STREAM CLASSIFICATION

for the Northern Appalachian - Acadian Region of Canada

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NATURE CONSERVANCY CANADA

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Photo: NCC / Mike Dembeck

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Introduction

This report describes an initiative undertaken by the Nature Conservancy of Canada–Atlantic Region to strengthen freshwater conservation efforts in the Canadian portion of the Northern Appalachian–Acadian ecoregion. With the assistance of a core team of freshwater experts from both the United States and Canada, a hierarchical classification of rivers and streams was developed and mapped using five biophysical characteristics that affect the distribution of aquatic biodiversity: size, gradient, temperature, alkalinity, and tidal influence. A standardized classification was then developed for all watersheds in New Brunswick, Nova Scotia, Prince Edward Island, and eastern Quebec, as well as for those watersheds that cross the Canadian border into Maine, New Hampshire, Vermont, and New York. The classification is seamless within and across provincial boundaries, and complements a similar classification completed for the U.S. portion of the ecoregion (Olivero and Anderson 2008).

Comprehensive and robust aquatic planning has numerous social, ecological, and economic benefits, and we envision that this classification will allow those involved in managing freshwater resources to achieve these benefits more efficiently and effectively. The classification will also serve as the foundation for a Freshwater Conservation Blueprint, a collection of planning tools to assess freshwater conservation and restoration priorities throughout the region. These tools, including the classification outlined in this report, are designed to be applicable at multiple spatial scales, from individual watersheds, to the provincial level, and to the region as a whole. Scheduled to be completed in spring 2019, the Freshwater Conservation Blueprint will enable organizations of all sizes and mandates to work collaboratively using a common language and a consistent dataset to guide freshwater conservation and management.

This report begins by explaining how the base hydrography, which underpins the classification, was developed. Chapter 2 describes various regional classifications that were incorporated into the final product to ensure the results were relevant at the landscape-scale. Chapter 3 presents the five variables used to classify streams across the region. Chapter 4 describes the various ways that these variables can be grouped into taxonomies depending on user needs. Lastly, Chapter 5 describes the utility of this stream classification, highlights several limitations, and indicates next steps. The five appendices provide supporting information and detail.

1. Approach and Base Layer Data

The objective of this project was to develop and map an ecological classification for all rivers and streams in the Canadian portion of the Northern Appalachian–Acadian ecoregion, including cross-border areas of transnational watersheds (Figure 1.1). A core team of 22 freshwater experts representing environmental nongovernmental organizations, academia, and government agencies from across the region guided the work (see Acknowledgements).

The team's guidance was critical to ensuring that the final product reflected a local understanding of stream and river ecosystems and their management. Team members also provided datasets and gave advice throughout the project. Team webinars were held regularly to solicit feedback on the best techniques and approaches. These discussions highlighted the variables that provinces currently use, or would like to use, for a regional classification. The team also provided recommendations regarding how the stream classes should be considered within a hierarchy of larger, regional-scale planning units, including Omernik ecoregions (Omernik 1995), freshwater ecoregions (Abell et al. 2008), freshwater ecological drainage units (TNC 2005), hydrologic unit code watersheds (USGS and NRCS 2013), and National Hydrographic Network work units (NHN, 2012). The initial stages of this project included a detailed literature review of freshwater classification frameworks, including taxonomic, environmental, and hydrologic classifications for natural stream and river types (McManamay et al., 2014). The team made recommendations on combining the variables into different stream and river classes, as described in subsequent chapters. Both the literature review and the detailed discussions of the team members revealed a high level of agreement on five primary variables: size, gradient, temperature, alkalinity, and tidal influence.

