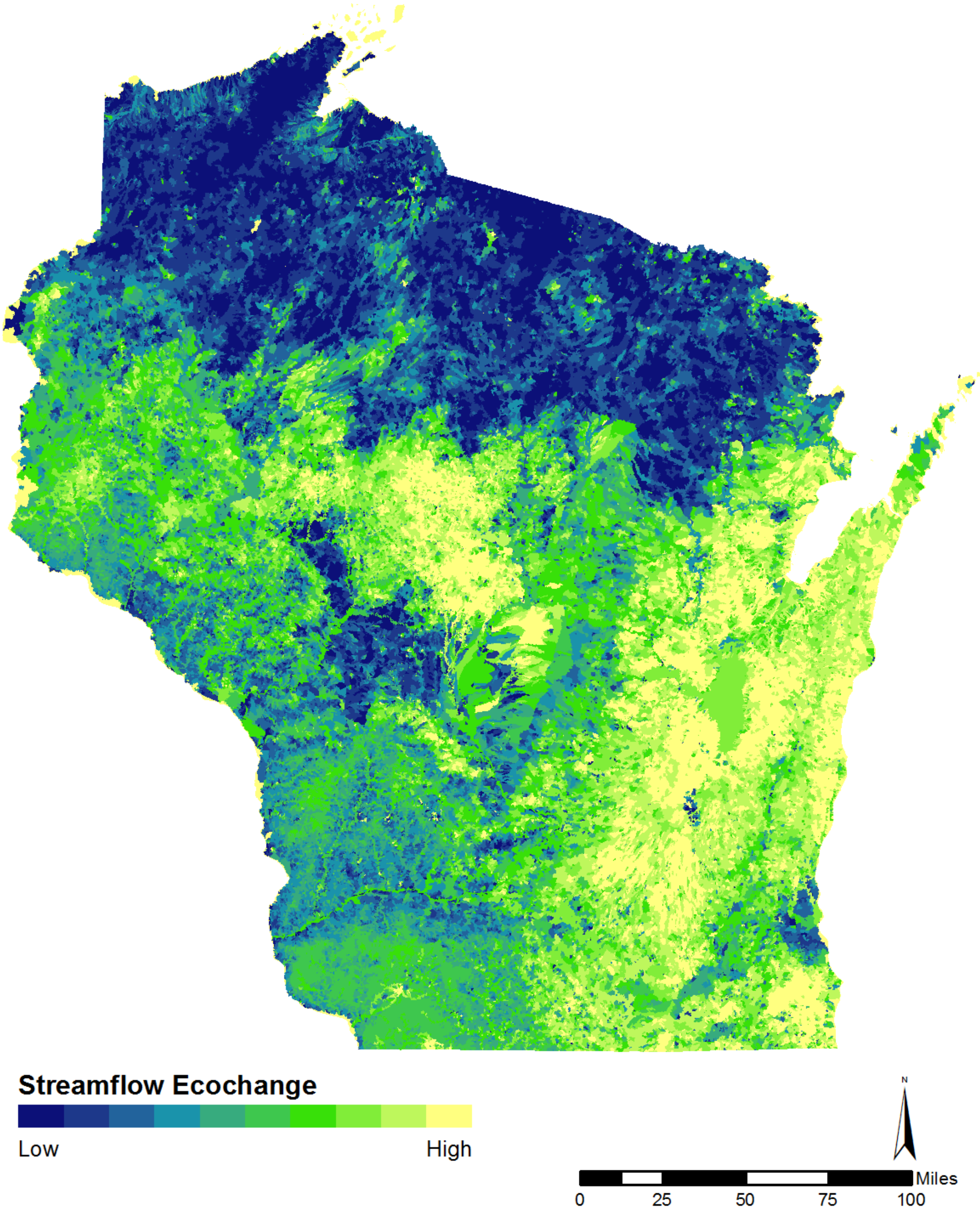

FIGURE 22. STREAMFLOW ECOCHANGE SCORES.

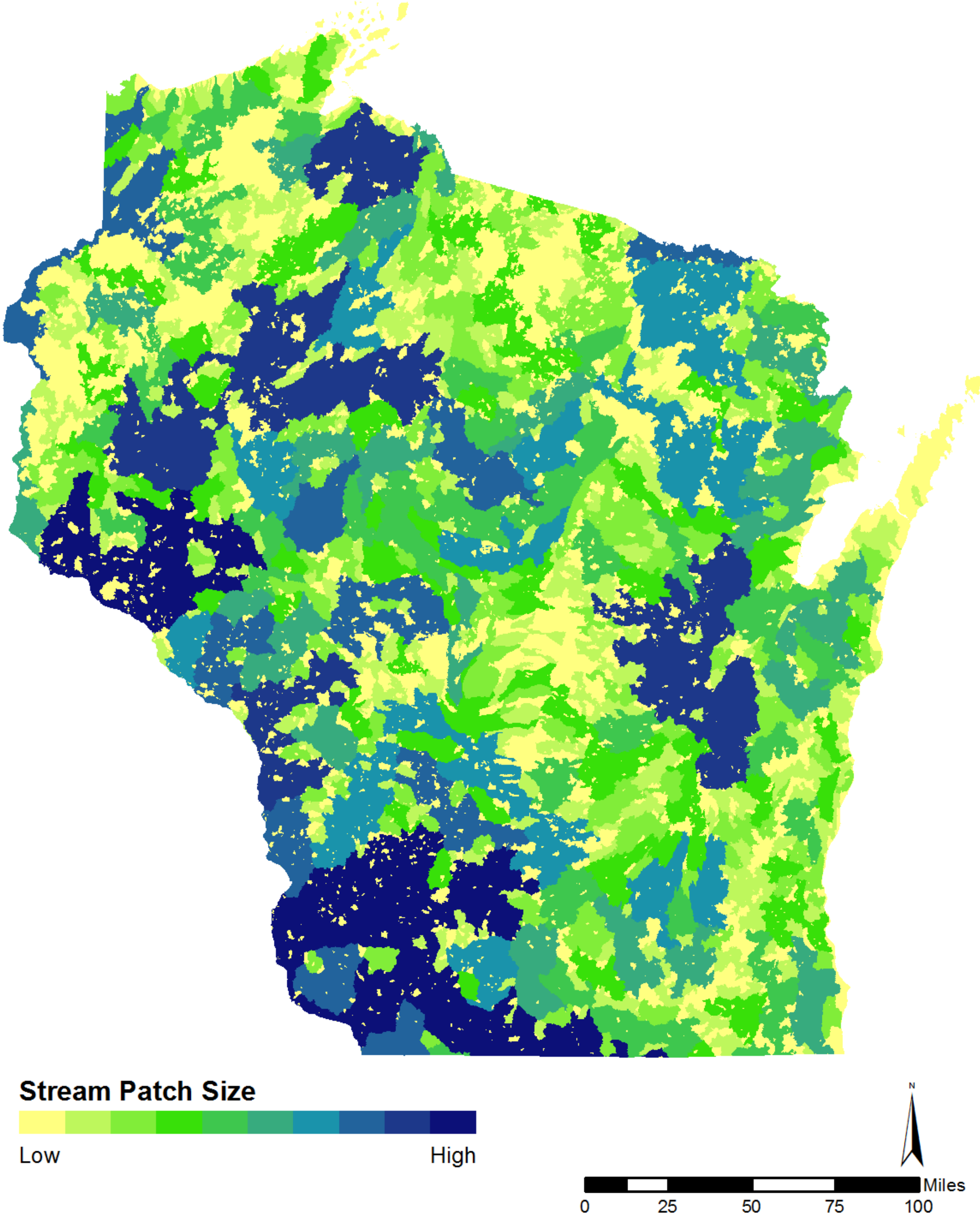

FIGURE 23. STREAM PATCH SIZE SCORES.

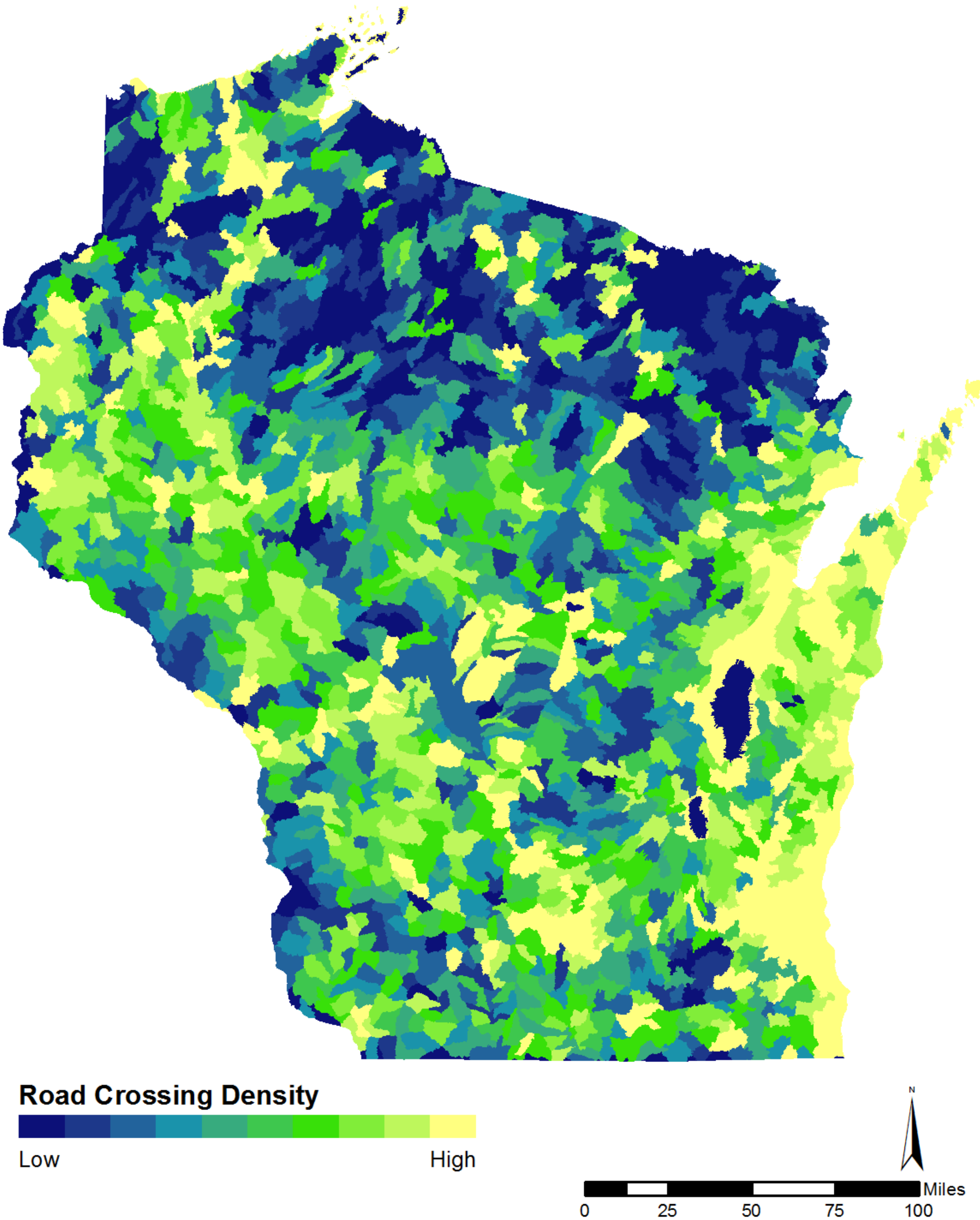

FIGURE 24. ROAD CROSSING DENSITY SCORES.

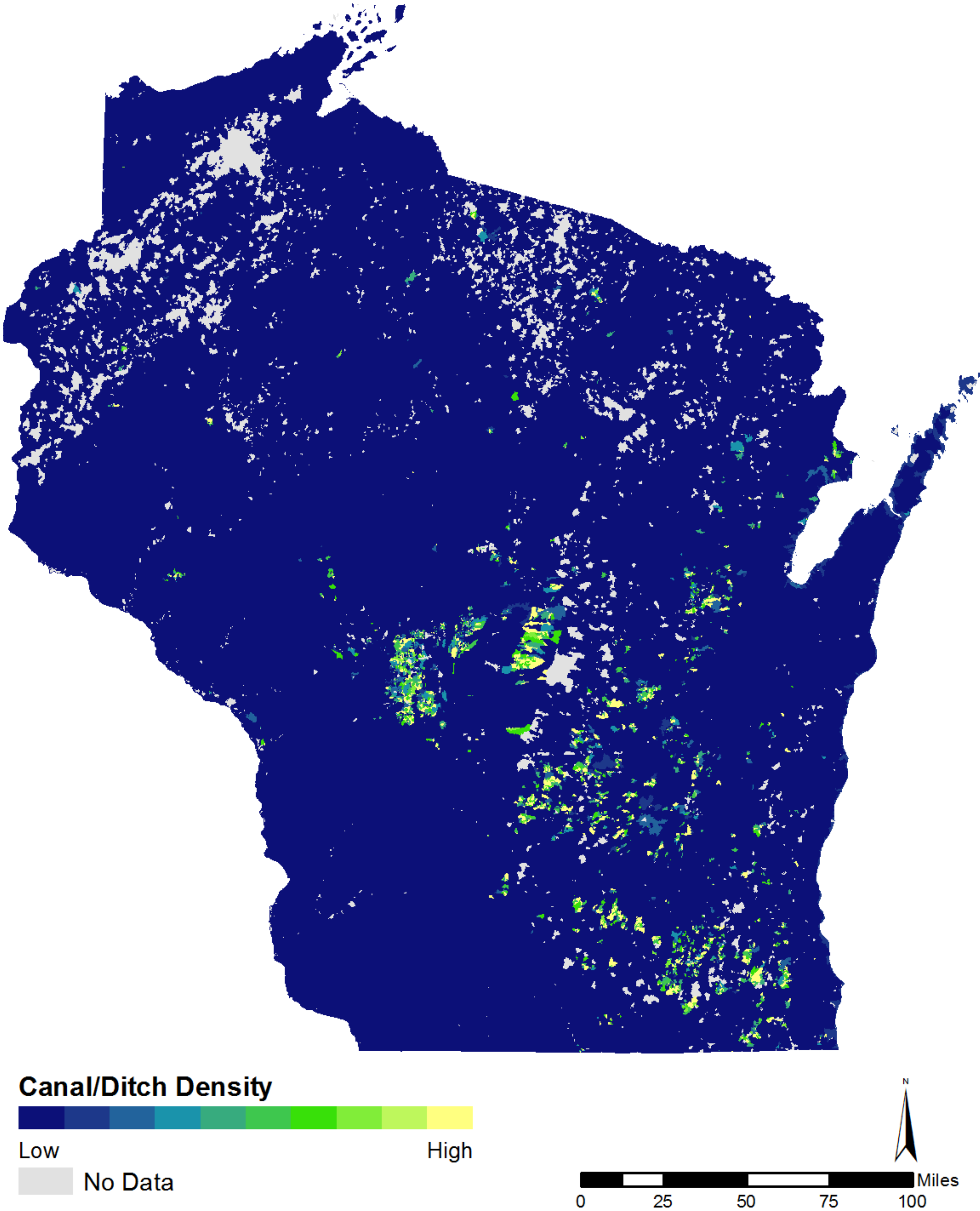

FIGURE 25. CANAL/DITCH DENSITY SCORES. CATCHMENTS WITH "NO DATA" DO NOT HAVE FLOWLINE FEATURES IN THE WHD.

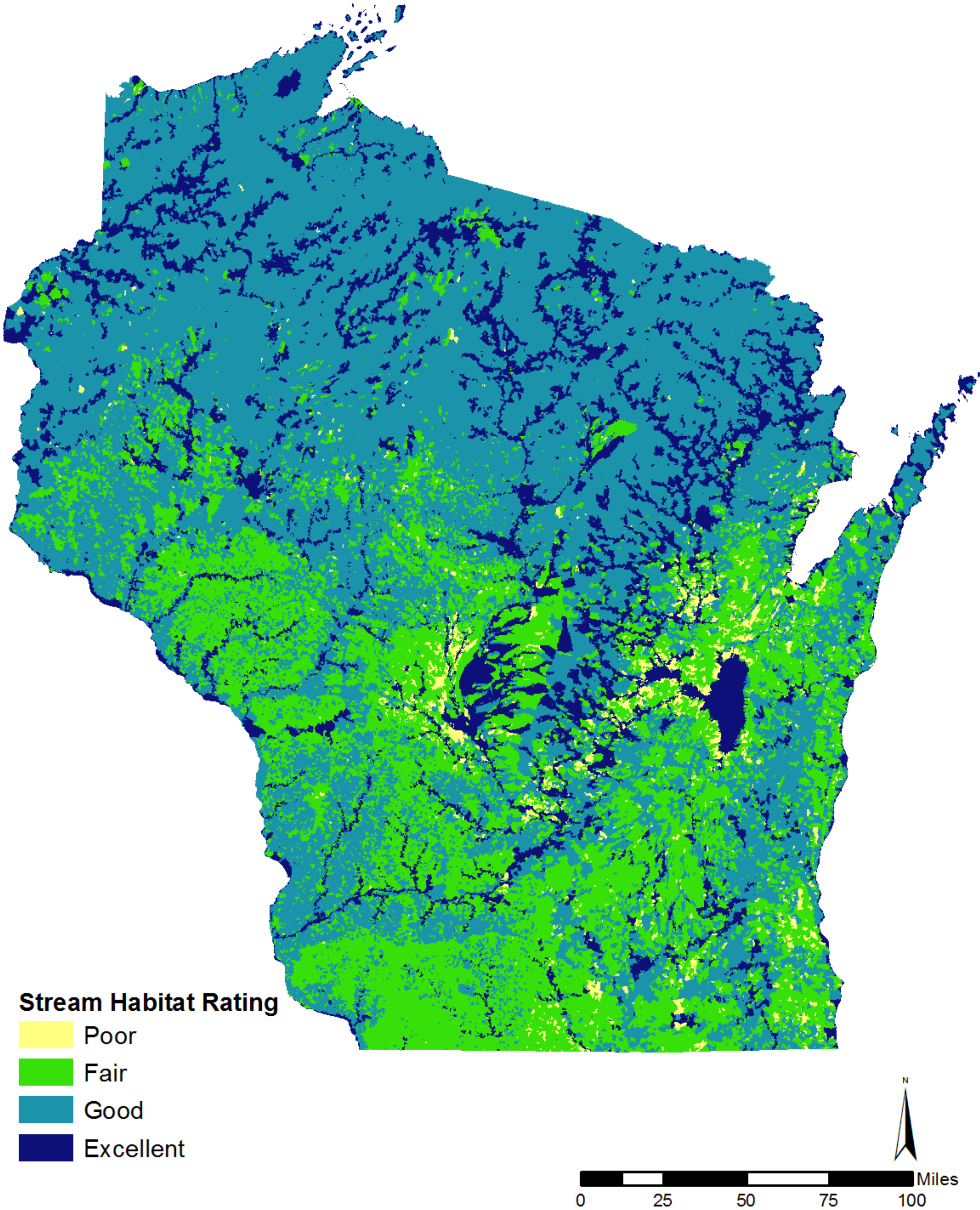

FIGURE 26. STREAM HABITAT RATINGS.

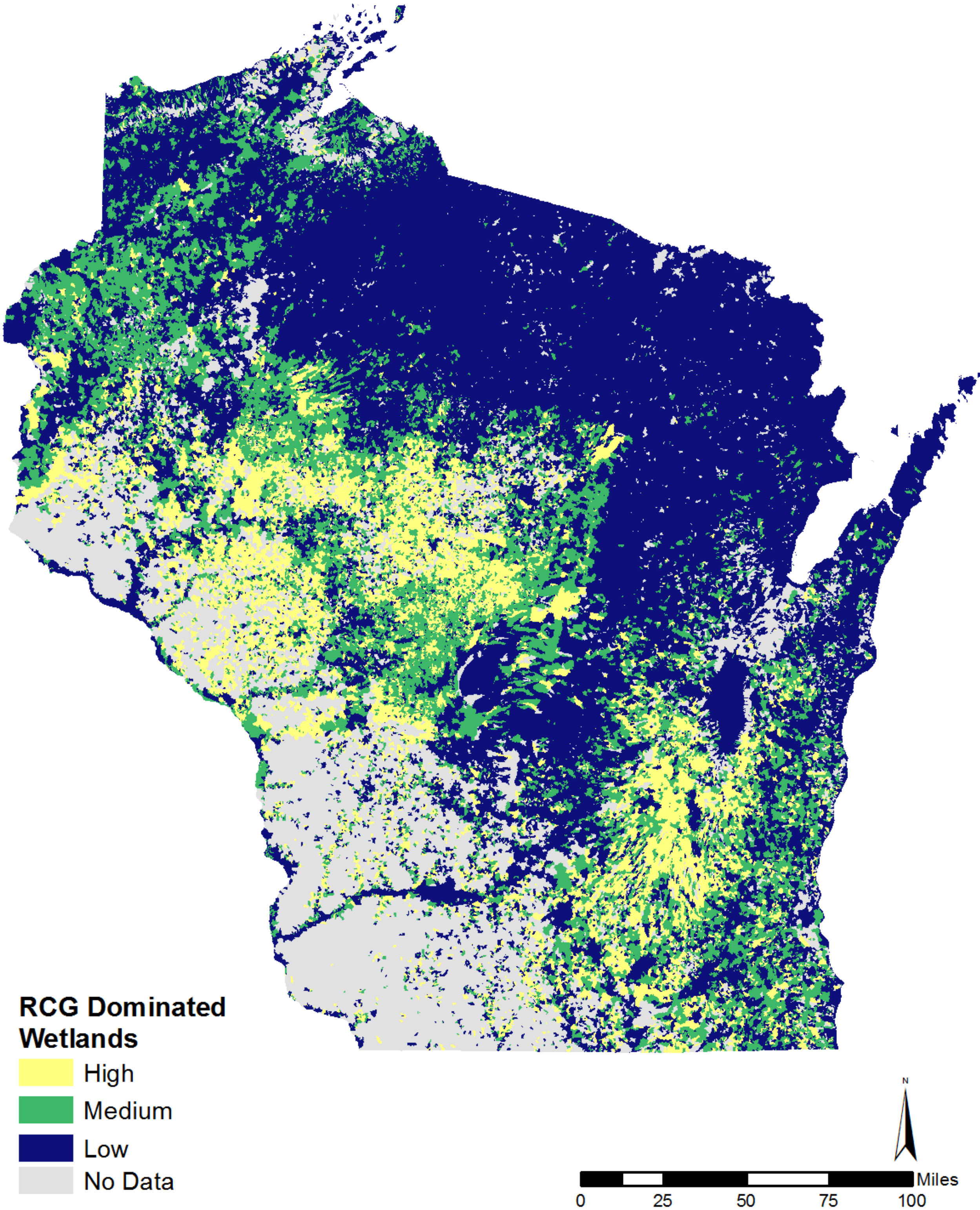

FIGURE 27. REED CANARY GRASS (RCG) DOMINATED WETLAND SCORES. CATCHMENTS WITH "NO DATA" CONTAIN NO WETLAND AREA.

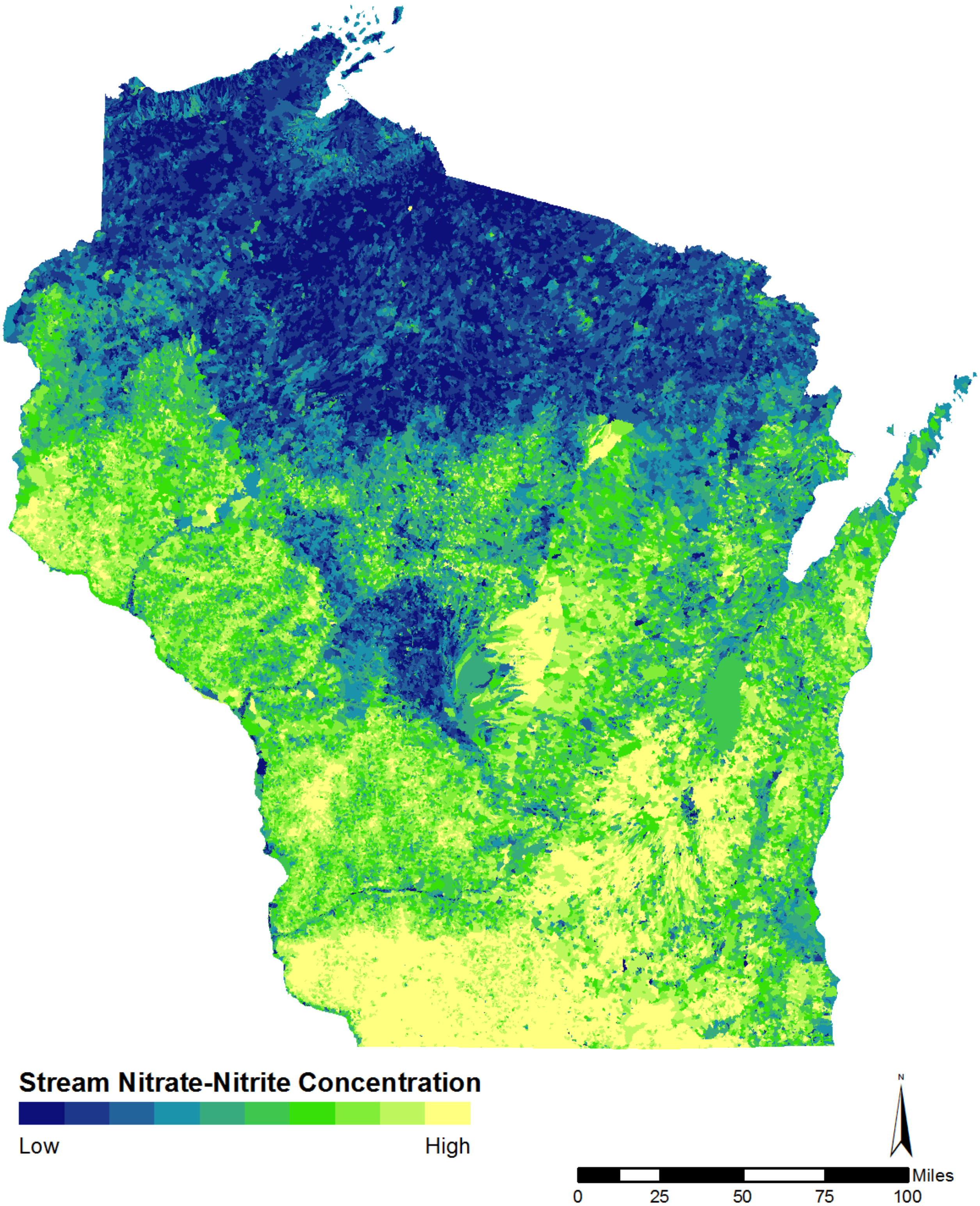

FIGURE 28. STREAM NITRATE-NITRITE CONCENTRATION SCORES.

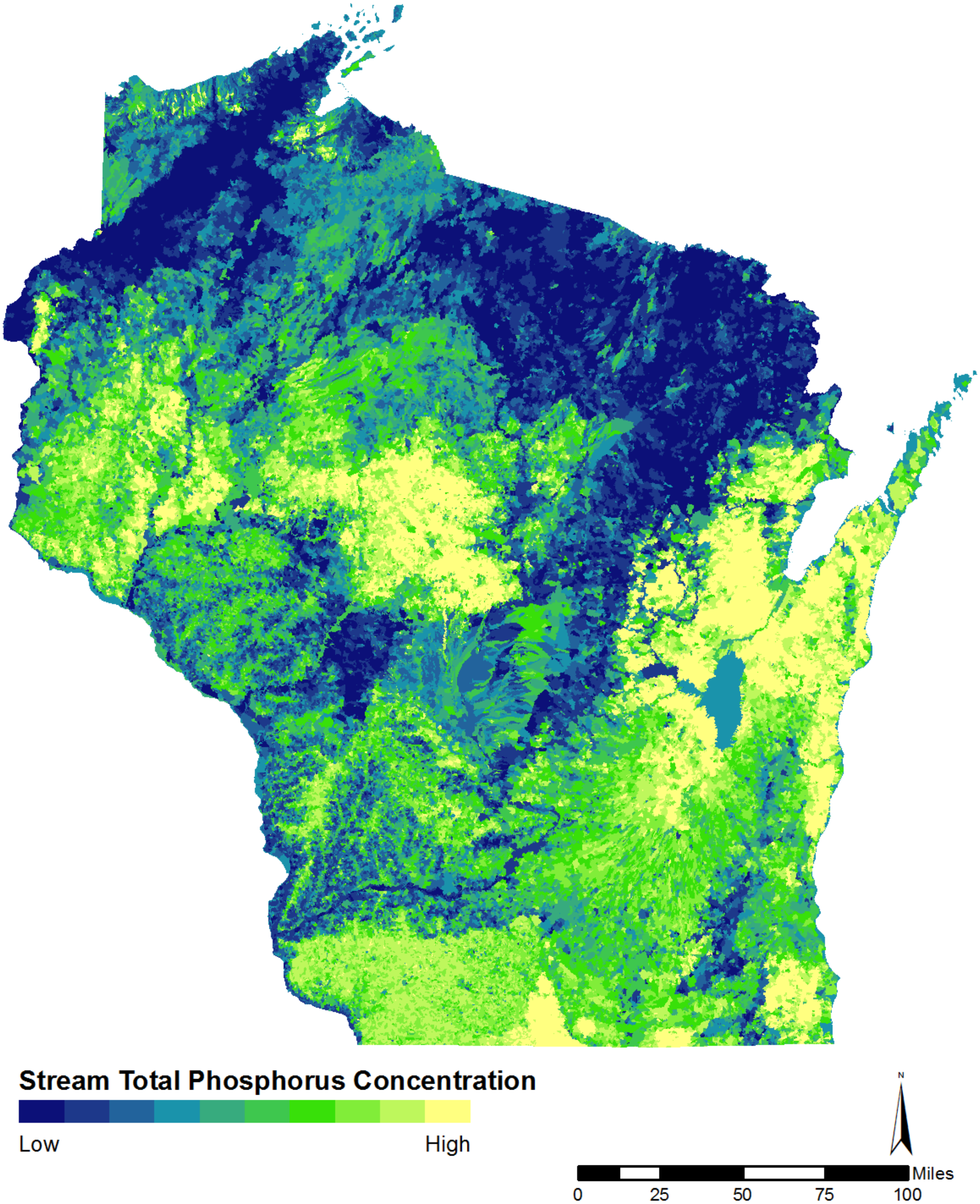

Figure 29. Stream total phosphorus concentration scores.

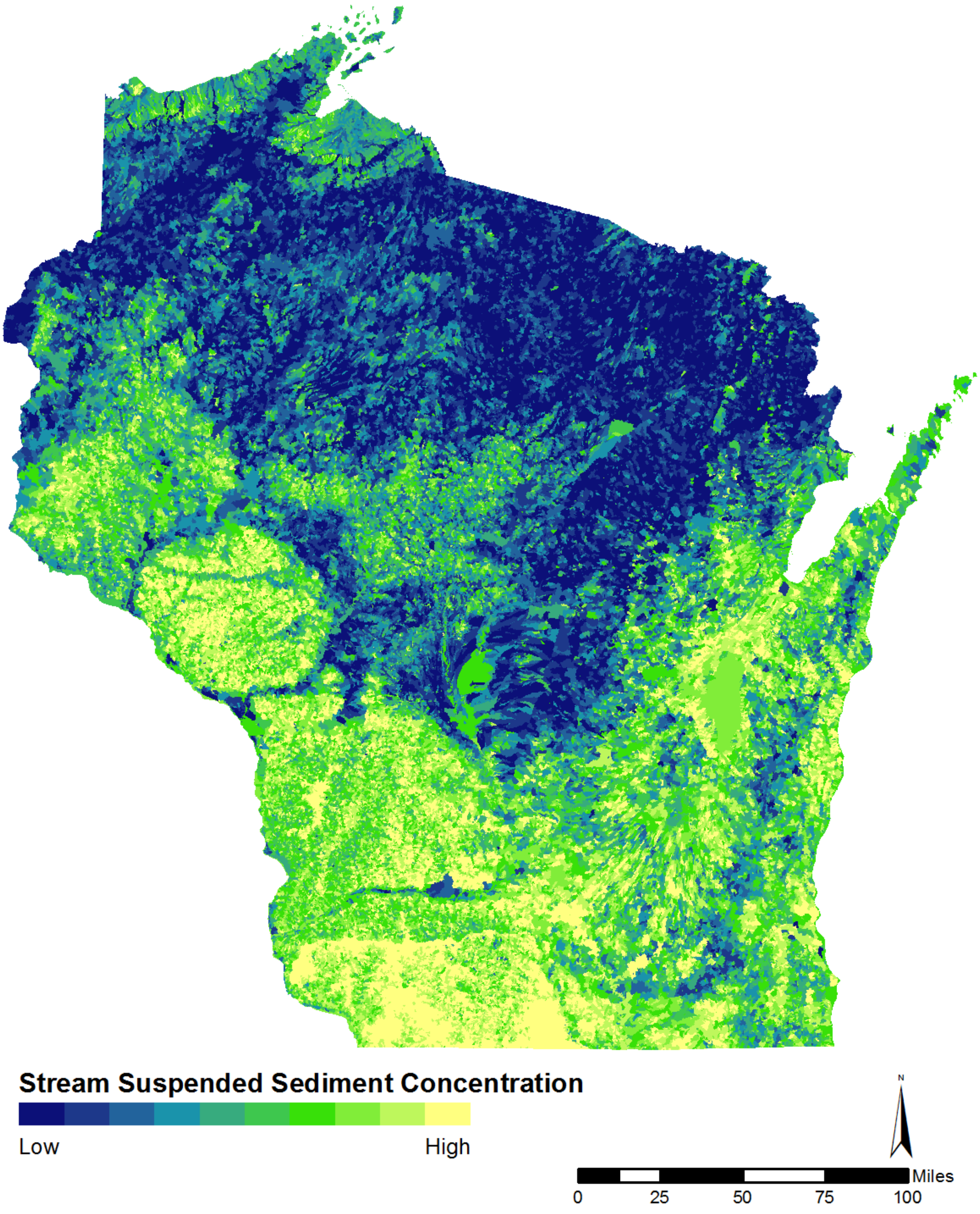

FIGURE 30. STREAM SUSPENDED SEDIMENT CONCENTRATION SCORES.

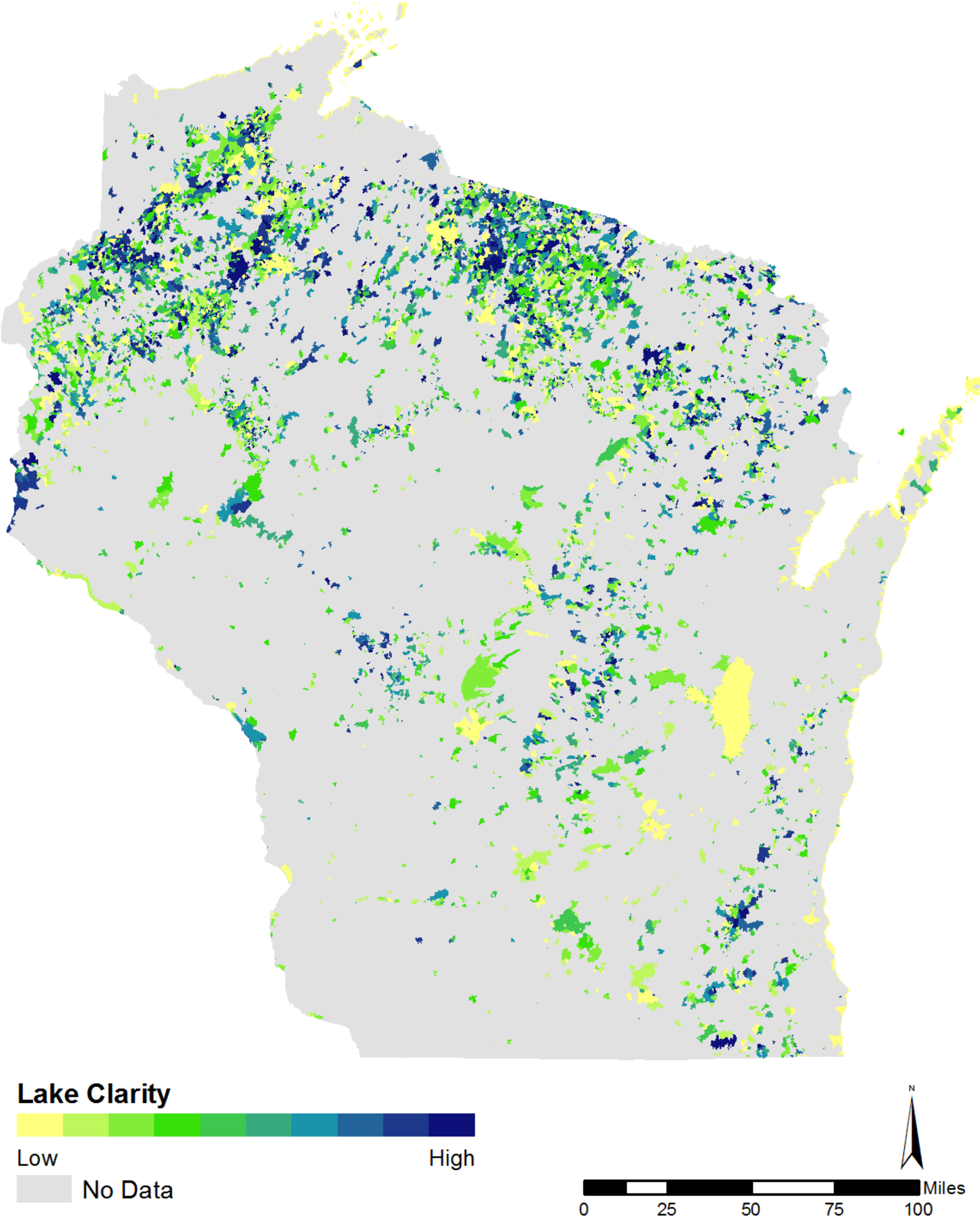

Figure 31. Lake water clarity scores. Catchments with "No Data" contain no lakes greater than 5 acres.

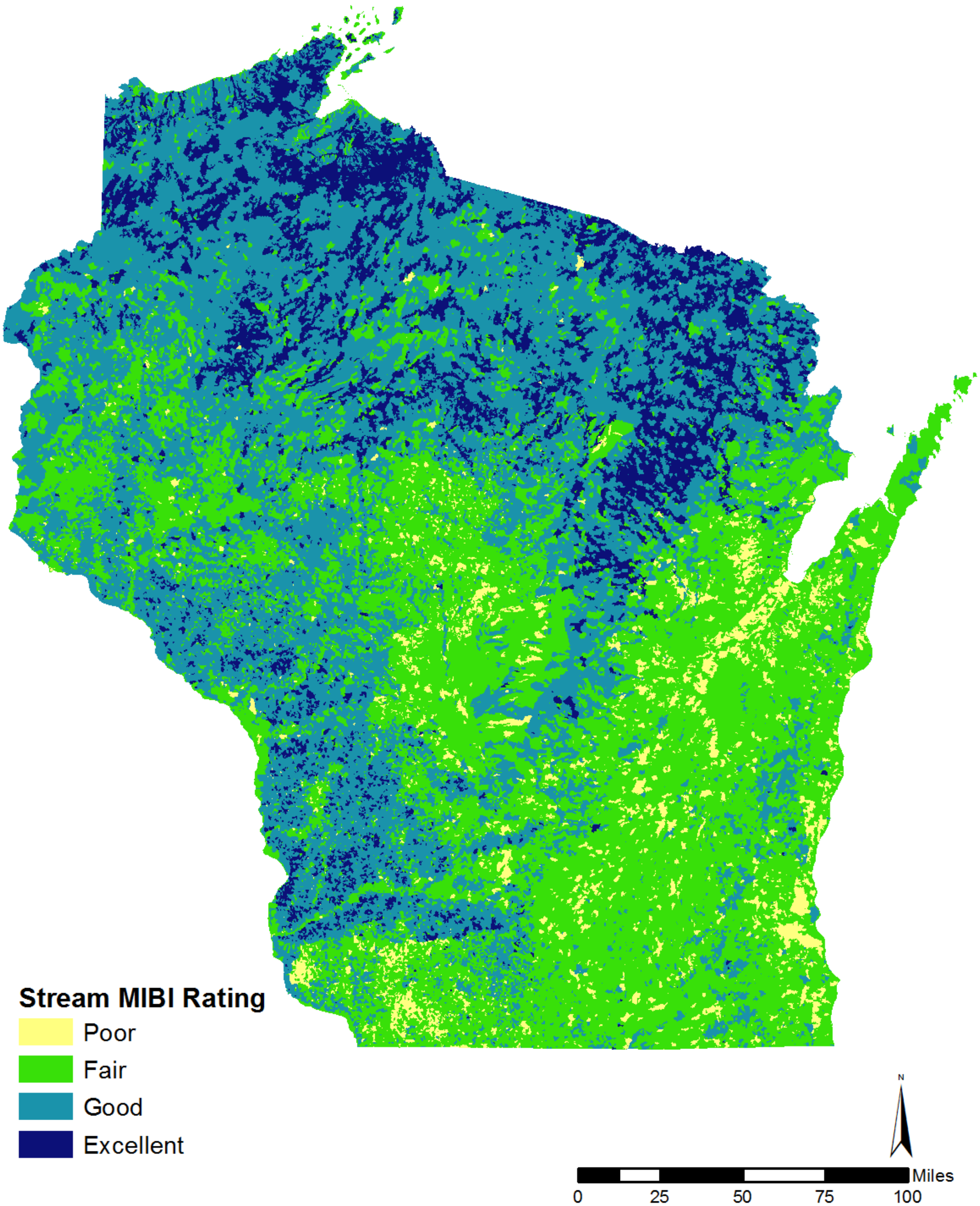

FIGURE 32. STREAM MACROINVERTEBRATE INDEX OF BIOTIC INTEGRITY (MIBI) RATINGS.