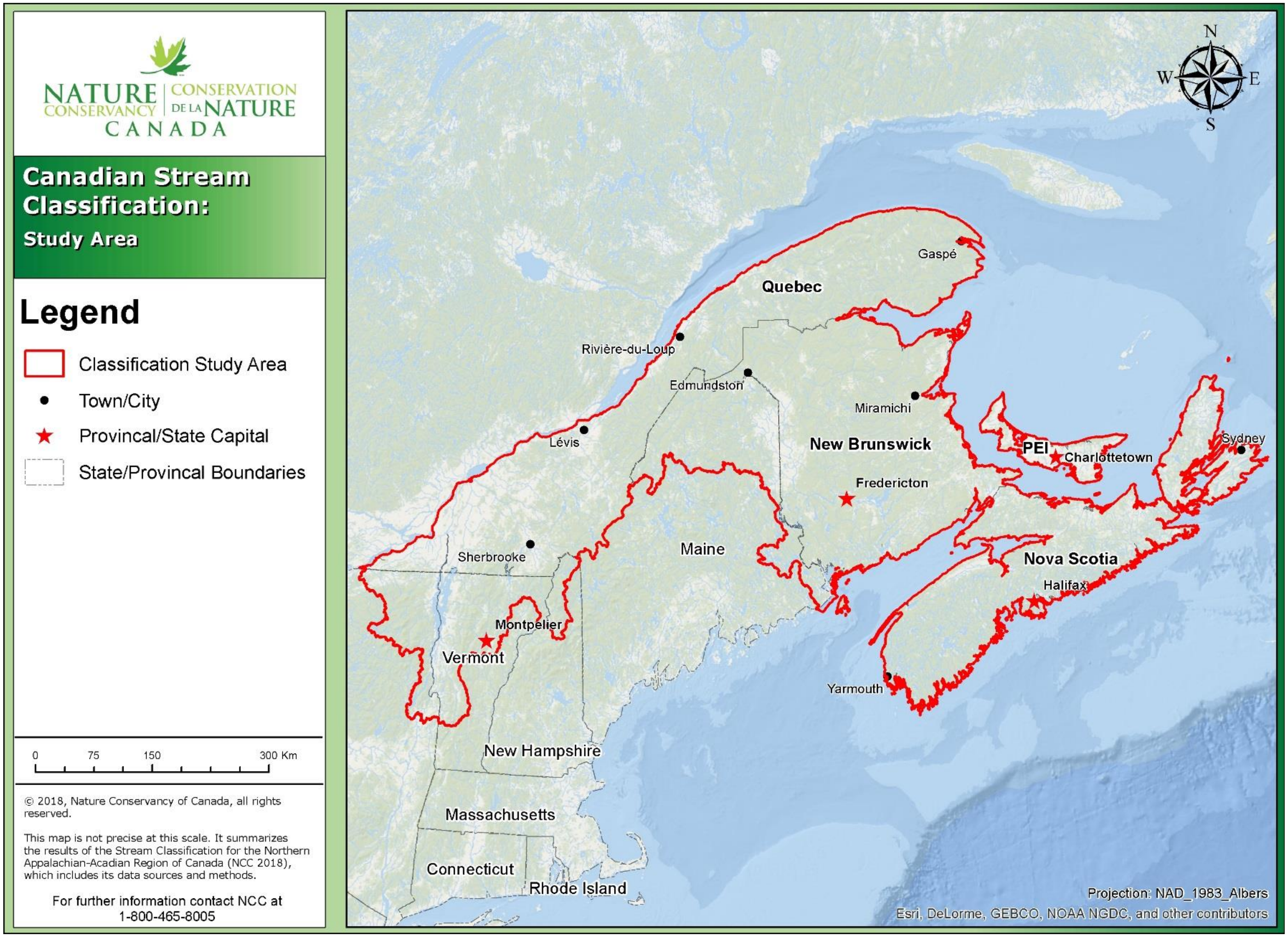
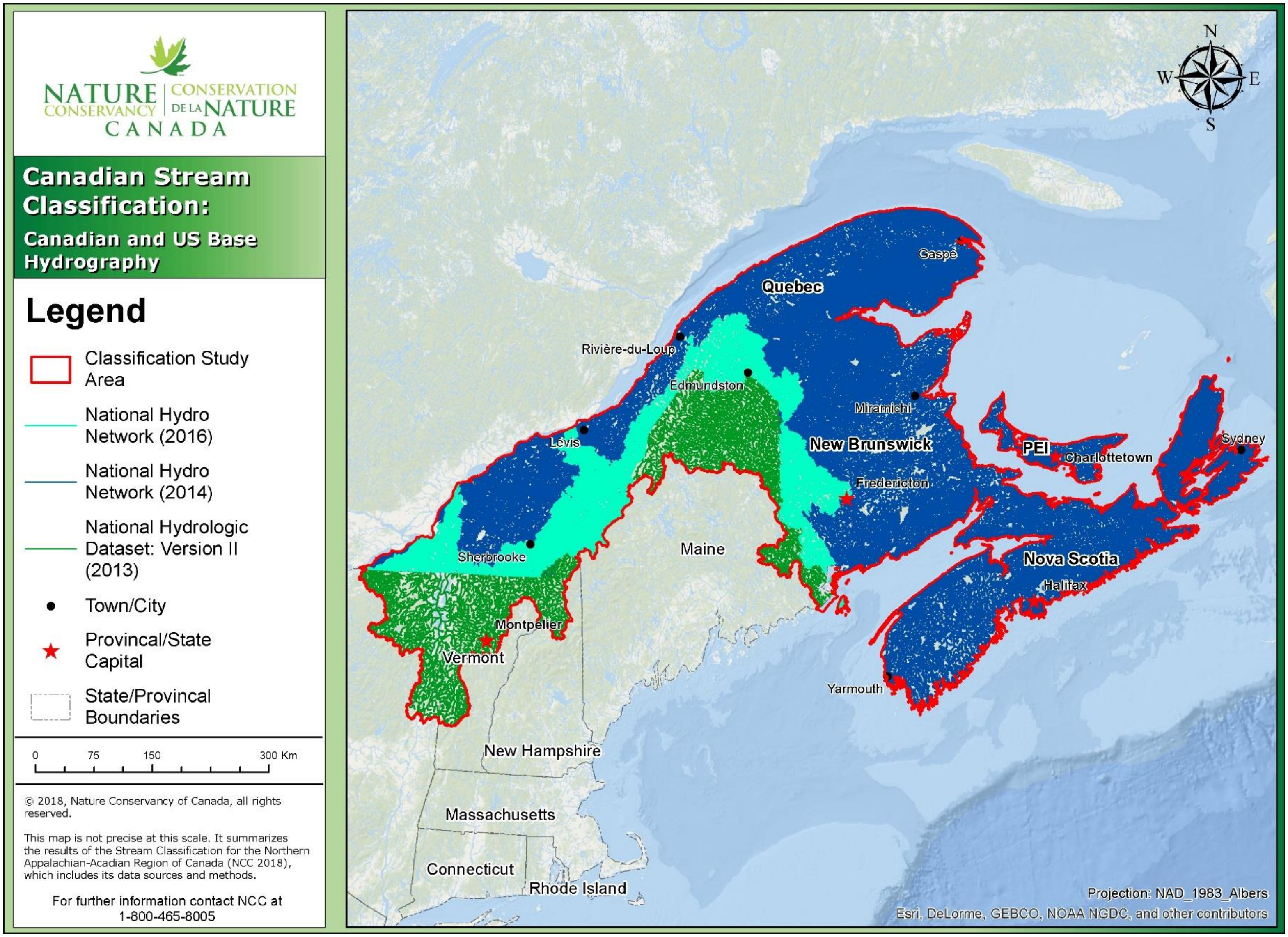


Figure 1.1: Canadian stream classification study area.