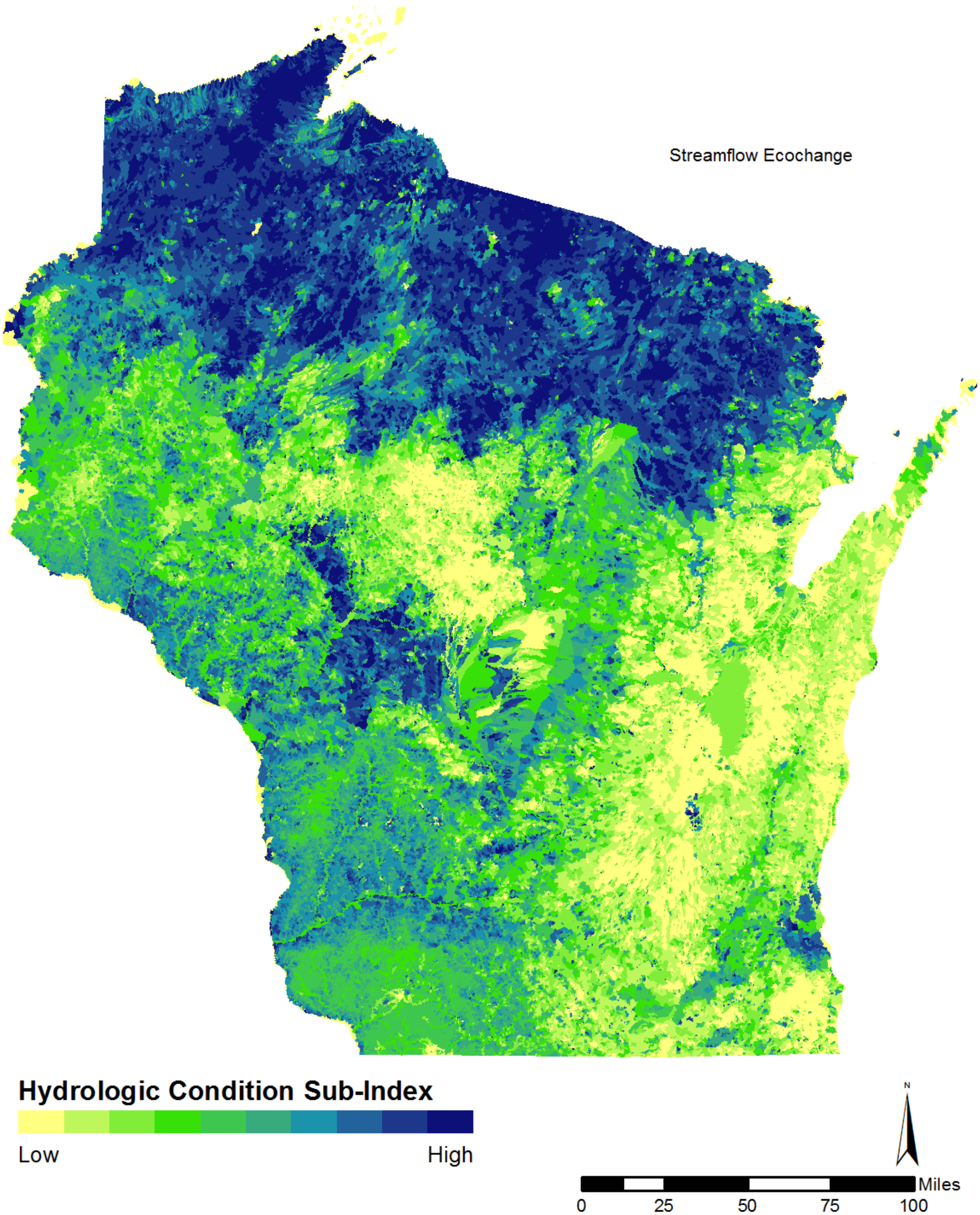

Figure 33. Hydrologic Condition Sub-Index scores.

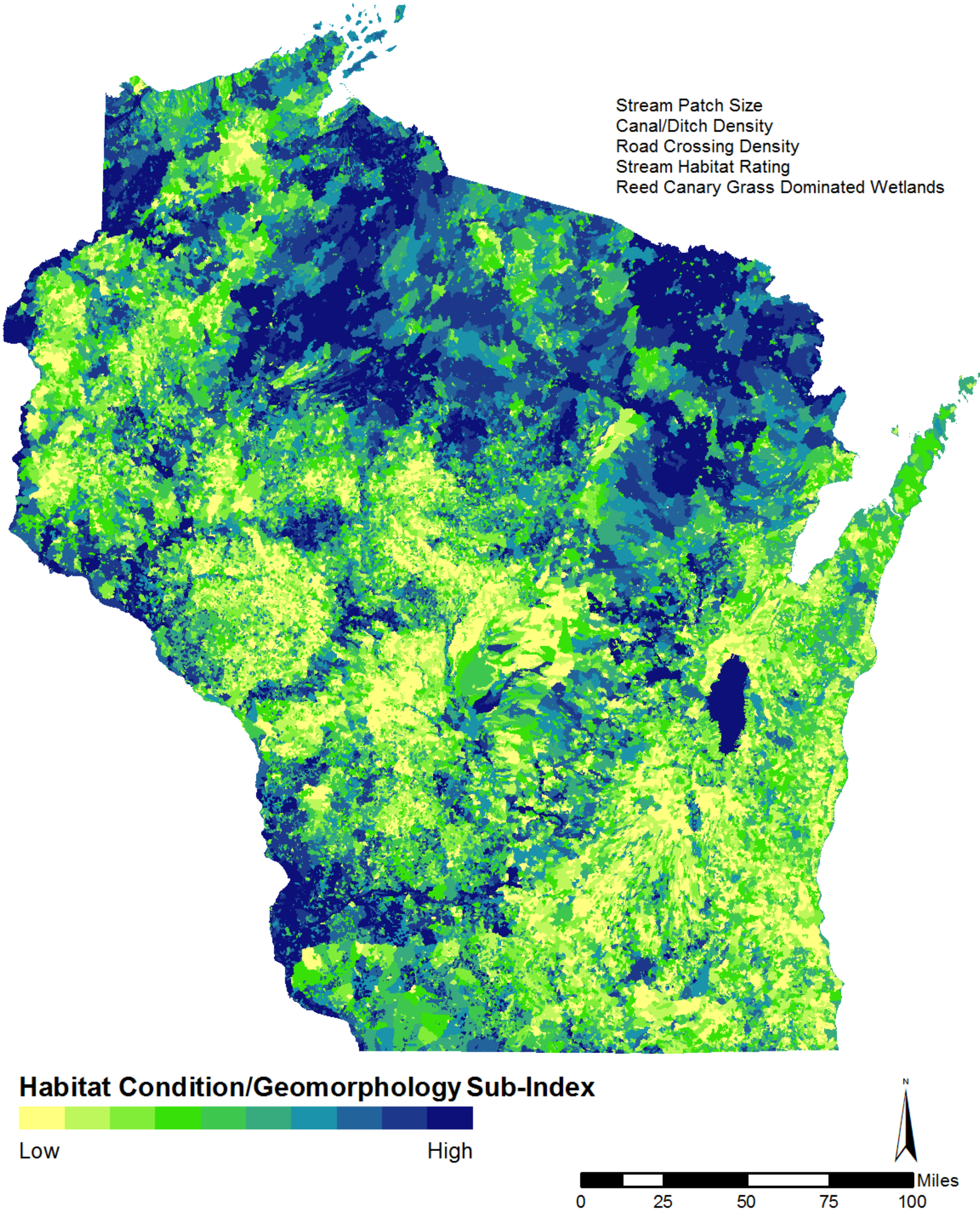

FIGURE 34. HABITAT CONDITION/GEOMORPHOLOGY SUB-INDEX SCORES.

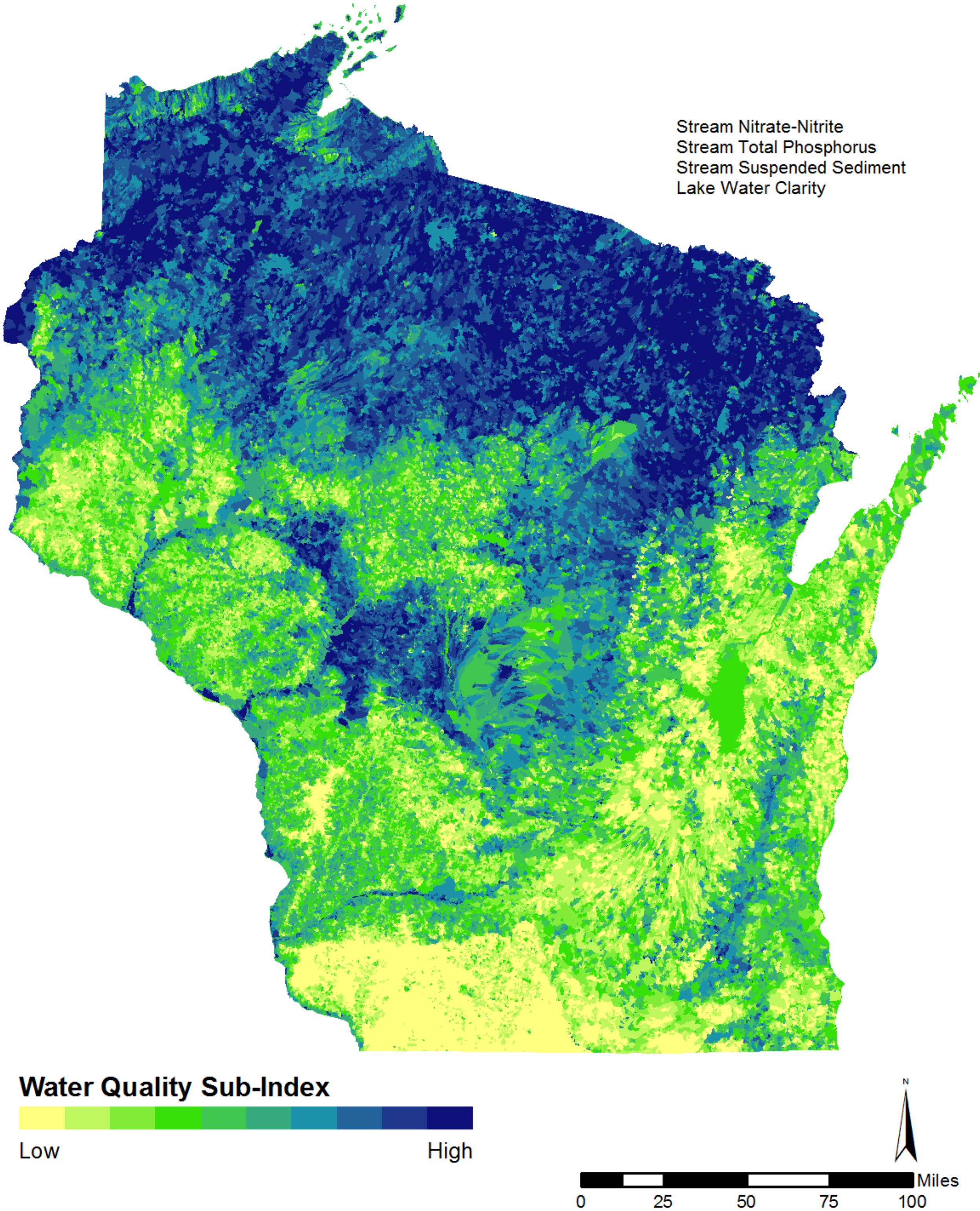

FIGURE 35. WATER QUALITY SUB-INDEX SCORES.

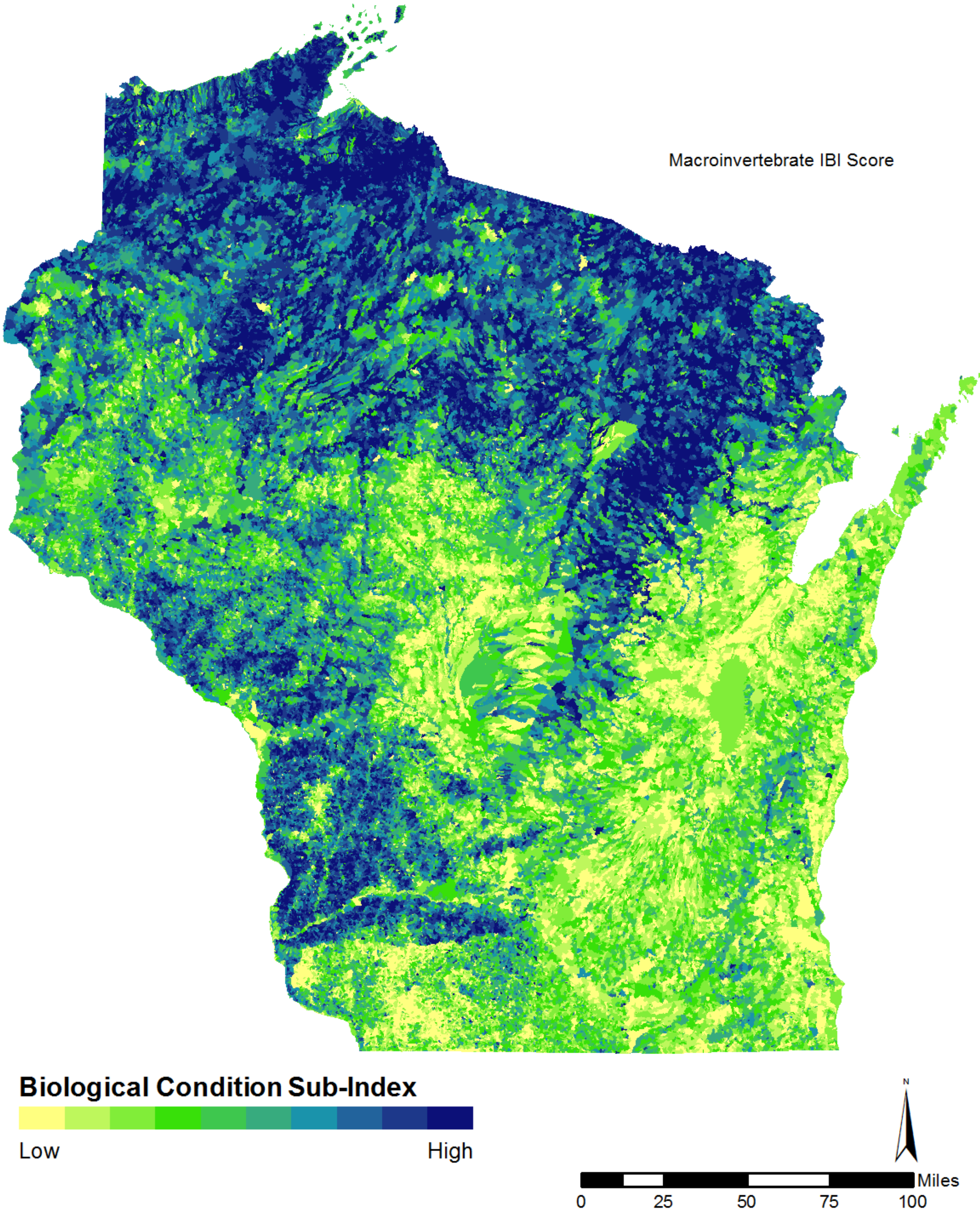

FIGURE 36. BIOLOGICAL CONDITION SUB-INDEX SCORES.

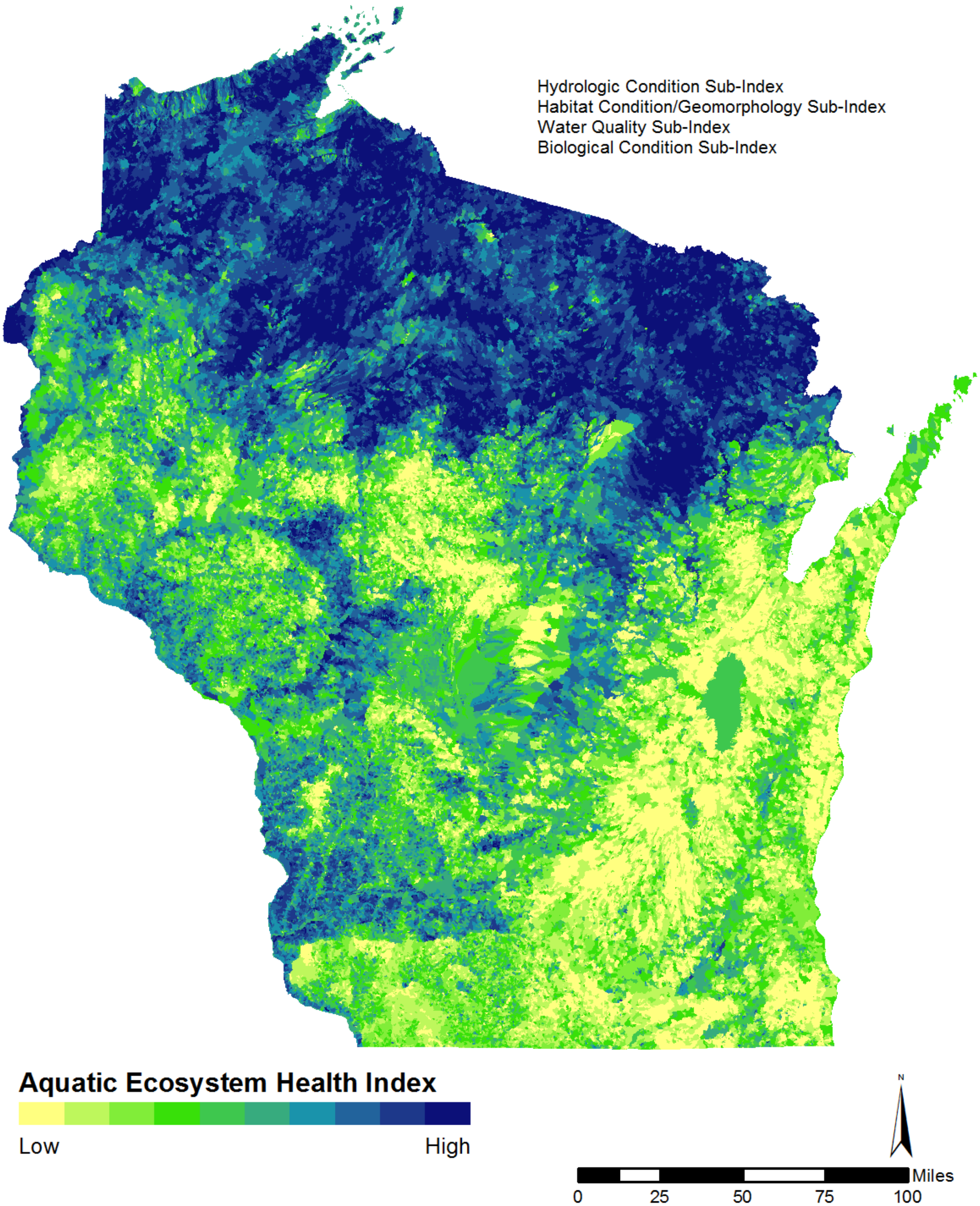

FIGURE 37. AQUATIC ECOSYSTEM HEALTH INDEX SCORES.

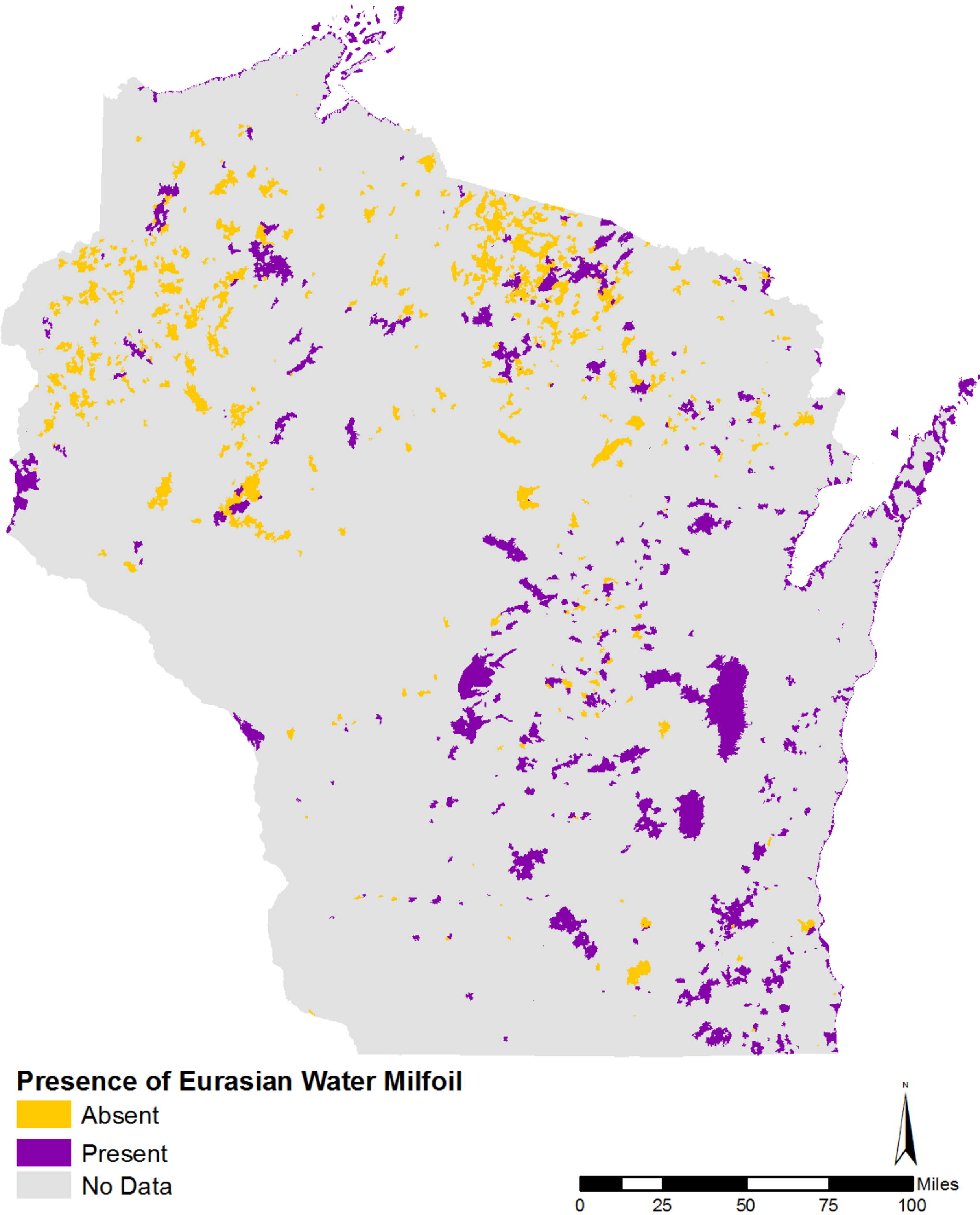

Figure 38. Presence of Eurasian Water Milfoil in lakes. Catchments with "No Data" have no reports of species presence/absence.