Base Hydrography

The base hydrography, which is the foundational dataset of the classification, was developed using three hydrography layers. The first layer was the National Hydrographic Network: GeoBase Series (Natural Resources Canada 2010), which is a publicly available 1:50,000-scale dataset. Edits previously made to this layer by the World Wildlife Fund as part of its Watershed Reports initiative were incorporated into the base hydrography. The second hydrography layer was an updated version of the NHN base hydrography (NHN, 2016) for a subset area along the Canada–U.S. border; it replaced an older NHN dataset where the two versions overlapped. Lastly, to maintain consistency across watersheds that spanned the border, the Canadian hydrography layer was joined to a hydrography layer developed for the U.S. side of the ecoregion (see Olivero and Anderson 2008; Olivero-Sheldon et al. 2015; McManamay et al. 2017, McKay et al., 2012)) based on the U.S. Environmental Protection Agency's 1:100,000-scale National Hydrography Dataset version 2 (2013).

To create distinct stretches of streams and rivers, the Canadian base hydrography layer was "split" wherever two or more watercourses joined together to form a single channel, or where a watercourse entered into a lake, pond, or reservoir. For the Canadian hydrography layer, lakes, ponds, and reservoirs were included only if they were larger than 2 hectares, whereas the U.S. hydrography layer included any mapped at the U.S. Geological Survey standard scale of 1:100,000. Once the three base hydrography layers were aligned, they were manually stitched together across the Canada-U.S. border (see Appendix A for methods), and topographic maps and aerial imagery were used to locate and resolve inconsistencies. Figure 1.2 shows coverage for the final working hydrography dataset.



This map is not precise at this scale. It summarizes the results of the Stream Classification for the Northern Appalachian-Acadian Region of Canada (NCC 2018), which includes its data sources and methods.

Figure 1.2: Base hydrography layers contributing to the classification.

Base Flowline Attributes

Flowlines represent discrete stream segments within the base hydrography that spatially identify where water collects and accumulates across the landscape. As water flows, it takes on new physical properties (e.g., velocity), and as it passes through different landscapes, it carries materials of that landscape with it. This creates dynamic freshwater ecosystems that have different ecological attributes. More than 100 ecological attributes were compiled for each of the 228,628 flowlines developed as part of this project. These ecological attributes represent geology, soils, elevation, slope, land use, monthly air temperature, monthly precipitation, and solar radiation, among other factors.

Land-use data were taken from Canadian Land Cover Dataset, circa 2000 (2015). Soil data came primarily from SoilGrids, a tool that consistently predicts soil properties at 250m x 250m resolution across the planet (see Hengl et al. 2016). SoilGrids provided all the numeric soil properties, including (1) cation exchange capacity, pH, soil texture, and coarse fragments at seven standard depths (0, 5, 15, 30, 60, 100, and 200 cm); (2) soil depth to bedrock; and (3) distribution of soil classes based on the World Reference Base and U.S. Department of Agriculture classification systems (IUSS Working Group WRB 2015).

Climatic variables were taken from WorldClim version 2 (Fick et al. 2017), which includes monthly air temperature, precipitation, and solar radiation data for 1970 through 2000. These data are available at an approximate 1km x 1km resolution. WorldClim version 2 also included 19 "bioclimatic" variables derived from the temperature and precipitation values to generate more biologically meaningful attributes. Bioclimatic variables are often used in species distribution models and related ecological modeling techniques (Elith and Leathwick 2009). The bioclimatic variables represent annual trends (e.g., mean annual temperature, annual precipitation), seasonality (e.g., annual range in temperature and precipitation), and extreme or limiting environmental factors (e.g., temperature of the coldest and warmest month, and precipitation of the wettest and driest three months of the year).

2. Regional Classifications

Stream classifications can be organized at different spatial scales, from an entire drainage basin, to individual pools and riffles of a single stream. Thus the individual watercourses described in Chapter 1 fit within multiple regional-scale frameworks. With a stream classification that fits within these regional frameworks, freshwater planners and managers can consider landscape-scale factors that are not apparent at local scales. For example, aquatic species found in a specific stream habitat will be highly influenced not only by the local physical characteristics of that habitat, but also by regional variation in ecology, topography, geology, and climate. To ensure that these landscape-scale factors were included in the development of the stream ecological classification, five regional-scale frameworks were incorporated into the analysis: Omernik ecoregions, freshwater ecoregions, ecological drainage units, hydrologic unit codes, and NHN work unit limits.

Omernik Level III Ecoregions

Omernik ecoregions denote areas of general similarity in ecosystems and the type, quality, and quantity of their environmental resources. They are designed to serve as a spatial framework for the research, assessment, management, and monitoring of ecosystems and ecosystem components. Omernik ecoregions are based on an analysis of biotic and abiotic phenomena, including geology, physiography, vegetation, climate, soils, land use, wildlife, and hydrology. The relative importance of each characteristic varies from one ecological region to another. Methods used to define the ecoregions are explained in Omernik (1995, 2004), Omernik et al. (2000), and Gallant et al. (1989). Five Omernik level III ecoregions intersect the study area (Figure 2.1).

Freshwater Ecoregions

Freshwater Ecoregions of the World (FEOW, Abell et al. 2008) was developed by the World Wildlife Fund in partnership with The Nature Conservancy and more than 200 freshwater scientists from around the globe. This freshwater biogeographic dataset is based on major drainage basins. The drainage basins cut across terrestrial ecoregions but are particularly useful for studying aquatic biodiversity patterns, which are often limited in their distribution by direct drainage connectivity. A freshwater ecoregion is distinguished by a unique pattern of native freshwater species resulting from large-scale geoclimatic processes, evolutionary history, and stream connectivity (Abell et al. 2008). The primary freshwater ecoregions intersecting the study area are the Canadian Atlantic Islands, Saint Lawrence, Northeast U.S. & Southeast Canada, and Scotia-Fundy (Figure 2.2).

Ecological Drainage Units

Ecological drainage units (EDUs, TNC 2005) delineate areas within Abell et al.'s (2008) freshwater ecoregions (Figure 2.3). They correspond roughly to large watersheds of approximately 4,800 to 16,000 square kilometres. EDUs were developed by combining watersheds with a shared historic species distribution, as well as local physiographic and climatic characteristics. Their boundaries were decided by staff of The Nature Conservancy's Freshwater Initiative after considering U.S. Forest Service fish zoogeographic subregions (Maxwell 2012), U.S. Forest Service ecoregions and subsections (Cleland et al. 2007), and major drainage divisions (Higgins et al. 2005). However, the EDU analysis did not cover the provinces of Nova Scotia and Prince Edward Island.

Hydrologic Unit Codes

The United States divides and subdivides regions into successively smaller hydrologic units (USGS and NRCS 2013), each of which is identified by a unique hydrologic unit code (HUC ; see Figure 2.4 for example). The hydrologic units are arranged or nested within each other, from the largest geographic area (HUC2 regions) to the smallest (HUC12 cataloging units). Hydrologic units are not true watersheds but are delineated so as to nest into a multilevel hierarchical drainage system. A unit may receive water from one or more points outside its boundary in addition to its internal surface drainage. Many state and federal agencies use HUC units for monitoring and reporting the status of freshwater systems.

National Hydro Network Work Unit Limits

The NHN is a spatially-defined set of basic attributes that describe Canada's inland surface waters (NHN, 2016). The NHN work unit limits are not true watersheds but territorial divisions that correspond to each NHN dataset (NHN 2012) based on watersheds from nationally standardized drainage datasets from the Atlas of Canada (Figure 2.5). These datasets are regularly updated, and many provincial and federal agencies use NHN work unit limits for monitoring and reporting the status of freshwater systems.

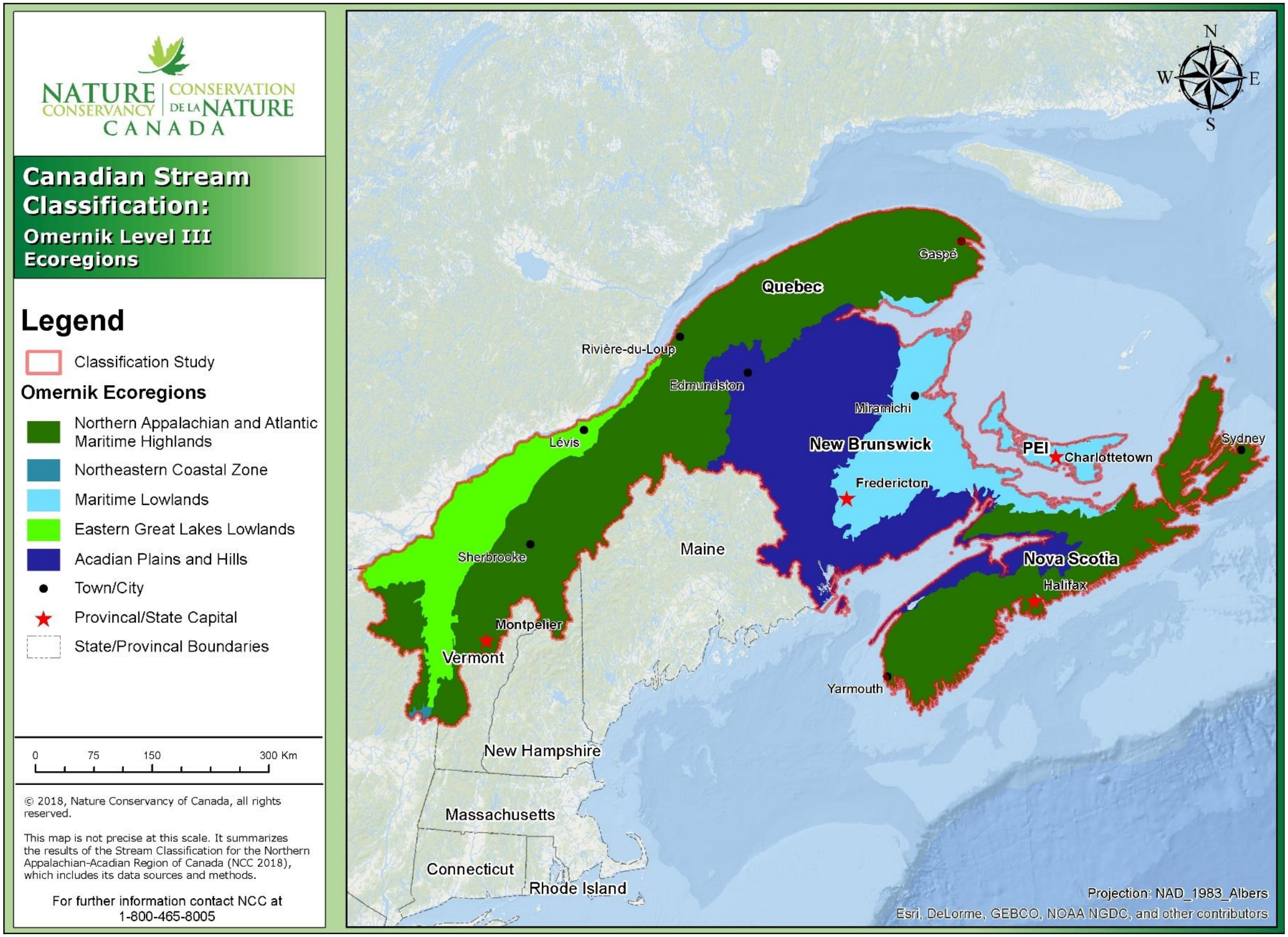


Figure 2.1: Omernik Level III Ecoregions.