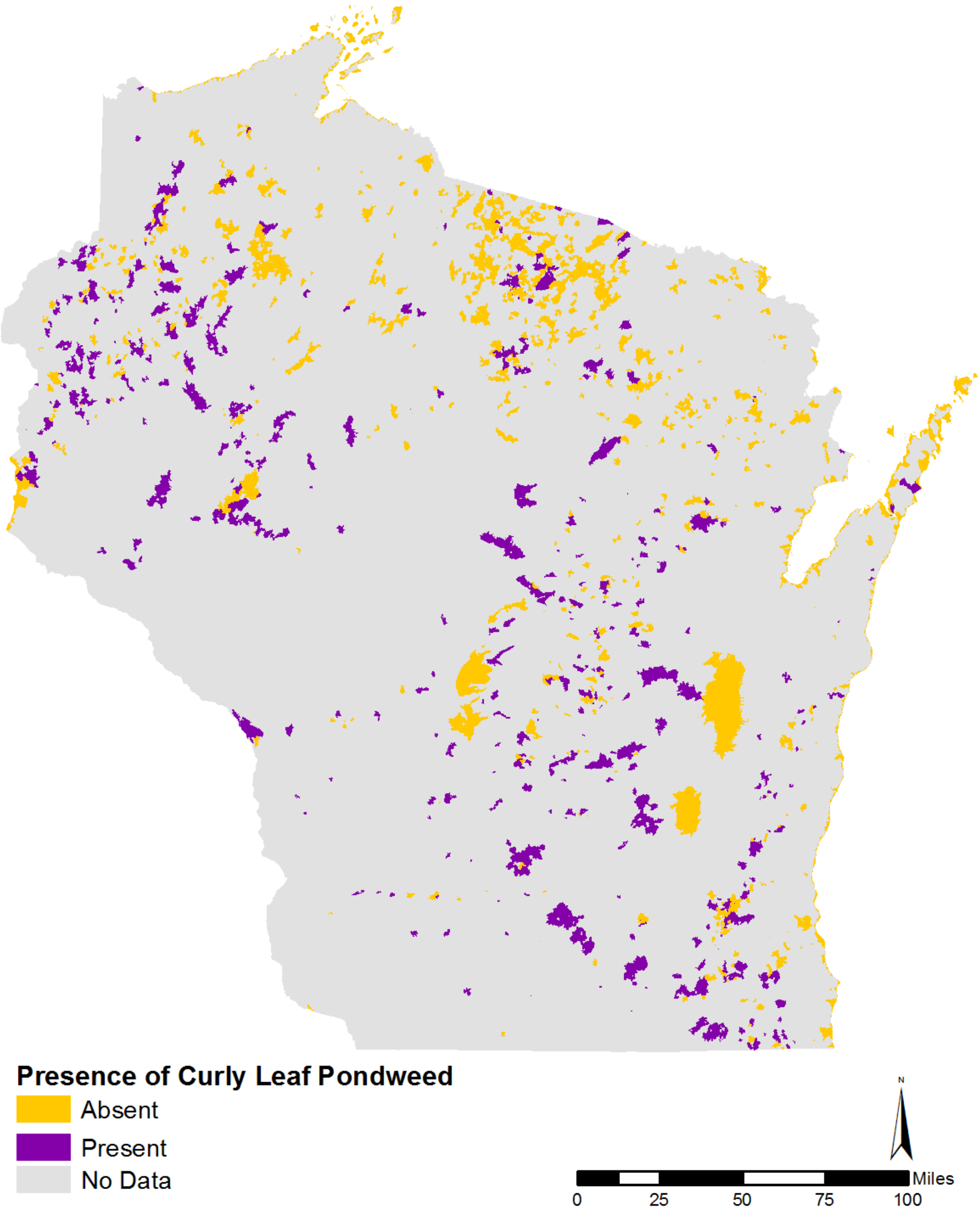

FIGURE 39. PRESENCE OF CURLY LEAF PONDWEED IN LAKES. CATCHMENTS WITH "NO DATA" HAVE NO REPORTS OF SPECIES PRESENCE/ABSENCE.

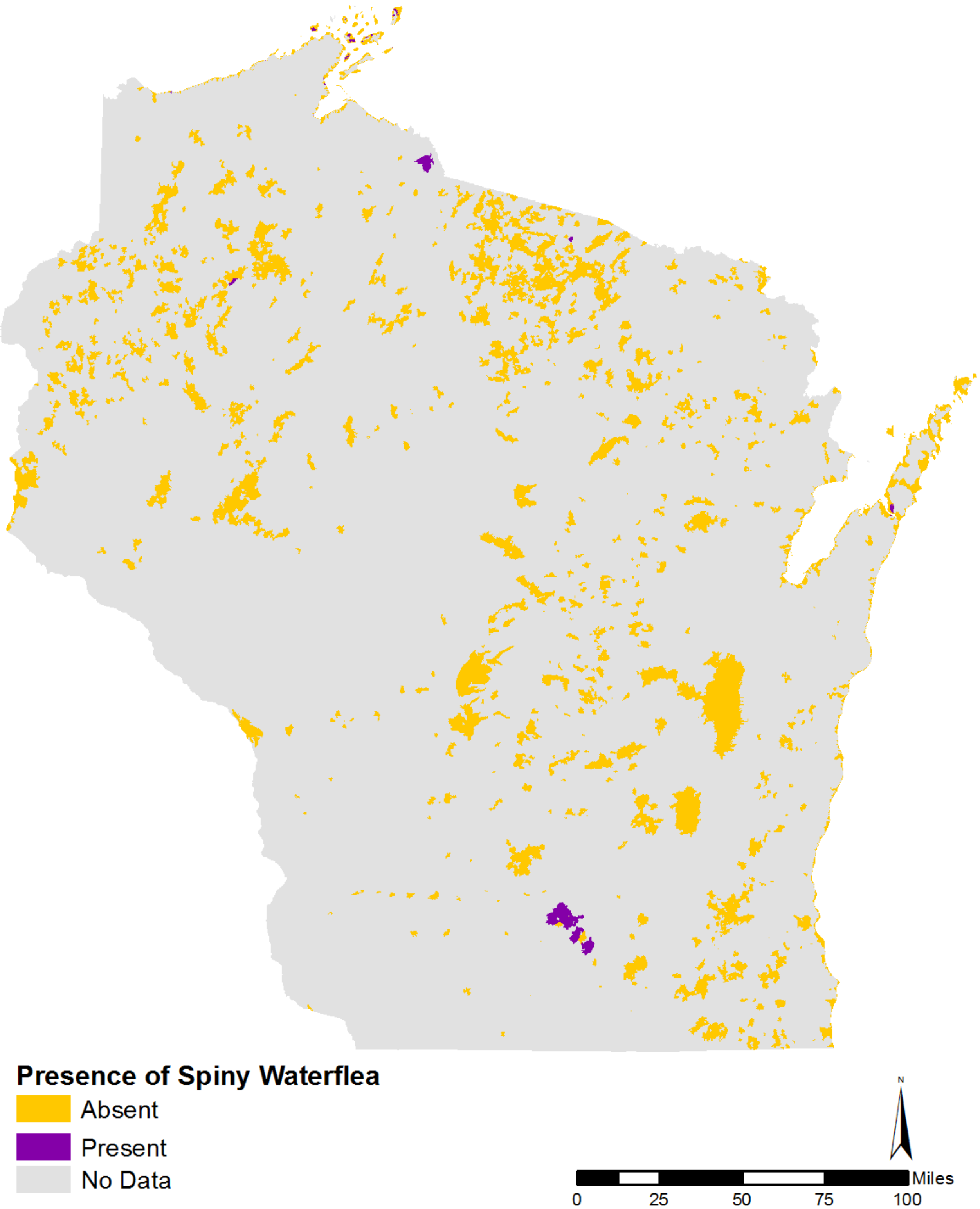

FIGURE 40. PRESENCE OF SPINY WATERFLEA IN LAKES. CATCHMENTS WITH "NO DATA" HAVE NO REPORTS OF SPECIES PRESENCE/ABSENCE.

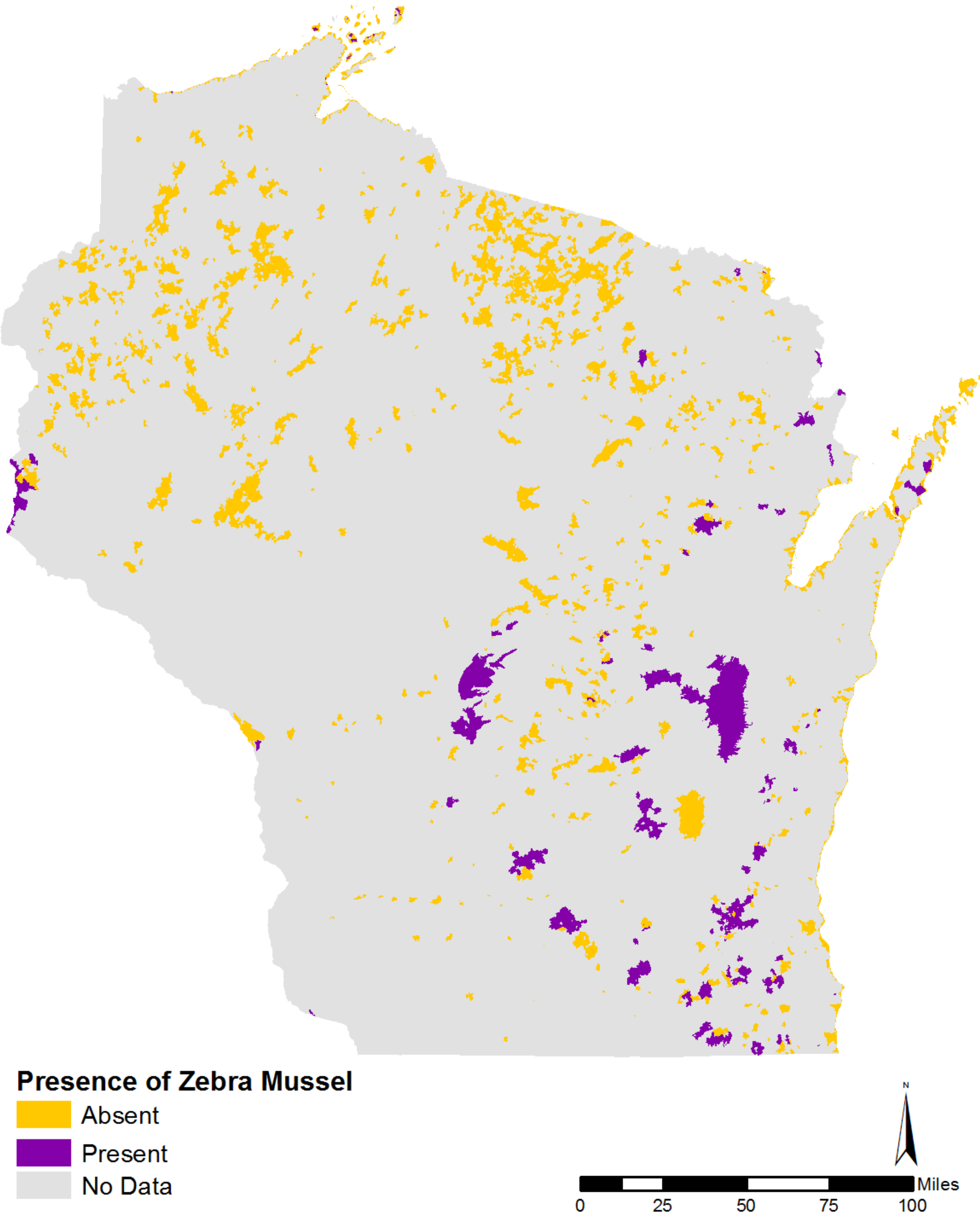

FIGURE 41. PRESENCE OF ZEBRA MUSSEL IN LAKES. CATCHMENTS WITH "NO DATA" HAVE NO REPORTS OF SPECIES PRESENCE/ABSENCE.

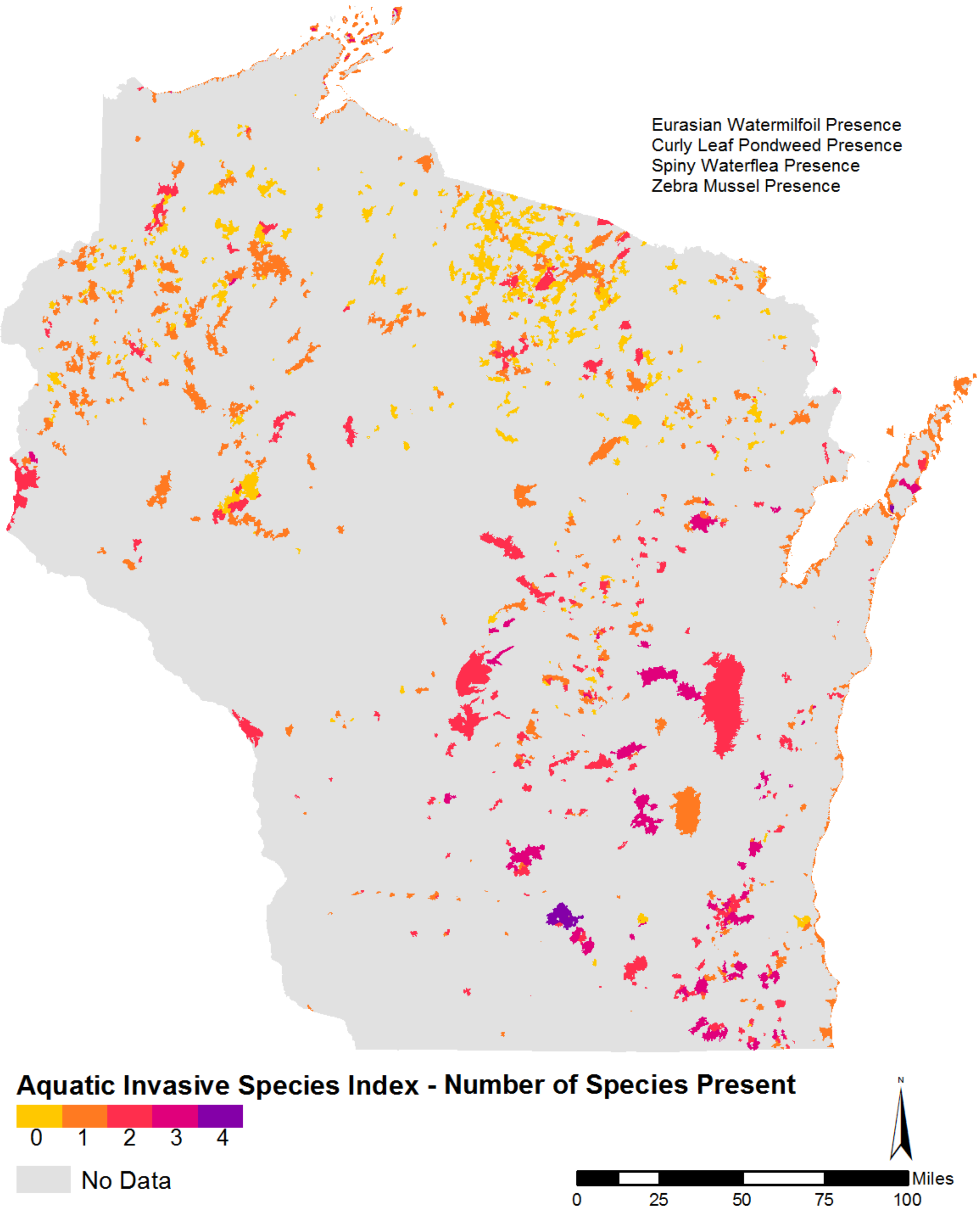

FIGURE 42. AQUATIC INVASIVE SPECIES INDEX SCORES. CATCHMENTS WITH "NO DATA" HAVE NO REPORTS OF SPECIES PRESENCE/ABSENCE.

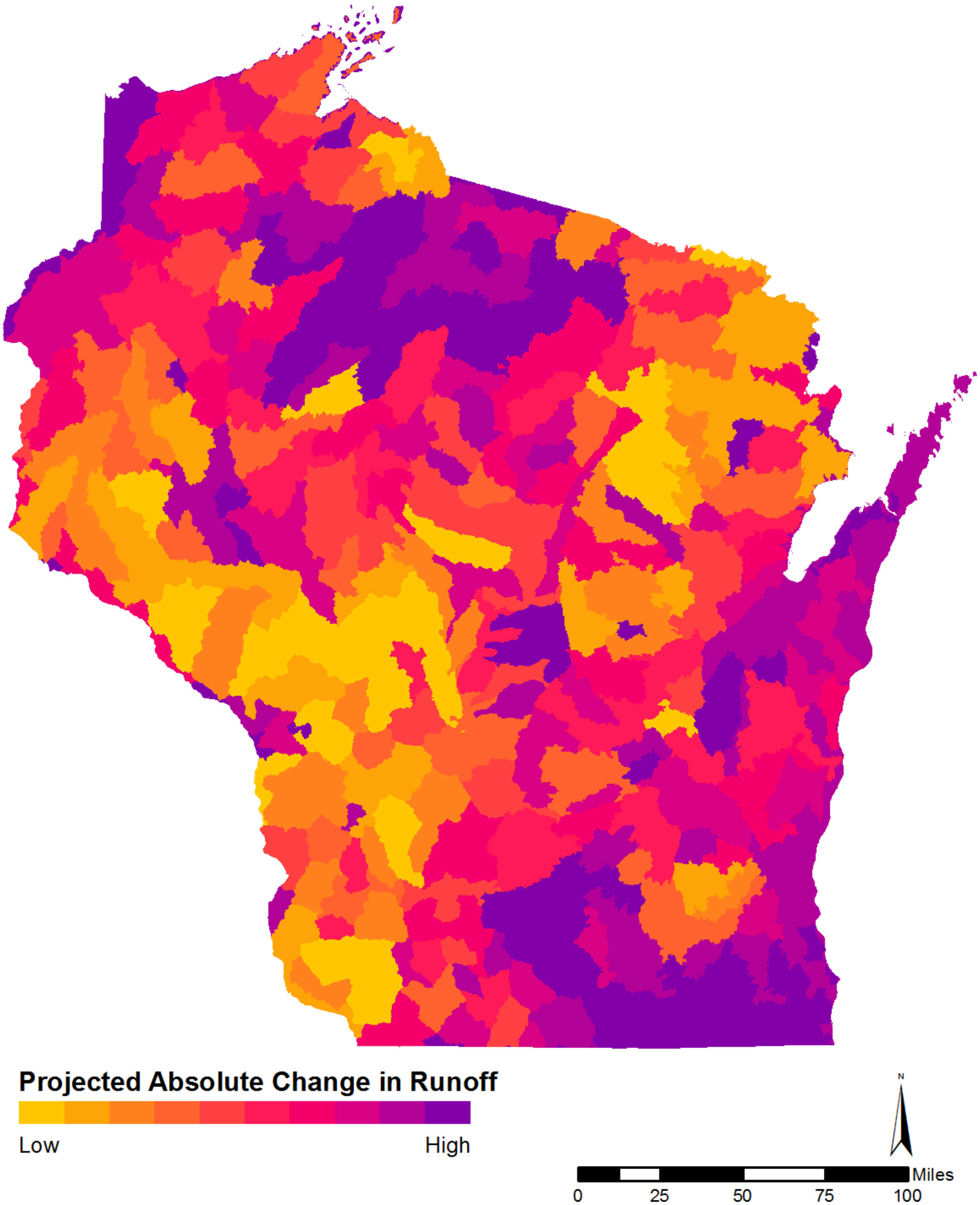

FIGURE 43. PROJECTED ABSOLUTE CHANGE IN GROWING SEASON RUNOFF SCORES.

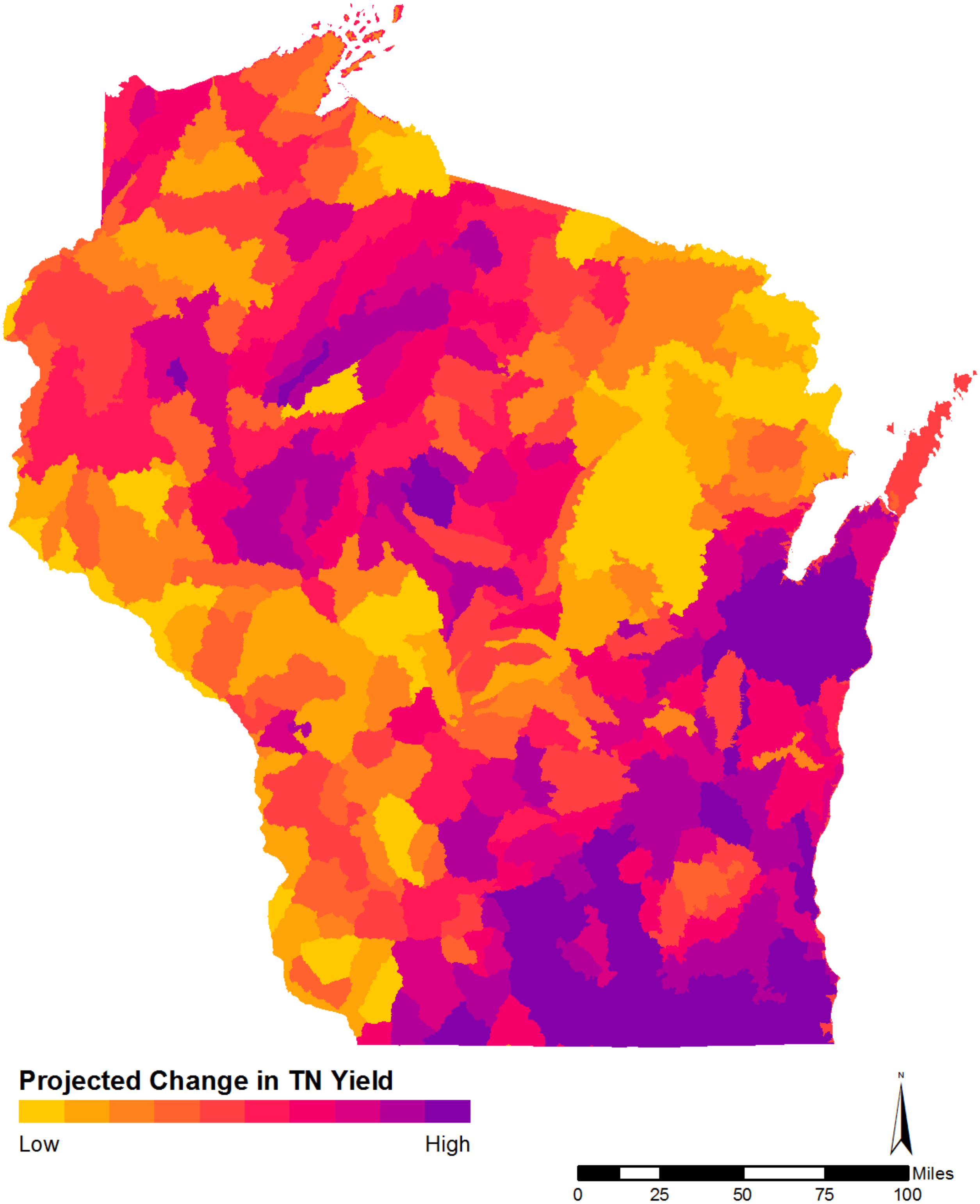

FIGURE 44. PROJECTED CHANGE IN TOTAL NITROGEN (TN) YIELD SCORES.