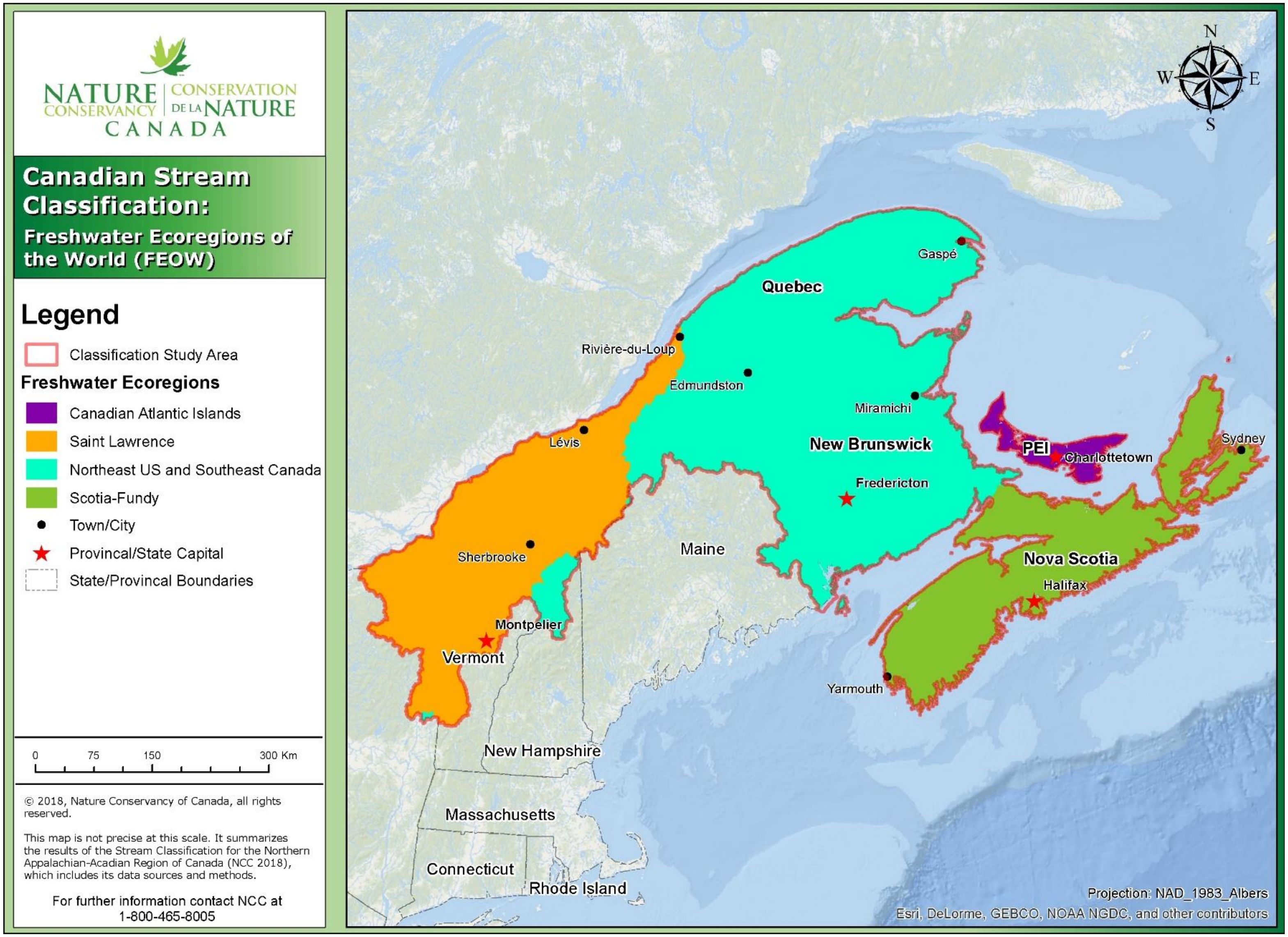


Figure 2.2: Freshwater Ecoregions of the World (FEOW).

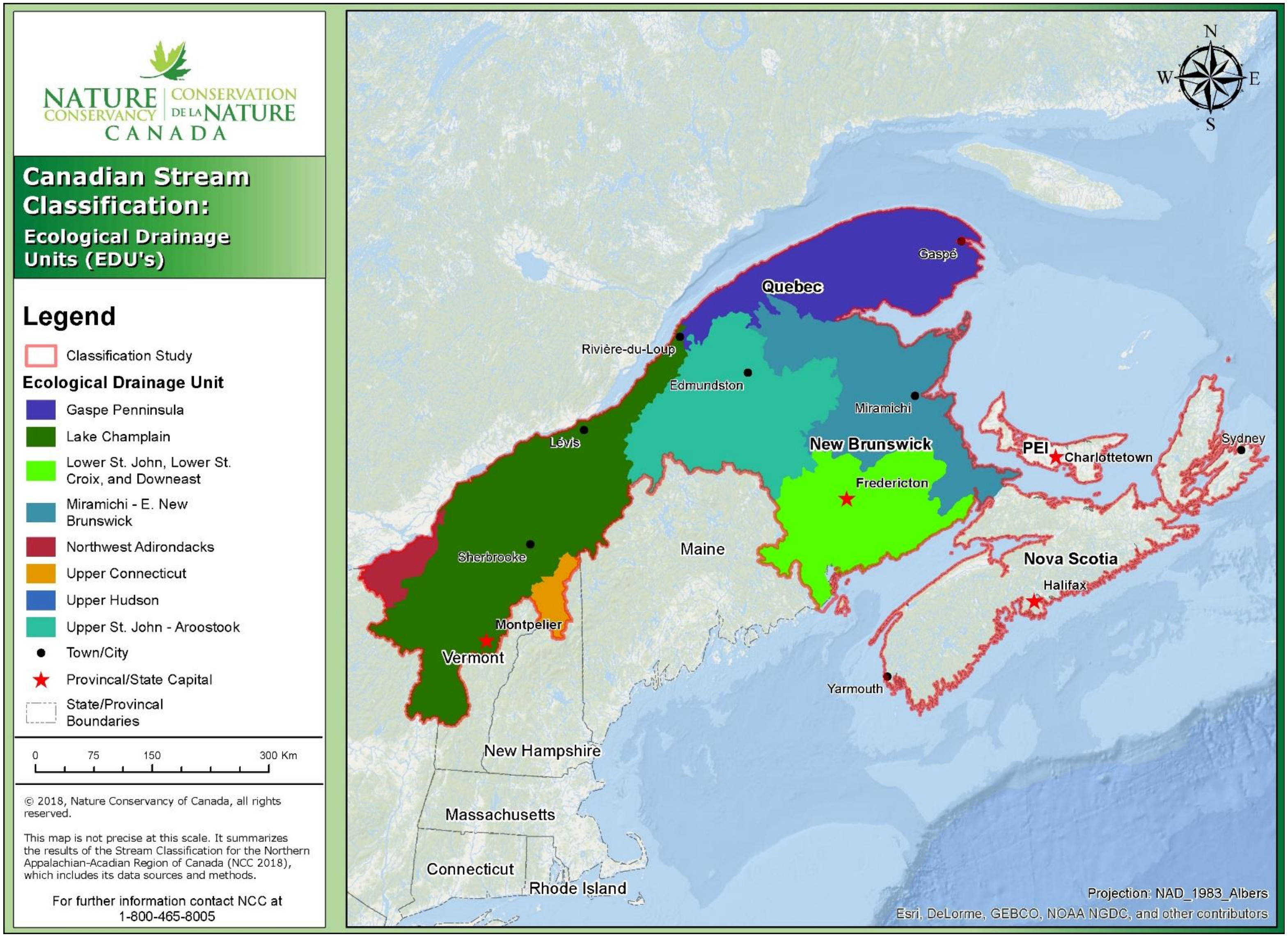


Figure 2.3: Ecological Drainage Units (EDUs).

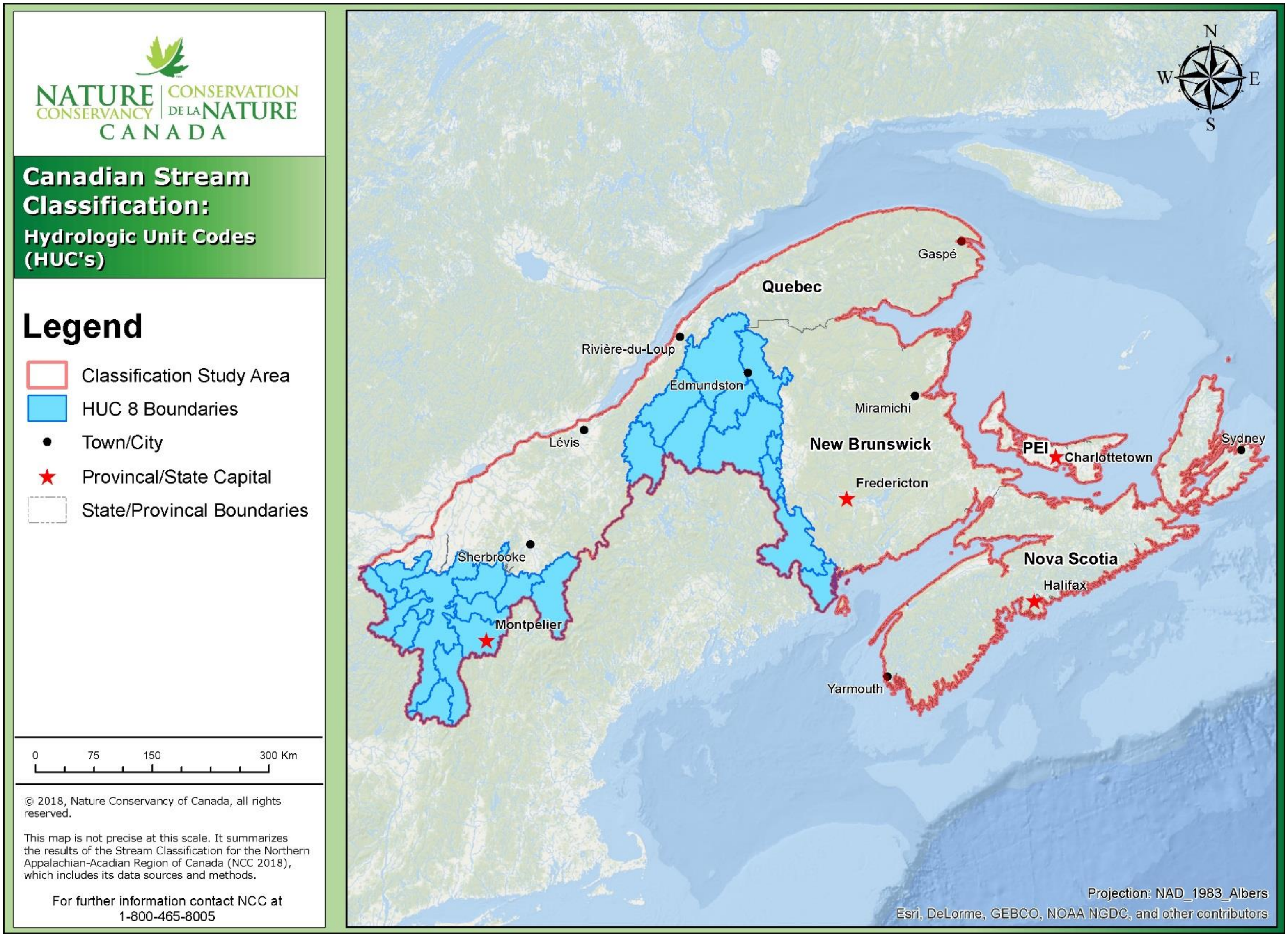


Figure 2.4: Hydrologic Unit Codes (HUC') 8 Boundaries.