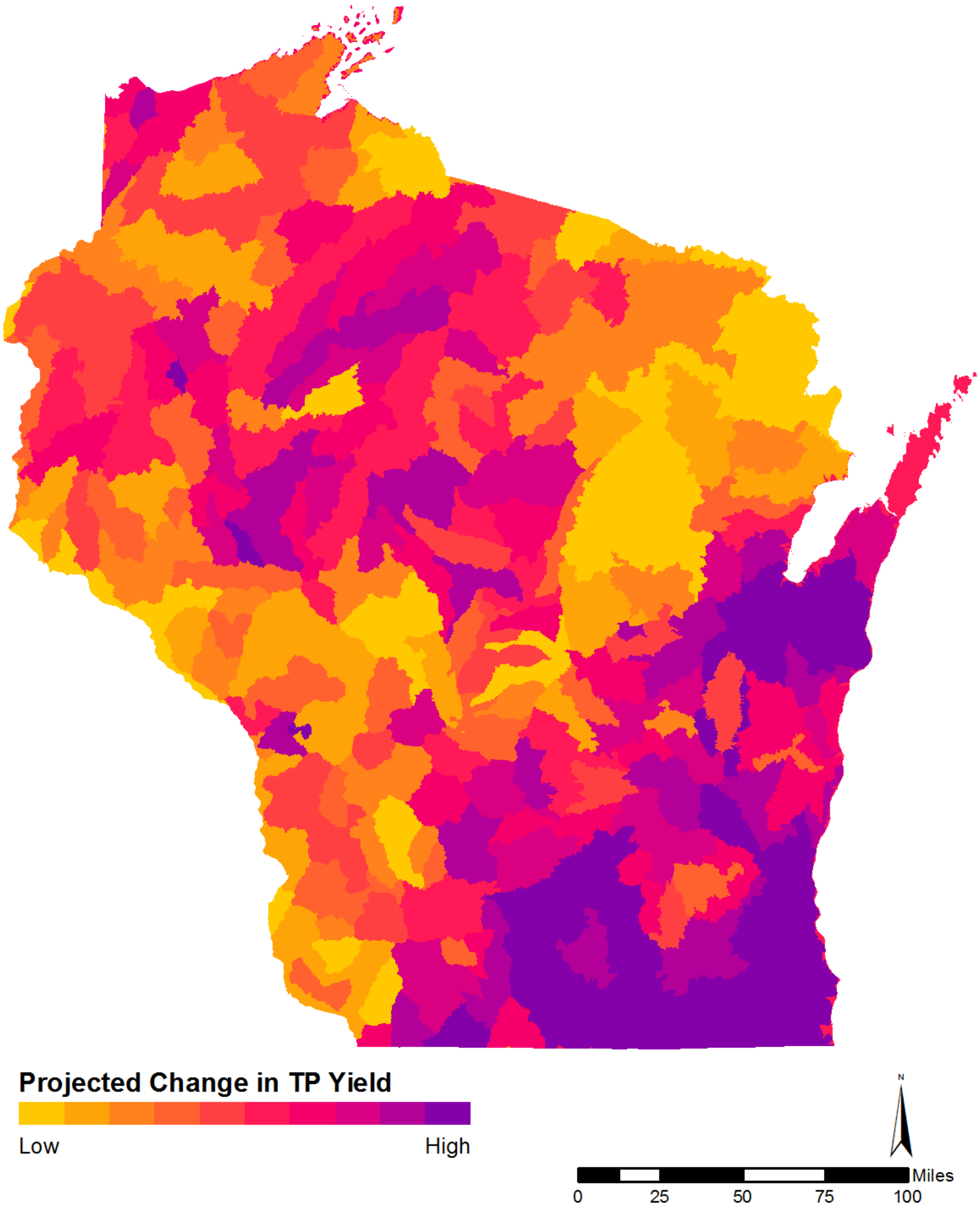

FIGURE 45. PROJECTED CHANGE IN TOTAL PHOSPHORUS (TP) YIELD SCORES.

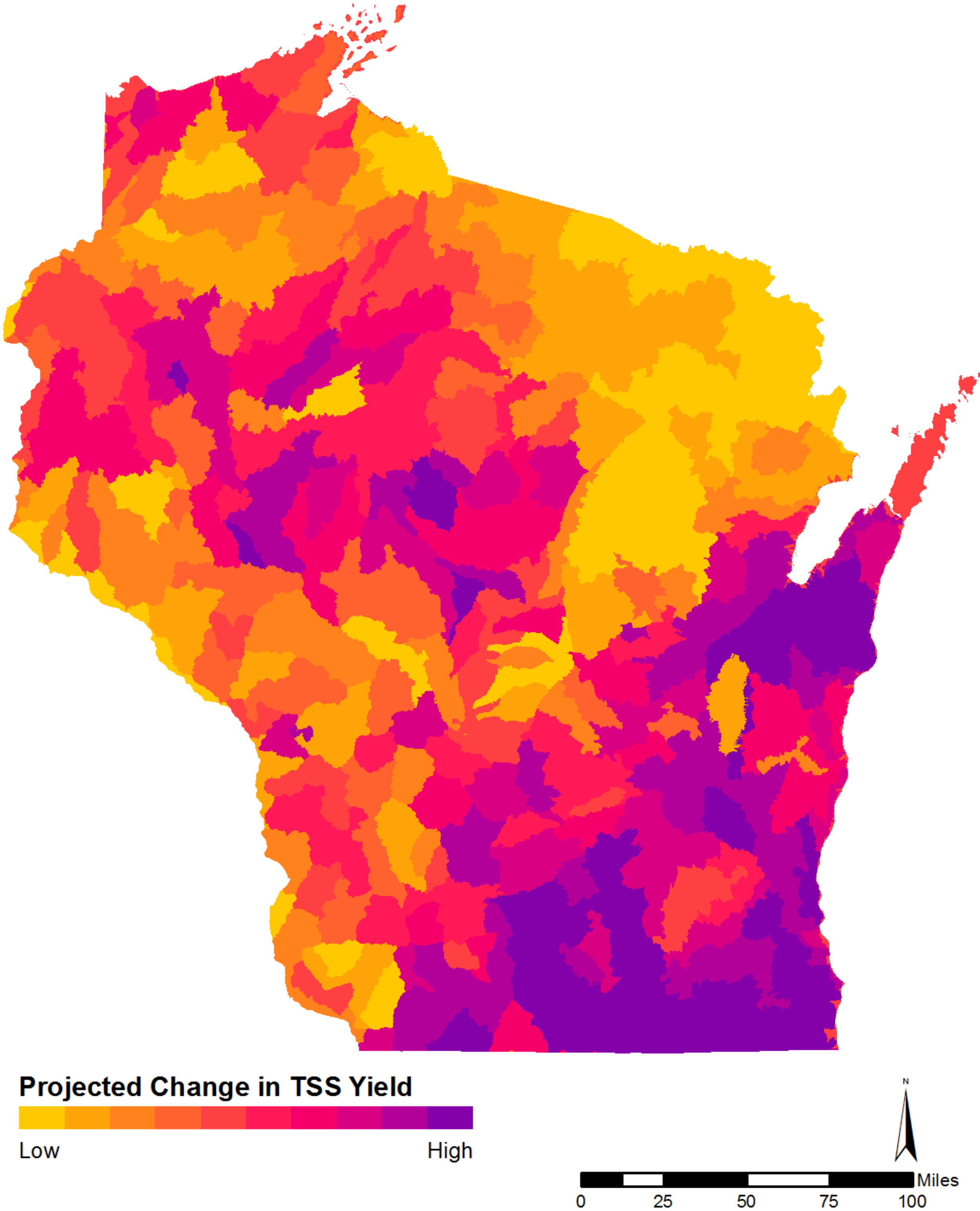

Figure 46. Projected change in total suspended solid (TSS) yield scores.

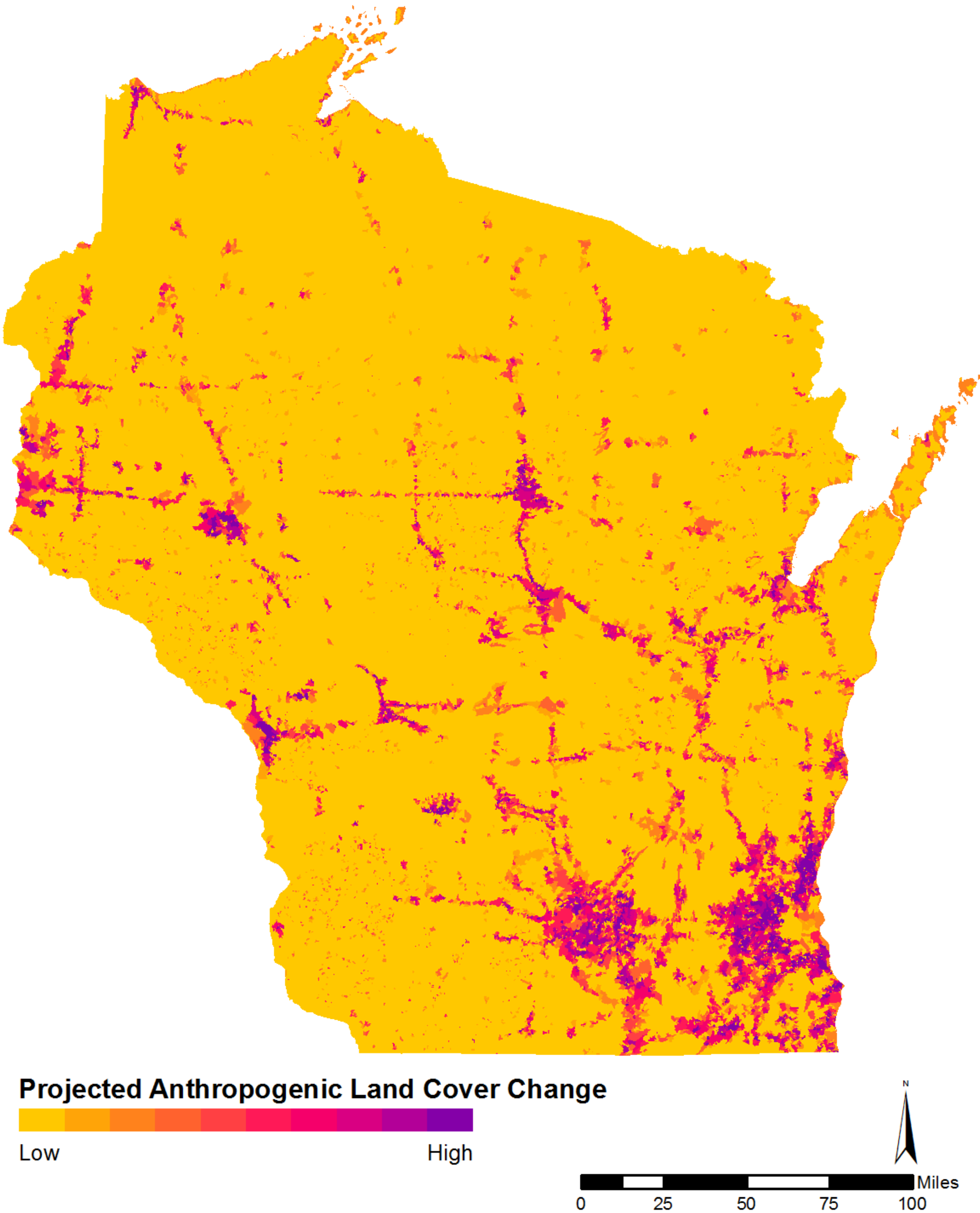

FIGURE 47. PROJECTED ANTHROPOGENIC LAND COVER CHANGE SCORES.

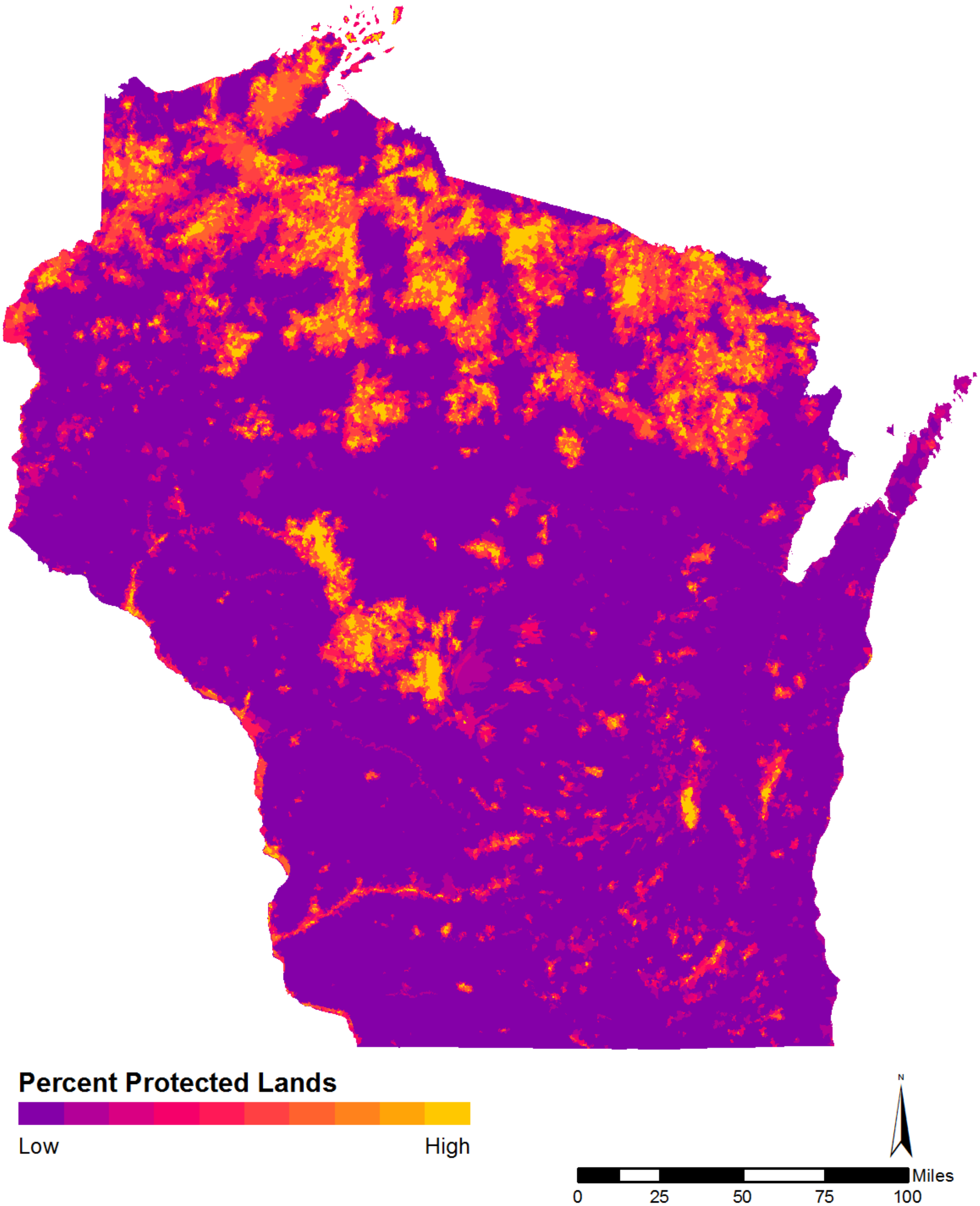

FIGURE 48. PERCENT PROTECTED LANDS SCORES.

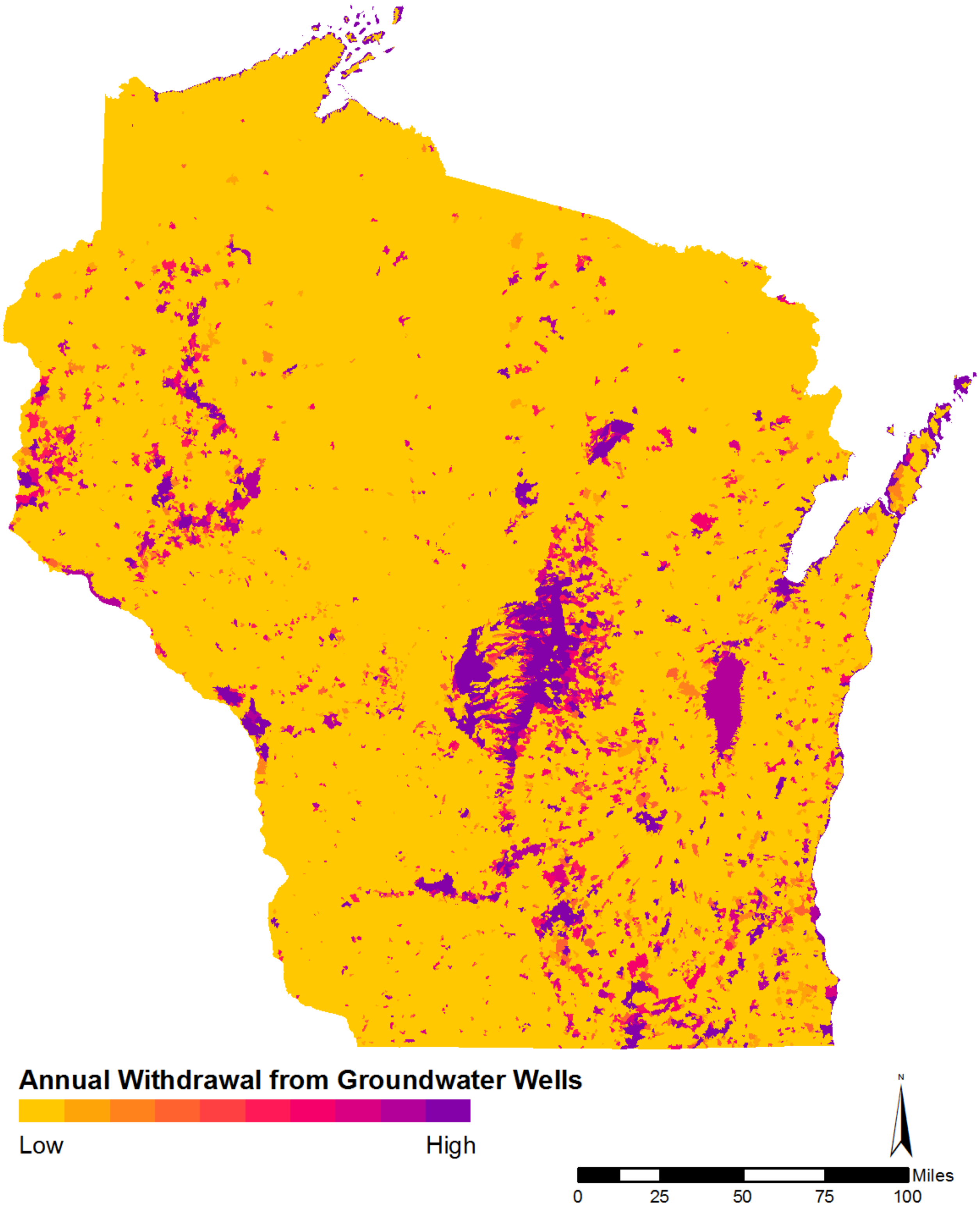

FIGURE 49. ANNUAL GROUNDWATER WITHDRAWAL SCORES.

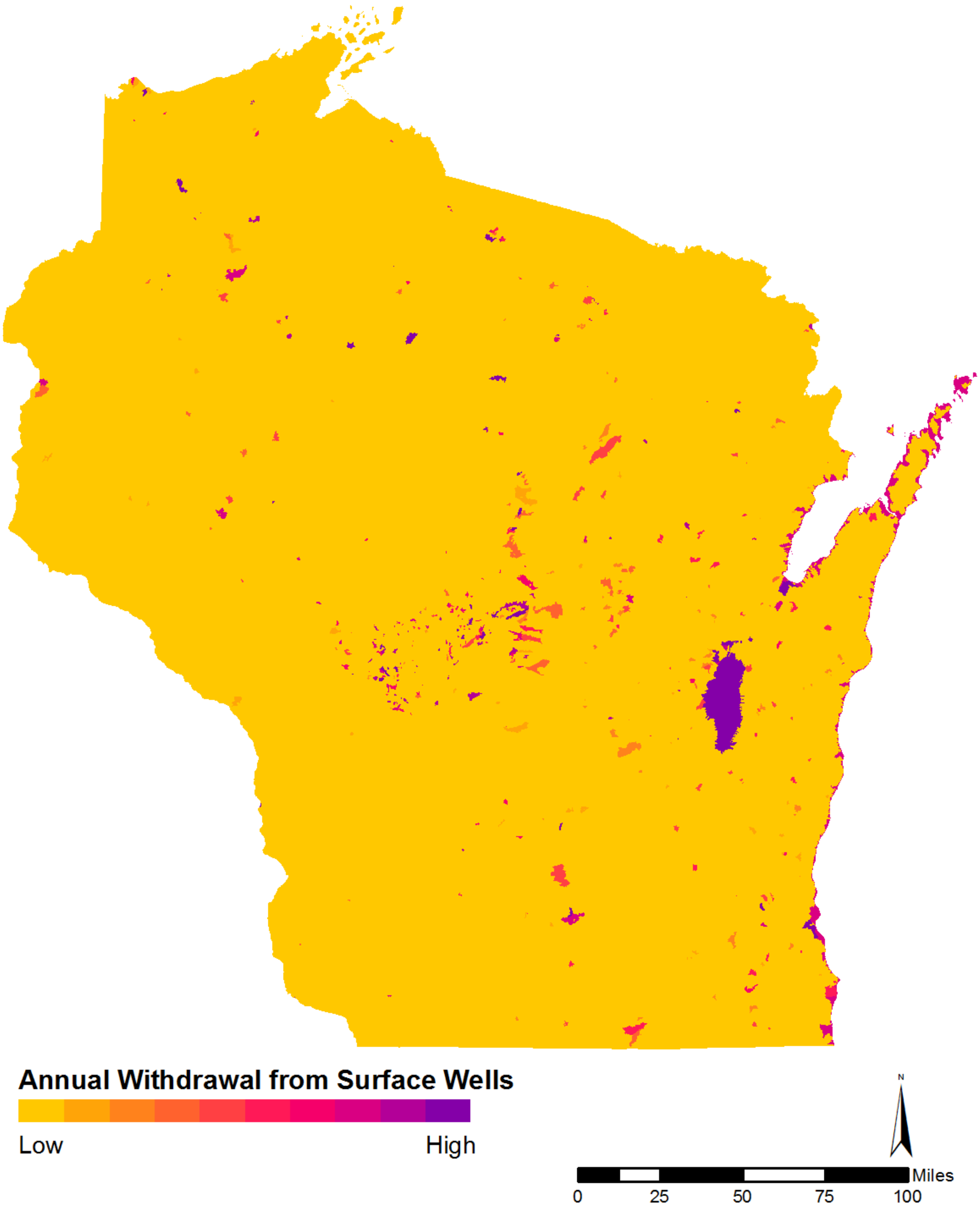

FIGURE 50. ANNUAL SURFACE WATER WITHDRAWAL SCORES.

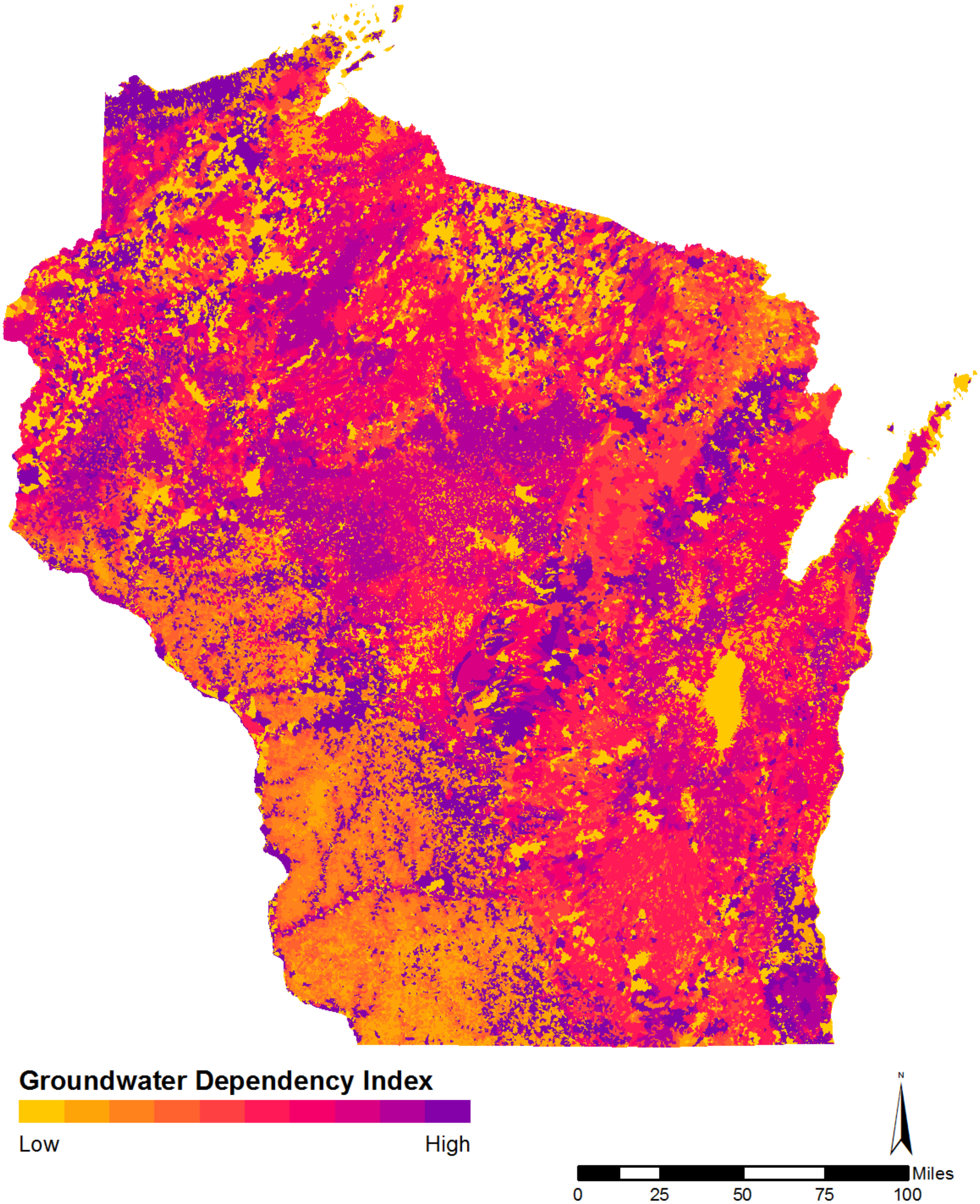

FIGURE 51. GROUNDWATER DEPENDENCY INDEX SCORES.

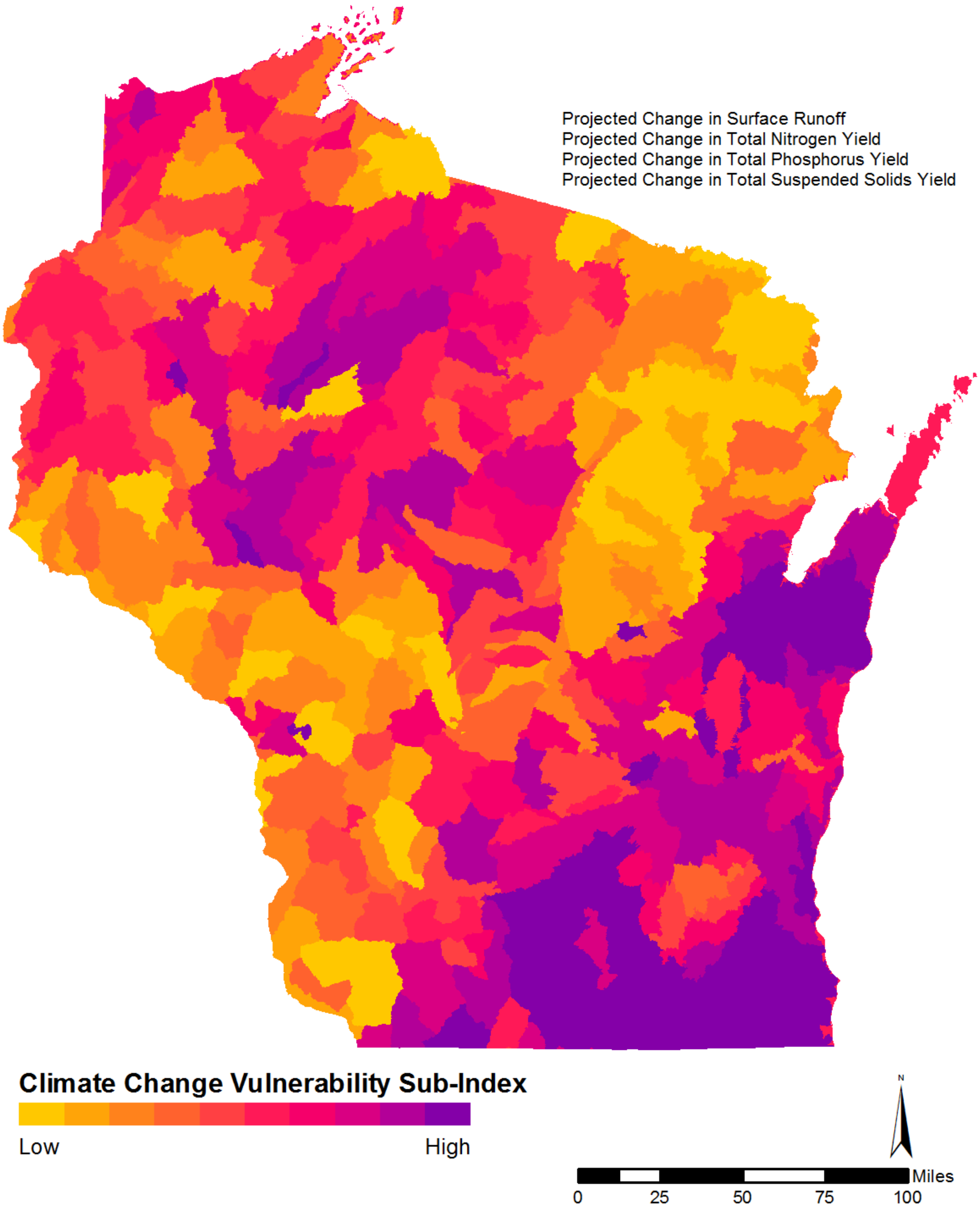

FIGURE 52. CLIMATE CHANGE VULNERABILITY SUB-INDEX SCORES.

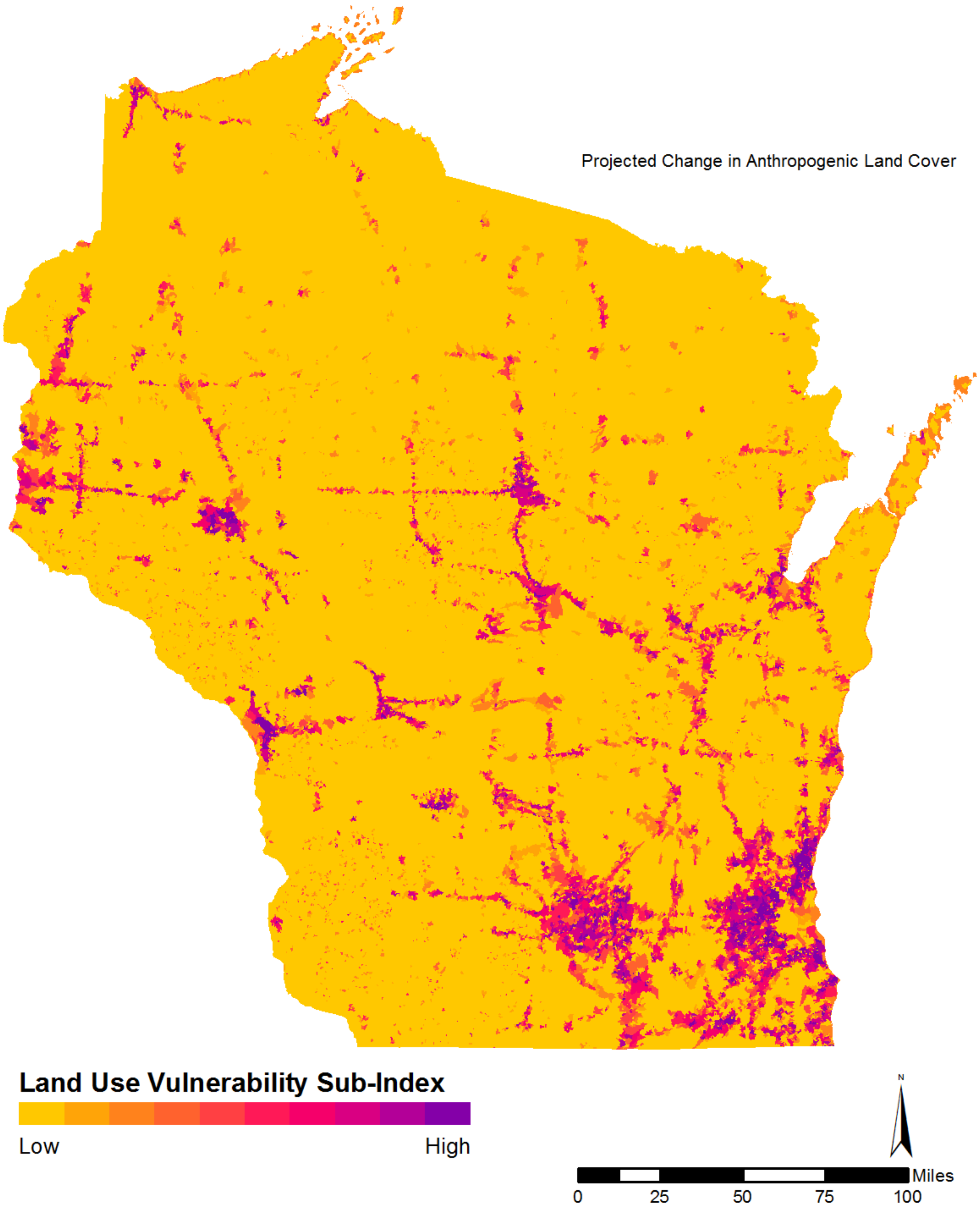

FIGURE 53. LAND COVER VULNERABILITY SUB-INDEX SCORES.

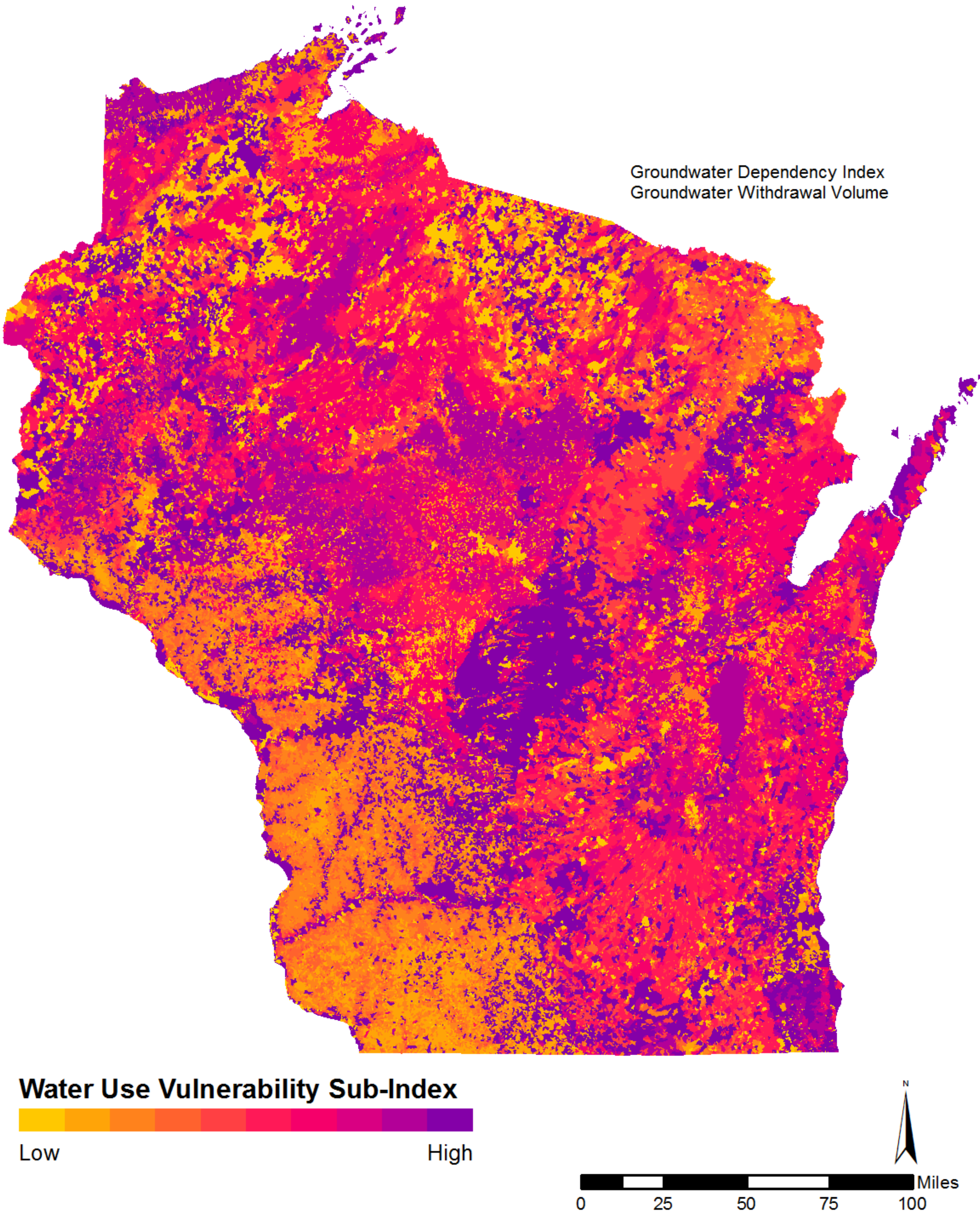

Figure 54. Water Use Vulnerability Sub-Index scores.

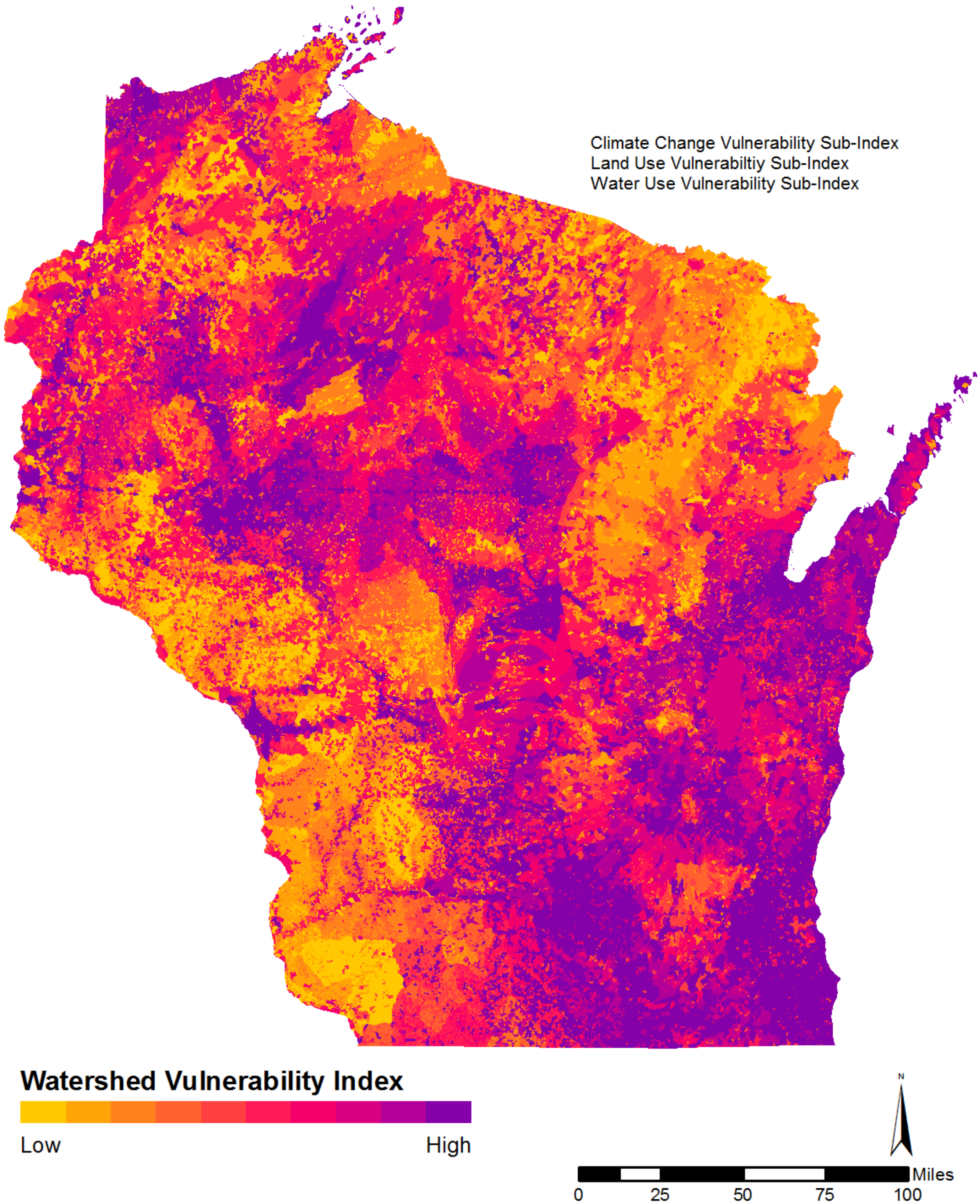

FIGURE 55. WATERSHED VULNERABILITY INDEX SCORES.