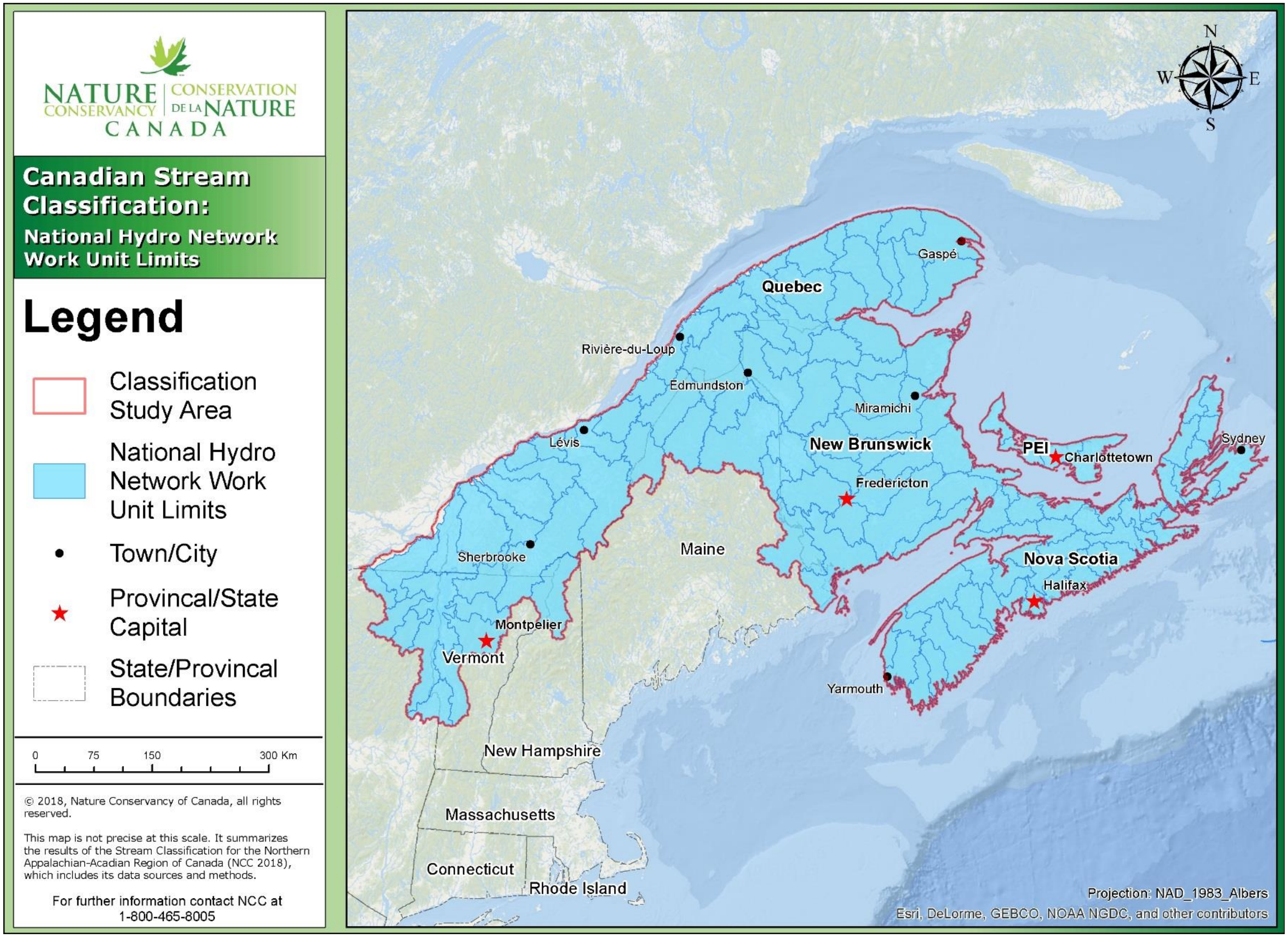


Figure 2.5: National Hydrological Unit (NHN) Work Unit Limits.

3. Stream Classification Variables

The Stream Classification for the Northern Appalachian–Acadian Region of Canada is based on five primary variables that influence aquatic habitats and species: size, gradient, temperature, alkalinity, and tidal influence (Higgins et al. 2005; Maxwell et al. 1995; Rosgen 1994; Frissell et al. 1986). When combined, these variables are strong predictors of the freshwater biodiversity that occurs across the region and can be used as the foundation layer for more complex analyses of species distributions and ecological relationships. This chapter describes the five variables used to classify streams and rivers, as well as the methods used to map them across the study area.

Size

Stream size is one of the most important predictors of aquatic biodiversity (Vannote et al. 1980; Higgins et al. 2005). The well-known river continuum concept as described by Vannote et al. (1980) illustrates the changes in aquatic ecosystems as they transition from small headwater streams to large river mouths. For example, small headwater streams are often shaded by riparian vegetation that regularly supplies organic matter, supporting an aquatic community with an abundance of plant-shredding insects. In contrast, larger streams and rivers often receive abundant sunlight, resulting in communities of aquatic plants and algae-grazing insects.

Stream size was determined using the *upstream drainage area,* defined as the total area of land that drains into a stream segment. Upstream drainage area was selected for several reasons: it is directly related to the volume of water that enters the stream, it can be applied across multiple scales of mapped hydrography, and it is widely applicable and has been used in several other regional stream classifications (see Olivero and Anderson 2008; Olivero-Sheldon et al, 2015; Anderson et al, 2013a; Anderson et al, 2013b, Beard and Whelen 2006). To calculate the upstream drainage area, a digital elevation model (DEM) was created for the study area by combining two layers (see Figure 3.1):

- a 30m resolution DEM from Government of Canada (2014): Geospatial Data Extraction Tool;
- a 30m resolution DEM developed by the U.S. Geological Survey (2014) to cover portions of watersheds that extend into the United States.