APPENDIX B METRIC MODELING

B1 Introduction

Five aquatic ecosystem health metrics are quantified for Wisconsin catchments from Boosted Regression Tree (BRT) models. BRTs are a relatively recent approach to modeling ecological relationships that combine two methods: 1) regression tree modeling; and 2) boosting (Elith, Leathwick, & Hastie, 2008).

A regression tree is comprised of a group of leaves that represent possible response variable outcomes and a group of branches connected to each leaf. Each split in the branch network denotes a relationship between a predictor value and a response outcome evident in the training dataset (i.e., a certain predictor value leads to one known outcome or group of outcomes while another predictor value leads to a different known outcome or group of outcomes). Regression trees are constructed to minimize the error between observed and predicted values.

Boosting is a method for improving model predictions by creating multiple submodels for a response variable rather than one single model. Submodels are developed iteratively, with the first submodel fit to minimize prediction errors in the entire dataset, and subsequent submodels focusing on improving predictions for observations that are poorly predicted by existing submodels. A BRT model therefore consists of several regression trees for any one response variable.

BRT models are well suited for modeling complex ecological relationships and have several advantages over traditional statistical methods (e.g., multiple linear regression or generalized linear modeling). Specifically, BRT models:

- Can be used to predict several data types (e.g., numeric, categorical, or binary) and can include any combination of data types as potential predictors;
- Aare insensitive to outliers in response and predictor datasets and do not require a pre-processing step to evaluate data distributions and remove outliers;
- Capture interactions between individual predictors in the regression tree structure and do not require the use of "interaction terms" as possible predictor variables (e.g., the product of two predictors that together have an interaction effect);
- Have no assumption of a linear relationship between predictor and response variables and account for nonlinear relationships ; and
- Address overfitting without subjective determinations of "significant" predictors.

This Appendix details the methods applied for developing regression models of aquatic ecosystem health metrics and model results.

B2 Methods

Preparation of Response Data

BRT modeling was undertaken to produce a group of statistical models to predict values of aquatic ecosystem health metrics for any catchment in the WDNR 24K hydro geodatabase (WHD). Six potential metrics were selected for modeling (hereafter referred to as *response variables*):

- Stream habitat rating;
- Stream nitrate-nitrite (NO_3-NO_2) concentration;

- Stream total phosphorus (TP) concentration;
- Stream suspended sediment concentration (SSC);
- Stream fish Index of Biotic Integrity (IBI) rating; and
- Stream macroinvertebrate IBI score.

Habitat and biological response variables (habitat rating, fish IBI rating, and macroinvertebrate IBI score) are multimetric indices used by WDNR to assess the overall condition of stream habitat, fish communities, and macroinvertebrate communities in streams throughout the state. Each was selected as a potential metric of aquatic ecosystem health because it integrates multiple characteristics of stream habitat or biology. Water quality response variables (NO_3-NO_2, TP, and SSC) were selected on the basis of data availability and relevance to overall aquatic ecosystem health.

Model development was initiated by acquiring and preparing stream monitoring data for input as observed response variable outcomes. The following paragraphs detail sources of data and processing steps for each response variable.

Stream Habitat Rating - WDNR monitors several habitat characteristics in streams across Wisconsin as part of reach-scale habitat assessments, including the extent of pools, riffles, and bends; channel dimensions; amount of fish cover; riparian buffer width; severity of bank erosion; and substrate properties. These characteristics are combined into an overall stream habitat score and rating (Excellent, Good, Fair, or Poor). Separate scoring systems are used to rate stream habitat in small streams (<10 meters wide), large streams (>10 meters wide), and low-gradient (<3 m/km) streams. Scoring methodologies also vary depending on whether a quantitative or qualitative habitat assessment is performed. As their name implies, quantitative habitat assessments are more rigorous than qualitative habitat assessments.

Stream habitat scores and ratings compiled for modeling were acquired from the WDNR SWIMS database. Data for five habitat rating types were available:

- Habitat scores and ratings for large streams (>10 meters wide), based on results of quantitative habitat assessments;
- Habitat scores and ratings for small streams (<10 meters wide), based on results of quantitative habitat assessments;
- Habitat scores and ratings for low gradient streams (<3 m/km), based on results of quantitative habitat assessments;
- Habitat scores and ratings for large streams (>10 meters wide), based on results of qualitative habitat assessments; and
- Habitat scores and ratings for small streams (<10 meters wide), based on results of qualitative habitat assessments.

Habitat data were processed to produce a single representative rating for each monitored catchment. Processing steps included:

- Filter data to remove ratings for assessments conducted before January 1, 2000;
- Determine the WHD catchment of each monitoring site using reported latitude/longitude coordinates;

- For each rating type (e.g., small stream quantitative), calculate the median of scores reported for sites within catchment boundaries. This provided a single score per rating type per monitored catchment;
- For catchments with median scores for multiple habitat rating types, a single score was selected. Priority was given to low gradient scores, followed by large stream (quantitative), small stream (quantitative), large stream (qualitative), and small stream (qualitative).
- Median habitat scores were converted to categorical ratings (Excellent, Good, Fair, Poor) using thresholds displayed in Table 7.

Note that categorical habitat *ratings* were modeled rather than numeric habitat *scores*. This is because scores are not directly comparable across the five different scoring systems used by WDNR. For example, a score of 75 corresponds to habitat in "excellent" condition for small streams but "good" condition for large streams. An attempt to model relationships between stream habitat condition and landscape predictors using habitat scores would be hindered by the lack of comparability between habitat scoring systems.

TABLE 7. THRESHOLDS APPLIED TO CONVERT NUMERIC STREAM HABITAT SCORES TO CATEGORICAL RATINGS.

Stream Habitat Type	Rating			
	Excellent	Good	Fair	Poor
Large Stream	80-100	60-79	20-59	<20
Small Stream, Low Gradient Stream	75-100	50-74	25-49	<25

Nitrate-Nitrite and Suspended Sediment – Samples of stream NO_3-NO_2 concentration and stream SSC were acquired from WDNR SWIMS. Samples were processed to produce a representative NO_3-NO_2 concentration and a representative SSC for each monitored catchment. Processing steps included:

- Filter data to remove samples collected before January 1, 2000 or samples that did not meet field or lab QA/QC standards;
- For samples with concentrations reported as "non-detect", substitute the reported detection limit;
- Determine the catchment of each monitoring site using reported latitude/longitude coordinates;
- For each monitored catchment, calculate the median of samples reported for sites within catchment boundaries.

Total Phosphorus – Median TP concentrations for Wisconsin streams reported in Robertson et al. (2006) were acquired from USGS (http://pubs.usgs.gov/pp/pp1722/). Stream TP data were processed to produce a representative TP concentration for each monitored catchment. Processing steps included:

- Determine the catchment of each monitoring site using reported latitude/longitude coordinates;
- For each monitored catchment, calculate the median of TP concentrations reported for sites within catchment boundaries.

Fish IBI and Macroinvertebrate IBI – WDNR monitors the number and proportion of several taxonomic and functional fish and macroinvertebrate groups in streams throughout the state. For each monitored site, fish community variables are combined into an overall fish IBI score and rating (Excellent, Good, Fair, or Poor). Similarly, macroinvertebrate community variables are combined into an overall macroinvertebrate IBI score and rating.

Fish and macroinvertebrate IBI data were acquired from WDNR SWIMS. Data for three fish IBI rating types were available:

- Fish IBI scores and ratings for coldwater streams;
- Fish IBI scores and ratings for intermittent streams; and
- Fish IBI scores and ratings for warmwater streams.

Macroinvertebrate IBI data included scores and ratings for wadeable streams only. IBI data were processed to produce a representative macroinvertebrate IBI score and a representative fish IBI rating for each monitored catchment. Processing steps included:

- Macroinvertebrate IBI score
  - Filter data to remove scores for assessments conducted before January 1, 2000;
  - Determine the catchment of each monitoring site using reported latitude/longitude coordinates; and
  - For each monitored catchment, calculate the median of macroinvertebrate IBI scores reported for sites within catchment boundaries.
- Fish IBI rating
  - Filter data to remove scores for assessments conducted before January 1, 2000;
  - Determine the catchment of each monitoring site using reported latitude/longitude coordinates;
  - For each fish IBI rating type (e.g., coldwater fish IBI), calculate the median of scores reported for sites within catchment boundaries. This step produced a single fish IBI score per rating type per catchment;
  - For catchments with median scores for multiple fish IBI rating types, a single score was selected. The appropriate score for a given catchment was determined from its natural aquatic community type. WDNR has assigned a natural aquatic community type (coldwater fish, warm headwater fish, warm mainstem fish, etc.) to each WHD catchment based on stream size and estimated water temperature.
  - Median fish IBI scores were converted to ratings using thresholds displayed in Table 8.

Note that categorical fish IBI *ratings* were modeled rather than numeric fish IBI *scores*. Like stream habitat scores, fish IBI scores are not directly comparable across the three different scoring systems used by WDNR. For example, a fish IBI score of 75 corresponds to fish communities in "excellent" condition for warmwater streams but "good" condition for coldwater and intermittent streams. An attempt to model relationships between fish community condition and landscape predictors using fish IBI scores would be hindered by the lack of comparability between fish IBI types.

TABLE 8. THRESHOLDS APPLIED TO CONVERT NUMERIC FISH IBI SCORES TO CATEGORICAL RATINGS.

Fish IBI Type	Rating			
	Excellent	Good	Fair	Poor
Coldwater	81-100	51-80	21-50	0-20
Intermittent	91-100	61-90	31-60	0-30
Warmwater	66-100	51-65	31-50	0-30

Table 9 lists the number of Wisconsin catchments with observations of each response variable and summary statistics. After processing catchment-specific values, the data distribution of each continuous response variable (NO_3-NO_2, TP, SSC, and macroinvertebrate IBI score) was reviewed using histograms. Logarithmic and quarter root transformations were applied as needed so that all variables were approximately normally distributed. Categorical response variables (habitat rating and fish IBI rating) were assumed to follow a multinomial distribution.

Table 9. Summary statistics for aquatic ecosystem health response variables.

Response Variable	No. of Catchments	Minimum	Maximum	Mean	Median
Habitat Rating	3,445	-	-	-	-
Nitrate-Nitrite Concentration (mg/L)	2,022	1	24.9	2.0	0.9
Total Phosphorus Concentration (µg/L)	239	12	1641	115.3	84
Suspended Sediment Concentration (mg/L)	332	2	372	19.4	7
Fish IBI Rating	2,566	-	-	-	-
Macroinvertebrate IBI Score	3,483	-8.3	12.3	5.5	5.4

Preparation of Predictor Data

Predictors of aquatic ecosystem health included in BRT modeling are landscape variables that describe land cover, soils, topography, geology, and anthropogenic features of WHD catchments (Table 10). Predictors were selected on the basis of data availability and relevance to aquatic ecosystem health. A predictor database was prepared by compiling predictor values for all catchments in Wisconsin at both incremental and cumulative scales. Incremental values reflect within-catchment conditions only. Cumulative values reflect conditions throughout all upstream catchments.

Pre-calculated values of many predictors were provided by WDNR (Matt Diebel, personal communication). Other predictors were quantified as part of this effort from existing geospatial datasets. Sources of predictor values are listed in Table 10.

Table 10. Landscape variables considered for aquatic ecosystem health modeling. Predictors included in final models are denoted with an "I" if incremental values were used and a "C" if cumulative values were used.

Predictor Variable Name	Source(s)[a]	Scale
Channel Sinuosity	WDNR(1)	I
Channel Centroid Latitude	WDNR(1)	I
Channel Centroid Longitude	WDNR(1)	I
Channel Dominant Surface Geology Class	WDNR(1)	I
Channel Dominant Bedrock Geology Class	WDNR(1)	I
Channel Dominant Bedrock Depth Class	WDNR(1)	I
Flowpath Distance to Large Lake	WDNR(1)	I
Flowpath Distance to Medium Lake	WDNR(1)	I
Flowpath Distance to Small Lake	WDNR(1)	I
Downstream Flowpath Distance to Large River	WDNR(1)	I
Downstream Flowpath Distance to Medium River	WDNR(1)	I
Riparian Percent Natural Land Cover	WDNR(1)	I, C

Predictor Variable Name	Source(s)[a]	Scale
Riparian Percent Agricultural Land Cover	WDNR(1)	I, C
Riparian Percent Urban Land Cover	WDNR(1)	I, C
Riparian Dominant Bedrock Depth Class	WDNR(1)	I, C
Riparian Dominant Bedrock Geology Class	WDNR(1)	I, C
Riparian Dominant Surficial Geology Class	WDNR(1)	I, C
Riparian Mean Darcy Value	WDNR(1)	I, C
Riparian Mean Slope	WDNR(1)	I, C
Riparian Mean Soil Permeability	WDNR(1)	I, C
Active River Area Percent Natural Land Cover	NLCD	I, C
Active River Area Percent Agricultural Land Cover	NLCD	I, C
Active River Area Percent Urban Land Cover	NLCD	I, C
Watershed Percent Natural Land Cover	NLCD	I, C
Watershed Percent Agricultural Land Cover	NLCD	I, C
Watershed Percent Urban Land Cover	NLCD	I, C
Cumulative Watershed Area	WDNR(1)	C
Watershed Dominant Bedrock Depth Class	WDNR(1)	I, C
Watershed Dominant Bedrock Geology Class	WDNR(1)	I, C
Watershed Dominant Surficial Geology Class	WDNR(1)	I, C
Watershed Mean Darcy Value	WDNR(1)	I, C
Watershed Mean Slope	WDNR(1)	I, C
Watershed Mean Soil Permeability	WDNR(1)	I, C
Watershed Percent Wetlands Remaining	NLCD & SSURGO	I, C
Annual Groundwater Withdrawal	WDNR(2)	I
Annual Surface Water Withdrawal	WDNR(2)	I
Daily Capacity of Groundwater Wells	WDNR(2)	I
Daily Capacity of Surface Water Wells	WDNR(2)	I

[a] Data sources: WDNR(1) – Pre-calculated by WDNR; NLCD – Calculated from 2006 National Land Cover Dataset; NLCD & SSURGO – Calculated from 2006 National Land Cover Dataset wetland area and Soil Survey Geographic Database hydric soil area; WDNR(2) – Calculated from 2011 WDNR Water Use Registration Program data

Model Development

BRT models were developed using R software, the *gbm* package (Ridgeway, 2013), and the *dismo* package (Hijmans, Phillips, Leathwick, & Elith, 2013). Key parameters for BRT modeling are the learning rate and tree complexity, which determine the number of regression trees in the full (boosted) model. With too few trees, the model is underfit and does not adequately describe relationships in the data. Too many trees create an overfitted model that provides poor predictions for the sites not used to train the model.

The optimal number of trees for each BRT model was determined using the k-fold cross-validation (CV) methodology described in Elith et al. (2008). This method randomly divides the full dataset into 10 subsets. Each subset is further divided into a training dataset, used for developing a BRT model, and a validation dataset, used for assessing predictive error. The optimal number of trees is the number that minimizes mean prediction error in the validation portion of the 10 CV subsets, and a final model is developed using the optimal number of trees and the full dataset. Here, the CV method was modified slightly by first setting aside a randomly selected portion (25%) of the full dataset for independent validation of final model predictions.

Observed response variable outcomes can be weighted for model fitting so that more emphasis is placed on minimizing predictive error for certain observations relative to others. Weighting was applied for the stream habitat rating model due to the skewed distribution of observations (52% of observed habitat ratings were "Good"; 25% were "Fair"; 20% were "Excellent"; and 4% were "Poor"). Observations were weighted in inverse proportion to their frequency of occurrence, with "Poor" ratings assigned the highest weight and "Good" ratings assigned the lowest weight. Weights were calculated for each rating as:

$$Weight = 1 - Proportion$$

Model Evaluation

A weight-of-evidence approach was used to evaluate model performance and select a final group of aquatic ecosystem health metrics. Models for continuous response variables (NO_3-NO_2, TP, SSC, and macroinvertebrate IBI score) were evaluated from the correlation between observations and predictions. Three correlation statistics were examined:

- Training Correlation – Pearson correlation coefficient for observations in the training dataset and predictions generated by the final model. This is a *goodness-of-fit statistic* for the final model.
- Cross Validation (CV) Correlation – Mean Pearson correlation coefficient for observations in the 10 CV validation subsets and predictions generated by CV models with the optimal number of regression trees. This is a *predictive performance statistic* for CV models.
- Independent Correlation – Pearson correlation coefficient for observations in the independent validation dataset and predictions generated by the final model. This is a *predictive performance statistic* for the final model.

Models for categorical response variables (stream habitat rating and fish IBI rating) were evaluated from their classification success rates. Classification success rates describe the percentage of catchments that are correctly classified "Excellent", "Good", "Fair", or "Poor". Two groups of classification success rates were examined:

- Training Success Rate – Classification success rate for observations in the training dataset based on predictions generated by the final model. This is a *goodness-of-fit statistic* for the final model.
- Validation Success Rate – Classification success rate for observations in the independent validation dataset based on predictions generated by the final model. This is a *predictive performance statistic* for the final model.

Models were also evaluated according to relative influence scores for predictor variables. Relative influence scores describe the importance of a given predictor on modeled responses relative to other predictors. Scores range from 0 to 100, with 100 corresponding to the highest possible influence. Relative influence scores are determined from the number of times a predictor appears in a regression tree and the average improvement in model performance resulting from the presence of the predictor.

B3 Results & Discussion

Model performance statistics for continuous response variables are displayed in Table 11, and scatterplots of observed and predicted values are displayed in Figure 56. Training correlation is highest for TP (0.96) and lowest for macroinvertebrate IBI (0.78). Among water quality variables, the pattern of goodness-of-fit between observations and predictions (highest for TP, lowest for SSC) is consistent with previous attempts to estimate nutrients and sediment in Wisconsin streams through regression modeling (Diebel, et al., 2009).

For each model, training correlation is greater than CV correlation, indicating that performance suffers from some overfitting, particularly for suspended sediment. CV and independent correlations are in line with one another, supporting the use of the CV methodology to optimize model parameters.

TABLE 11. CORRELATION COEFFICIENTS FOR CONTINUOUS RESPONSE VARIABLES.

Response Variable	Correlation		
	Training	Cross Validation	Independent Validation
Nitrate-Nitrite	0.94	0.82	0.82
Total Phosphorus	0.96	0.79	0.70
Suspended Sediment	0.88	0.58	0.57
Macroinvertebrate IBI Score	0.78	0.65	0.64

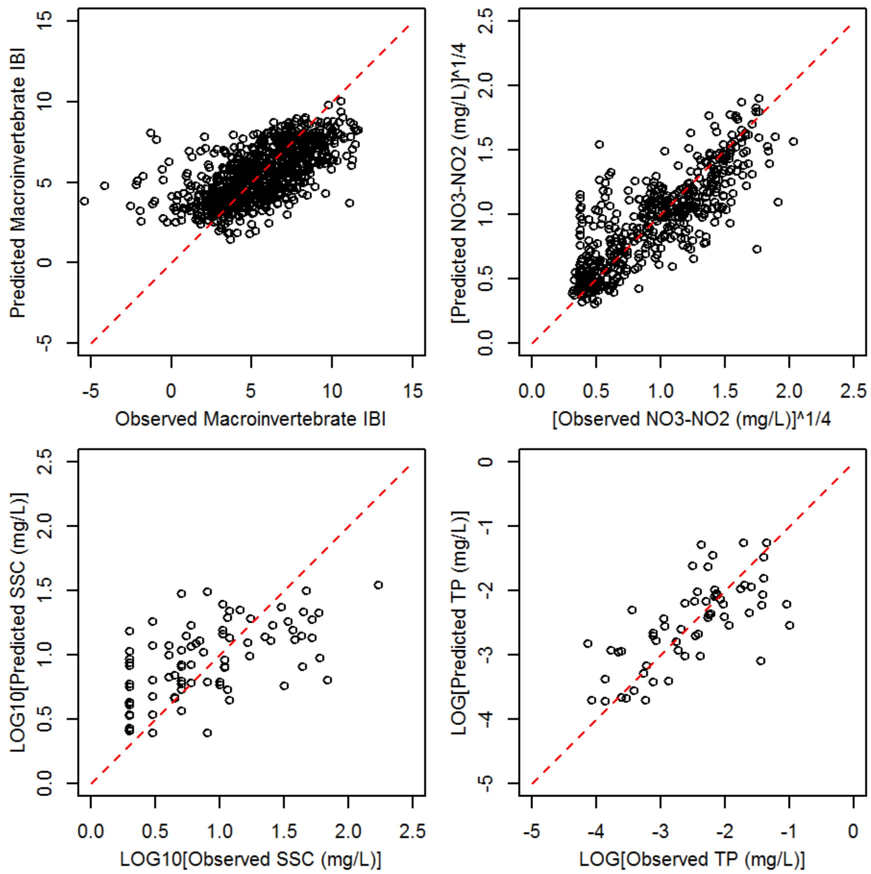

FIGURE 56. SCATTERPLOTS OF OBSERVED AND PREDICTED VALUES OF CONTINUOUS RESPONSE VARIABLES FOR CATCHMENTS IN THE INDEPENDENT VALIDATION DATASET.

Model performance statistics for categorical response variables are displayed in Table 12. Training classification success rates are similar for stream habitat rating (56% of sites correctly classified) and fish IBI rating (55% of sites correctly classified). For reference, the "by-chance" success rate is also shown in Table 12, calculated from the distribution of observed ratings as the expected success rate if catchments were randomly assigned a rating. Training success rates are 51% and 113% higher than by-chance rates for stream habitat and fish IBI, respectively.

Similar to models for continuous response variables, overfitting is evident in models of stream habitat rating and fish IBI rating. Validation success rates are lower than training values by several percentage points, with fish IBI rating showing a larger discrepancy between training and validation performance.

TABLE 12. CLASSIFICATION SUCCESS RATES FOR CATEGORICAL RESPONSE VARIABLES.

Response Variable	Model Success Rate		By-Chance Success Rate
	Training	Validation	
Stream Habitat Rating	56%	49%	37%
Fish IBI Rating	55%	40%	26%

The contingency table for observed and predicted stream habitat ratings for validation catchments (Table 13) shows that model performance varies considerably by rating category. The classification success rate for catchments with a "good" stream habitat rating (67%) is notably larger than that of "excellent" (25%), "fair" (38%), or "poor" (3%) rated catchments. This is strongly related to the uneven distribution of ratings in the observation dataset, in which "good" condition catchments dominate.

TABLE 13. STREAM HABITAT RATING CONTINGENCY TABLE FOR VALIDATION CATCHMENTS.

		Predicted				
		Excellent	Good	Fair	Poor	Success Rate
Observed	Excellent (178 sites)	44	119	14	1	25%
	Good (449 sites)	51	303	93	2	67%
	Fair (200 sites)	14	107	76	3	38%
	Poor (34 sites)	2	9	22	1	3%
	Error Rate	40%	56%	37%	14%	-

The contingency table for observed and predicted fish IBI ratings for validation catchments (Table 14) shows a more even performance by rating category. Classification success rate is highest for catchments with a "poor" fish IBI rating (54%), followed by "good" (39%), "excellent" (34%), and "fair" (31%) rated catchments.

TABLE 14. FISH IBI RATING CONTINGENCY TABLE FOR VALIDATION CATCHMENTS.

		Predicted				
		Excellent	Good	Fair	Poor	Success Rate
Observed	Excellent (122 sites)	41	38	21	22	34%
	Good (184 sites)	22	72	37	53	39%
	Fair (167 sites)	14	46	51	56	31%
	Poor (169 sites)	7	41	29	92	54%
	Error Rate	49%	37%	37%	41%	-

Relative influence plots for aquatic ecosystem health response variables are provided in Figure 57 through Figure 62. Each plot displays relative influence scores for the 10 most influential predictors of metric values. Influential predictors characterize a combination of natural watershed characteristics and anthropogenic features. For most models, predictors with the highest influence are expected based on known relationships between landscape variables (e.g., extent of agricultural or urban land cover) and stream conditions. One exception is the fish IBI rating model, in which several natural characteristics (e.g., cumulative watershed area, channel latitude) have the greatest influence on predicted ratings (Figure 61). This contrasts with the fish IBI scoring methodology used by WDNR, which is designed to control for natural variability and reflect the influence of key stressors on fish communities.

Results of BRT modeling indicate that models of stream nitrate-nitrite, total phosphorus, and suspended sediment concentrations, macroinvertebrate IBI score, and stream habitat rating are adequate for supporting a statewide or regional screening-level assessment of watershed protection and restoration priorities. Predictions generated by these models for all WHD catchments are used to develop the indices of aquatic ecosystem health presented in Section 3 of this report. The application of model predictions for uses requiring highly accurate estimates of reach-scale conditions is not recommended.

Fish IBI is not included as a metric of aquatic ecosystem health due to model structure and performance. The combination of a low classification success rate (40% for validation catchments) and high influence of natural landscape variables on predicted ratings indicates that the model is likely reflecting sampling bias in the monitoring dataset acquired for model development. For example, the monitoring dataset includes a spurious correlation between stream size and IBI rating, with median watershed area equal to 7 square miles for excellent condition streams and 3.6 square miles for poor condition streams. This contributes to a disproportionately large number of small stream catchments predicted to be in poor condition across the state.

Finally, although relative influence plots provide some insight into cause-effect relationships between watershed condition and aquatic ecosystem health, BRT models were not explicitly developed to uncover cause-effect relationships. Rather, the goal of BRT modeling was to extrapolate patterns between observations of aquatic ecosystem health and landscape variables for the purpose of predicting aquatic ecosystem health metrics for any WHD catchment. Nevertheless, influential predictors can serve as a starting point for discussion of management approaches to maintain or improve aquatic ecosystem health, and predictors that can be influenced by management efforts are highlighted in red in relative influence plots.

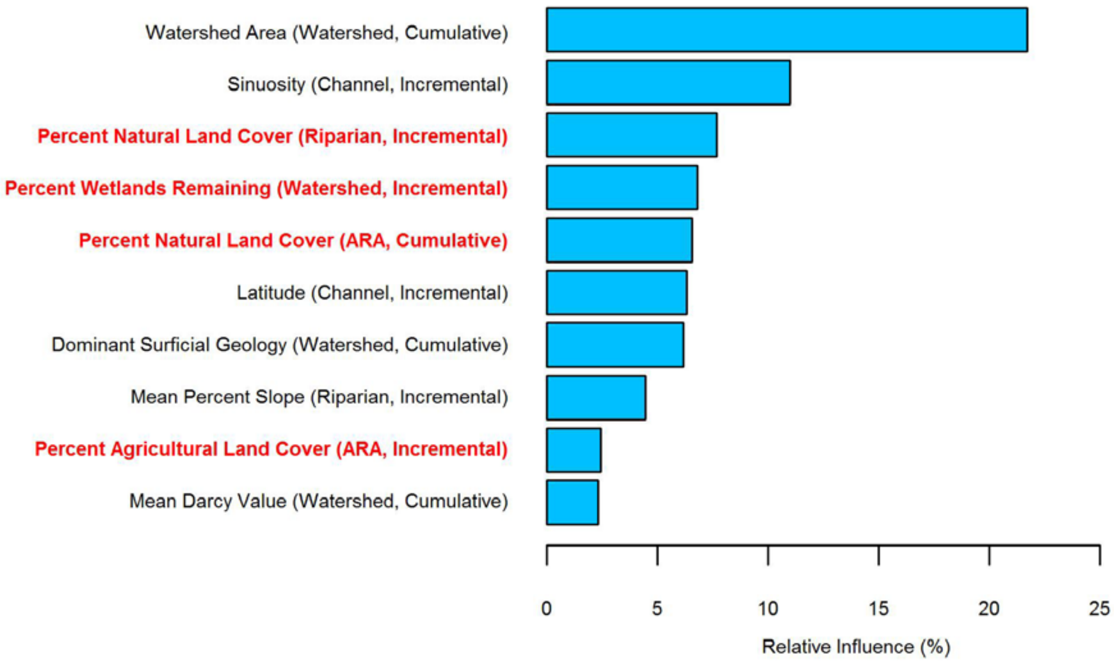

FIGURE 57. RELATIVE INFLUENCE PLOT FOR STREAM HABITAT RATING.

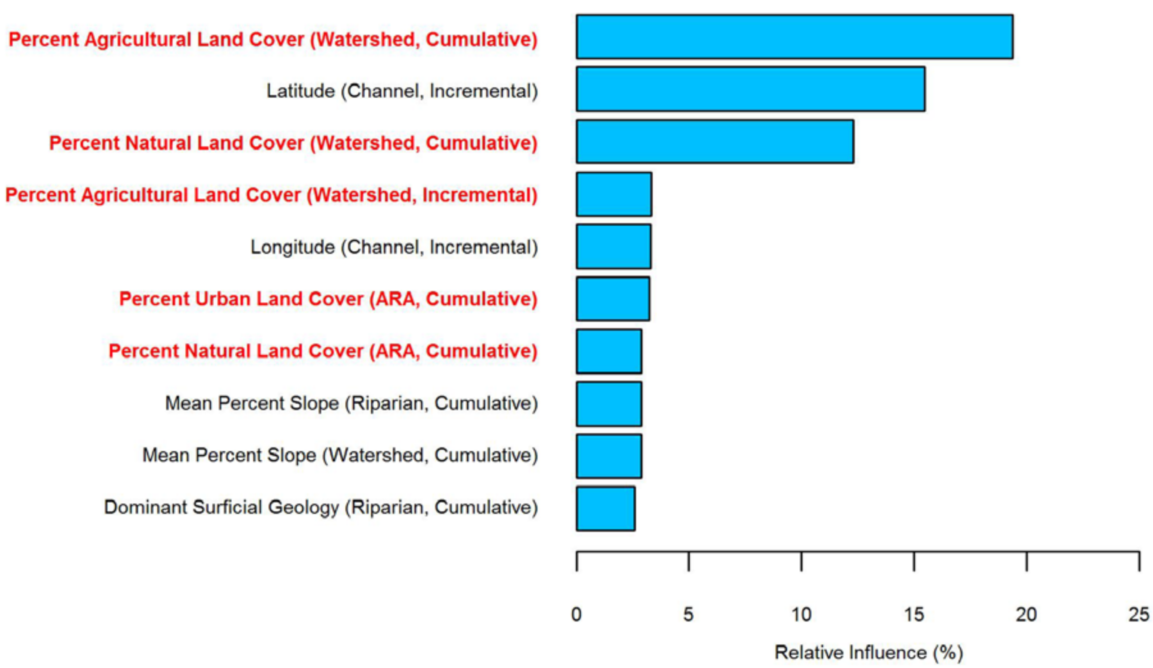

FIGURE 58. RELATIVE INFLUENCE PLOT FOR STREAM NITRATE-NITRITE CONCENTRATION.

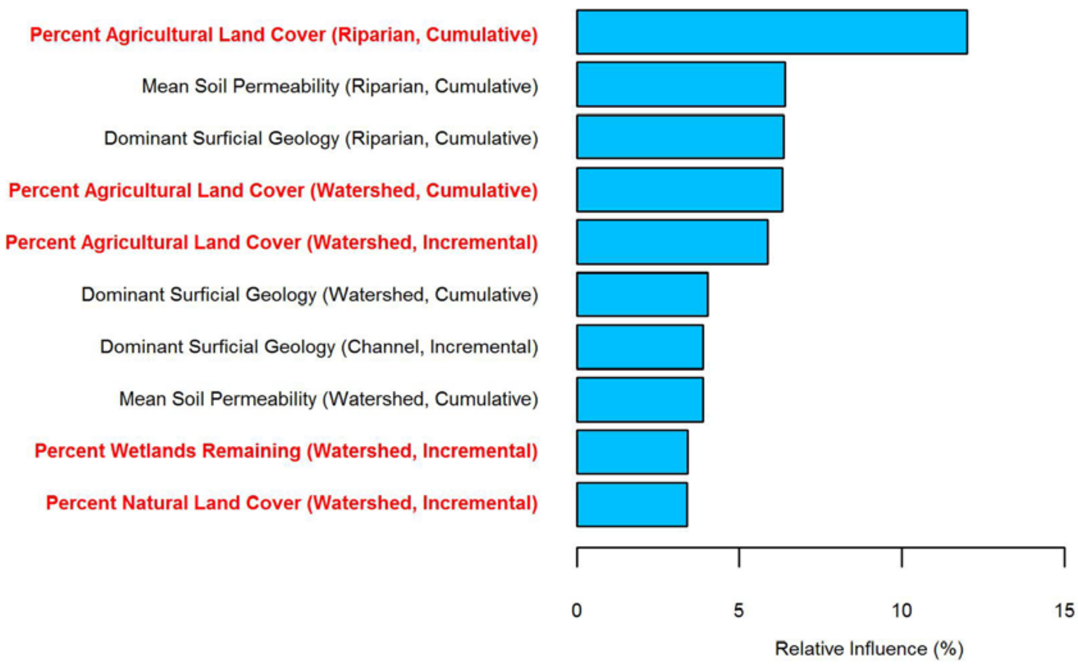

FIGURE 59. RELATIVE INFLUENCE PLOT FOR STREAM TOTAL PHOSPHORUS CONCENTRATION.

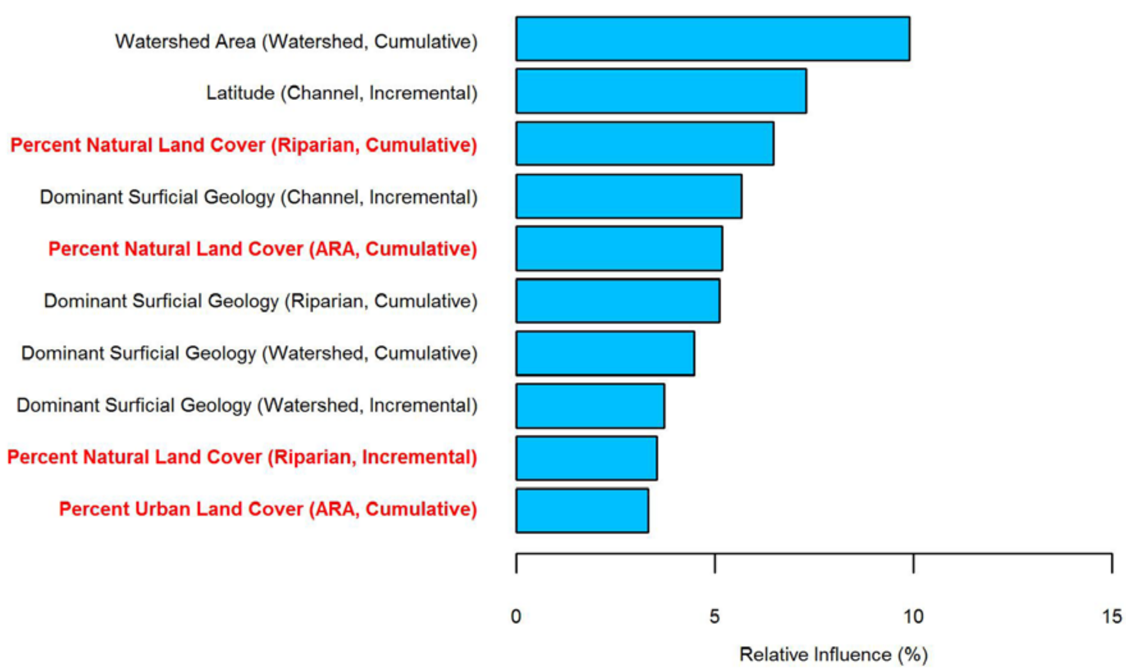

FIGURE 60. RELATIVE INFLUENCE PLOT FOR STREAM SUSPENDED SEDIMENT CONCENTRATION.

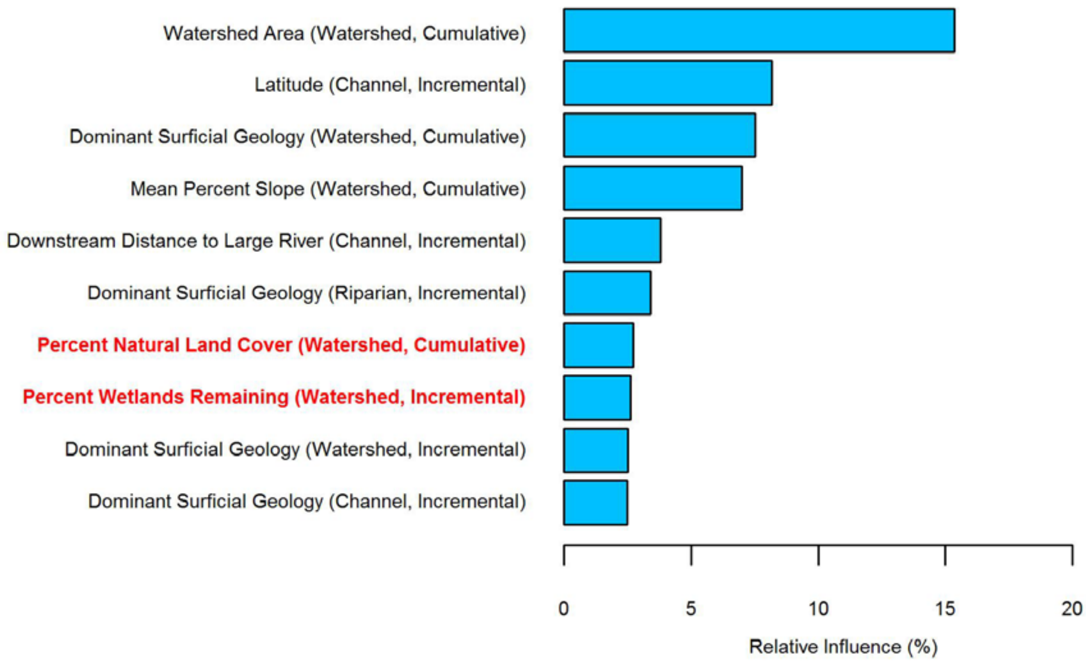

Figure 61. Relative influence plot for fish Index of Biotic Integrity rating.

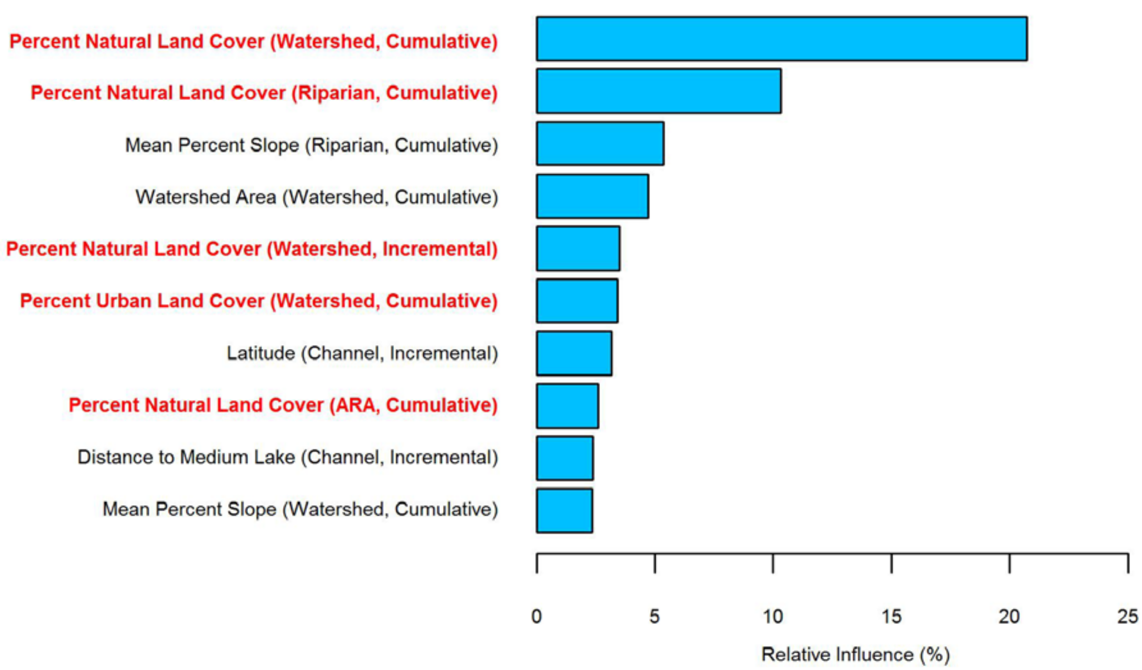

Figure 62. Relative influence plot for macroinvertebrate Index of Biotic Integrity score.

APPENDIX C ACTIVE RIVER AREA DELINEATION

Wisconsin's Active River Area (ARA) was delineated using an ArcGIS geoprocessing toolbox provided by The Nature Conservancy (Analie Barnett, personal communication). Geospatial data used in the toolbox included the WI DNR 24K flowline and water body shapefiles and a National Elevation Dataset 10 meter resolution digital elevation model (DEM). Deviations from default settings of the toolbox are described below:

- ARA Data Preparation Step 1: Flowline Data
  - This step classified WHD flowlines as headwaters, medium-size rivers, and large rivers using the WHD Stream Order attribute. Classified flowlines were subsequently converted to raster format, with the raster cell value equal to size class of the flowline.
  - In our analysis, we classified flowlines as:
    - Headwaters if stream order was 0 or 1.
    - Medium-sized rivers if stream order was 2, 3, or 4.
    - Large rivers if stream order was greater than or equal to 5.
  - Flowlines whose "FTYPE" attribute did not equal "StreamRiver" or "ArtificialPath" were not classified during this step.
- ARA Data Preparation Step 2: Water body Data
  - This step classified WHD water bodies as headwaters, medium-size rivers, and large rivers using the WHD Stream Order attribute. The stream order of each water body was determined by finding all flowlines that intersect with each water body (using the "Intersect" geoprocessing tool) and then finding the maximum stream order value for each water body (using the "Summary Statistics" geoprocessing tool). Classified water bodies were subsequently converted to raster format, with the raster cell value equal to the class of the water body.
  - In our analysis, we classified water bodies as:
    - Headwaters if maximum intersecting stream order was 0 or 1.
    - Medium-sized rivers if maximum intersecting stream order equal was 2, 3, or 4.
    - Large rivers if maximum intersecting stream order was greater than or equal to 5.
  - Flowlines whose "FTYPE" attribute did not equal "StreamRiver" or "ArtificialPath" were not considered when assigning water body classes.
  - The raster produced from this step was merged with the raster produced from Data Preparation Step 1.
- ARA Step 1: Option A – Create Cost Distance Surface, Does Not Fill DEM
  - This step computed three cost distance grids (one for each river class) using a DEM raster and the flowline/water body raster. It also generates flow accumulation and slope grids.

- ARA Step 2: Reclass Cost Distance Surface
    - This step classified the cost distance grids produced from Step 1 into binary classes. We used thresholds of 75, 150, and 300 for headwaters, medium-sized rivers, and large rivers, respectively.
- ARA Step 3: Create Moisture Index to Build Wetflats
    - This step used the flow accumulation and slope rasters created in Step 1 to generate a moisture index. No adjustments were made to default tool settings.
- ARA Step 4: Option A – Refine Wetflats and Add to Base Riparian Zones
    - This step used the moisture index created in Step 3 to create a wetflat grid. No adjustments were made to default tool settings.
- ARA Step 5: Generate Non-Headwater Material Contribution Zones and Add to Wetflats and Base Riparian Zones
    - This step added material contribution zones adjacent to flowlines to the ARA. No adjustments were made to default tool settings.

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Healthy Watersheds