The base hydrography was then aligned with the final DEM using an automated tool called AGREE.AML, developed by the Center for Research in Water Resources at the University of Texas at Austin (see Appendix B for a description). Finally, the upstream drainage area was calculated for each stream segment, and size class thresholds were developed.

To maintain consistency across the Canada-U.S. border, size class thresholds were adopted from the adjacent U.S. freshwater classification (Olivero and Anderson 2008). These thresholds were chosen based on several factors, including the known distribution of freshwater species across different watercourse sizes, as well as a comparison with the U.S. National Fish Habitat Classification (Olivero-Sheldon et al., 2015; Beard and Whelan 2006). The results of the size classification highlight four primary classes (Table 3.1, Figure 3.2); however, the classification is not limited to these four (see Chapter 4) and can be modified to include fewer or more classes, depending on the user's needs.

Table 3.1. Stream and river size classes

Description	Upstream drainage area (km^2)	Total length in region (km)
Headwaters and Creeks	< 100	203,921
Small Rivers	≥ 100 and < 518	14,596
Medium Tributary Rivers	≥ 518 and < 2,590	5,367
Large Rivers	≥ 2,590	2,105

To verify these classes, a statistical analysis was completed that related benthic species distributions to changes in stream size. Benthic species data were obtained from the CABIN dataset (2017), a standardized database of aquatic species abundance and distribution covering 2002 to 2016. Statistical analysis included a threshold indicator taxa analysis (TITAN2, Baker and King 2010), which used indicator species to detect changes in species distribution and abundance across different stream sizes (for a detailed explanation of this analysis, please see Appendix C). Results highlighted 30 benthic families whose distribution and abundance significantly responded to changes in stream size. These taxa were associated with specific size classes by studying the resultant plots and significant change points.

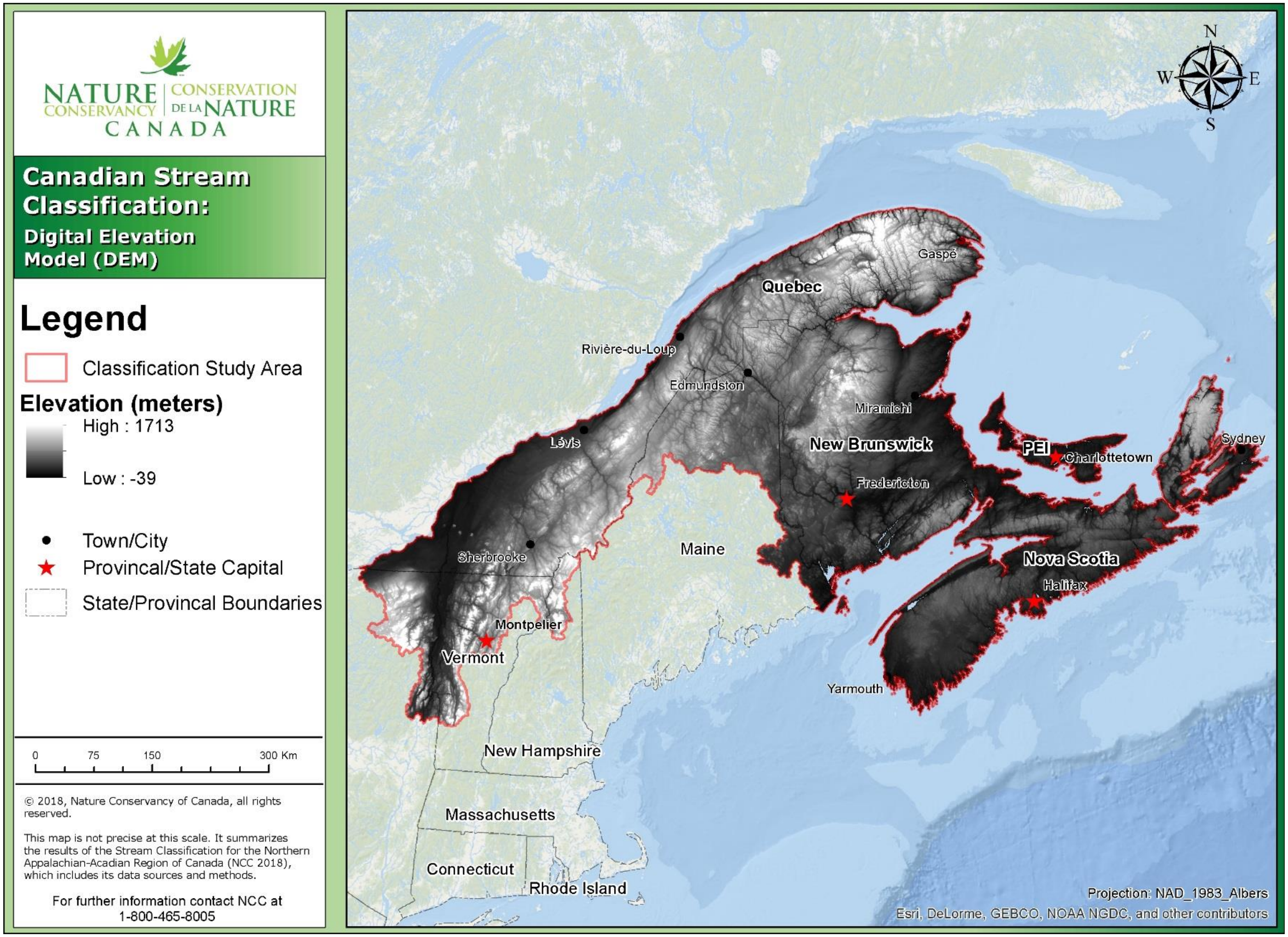


Figure 3.1: Digital Elevation Model (DEM).

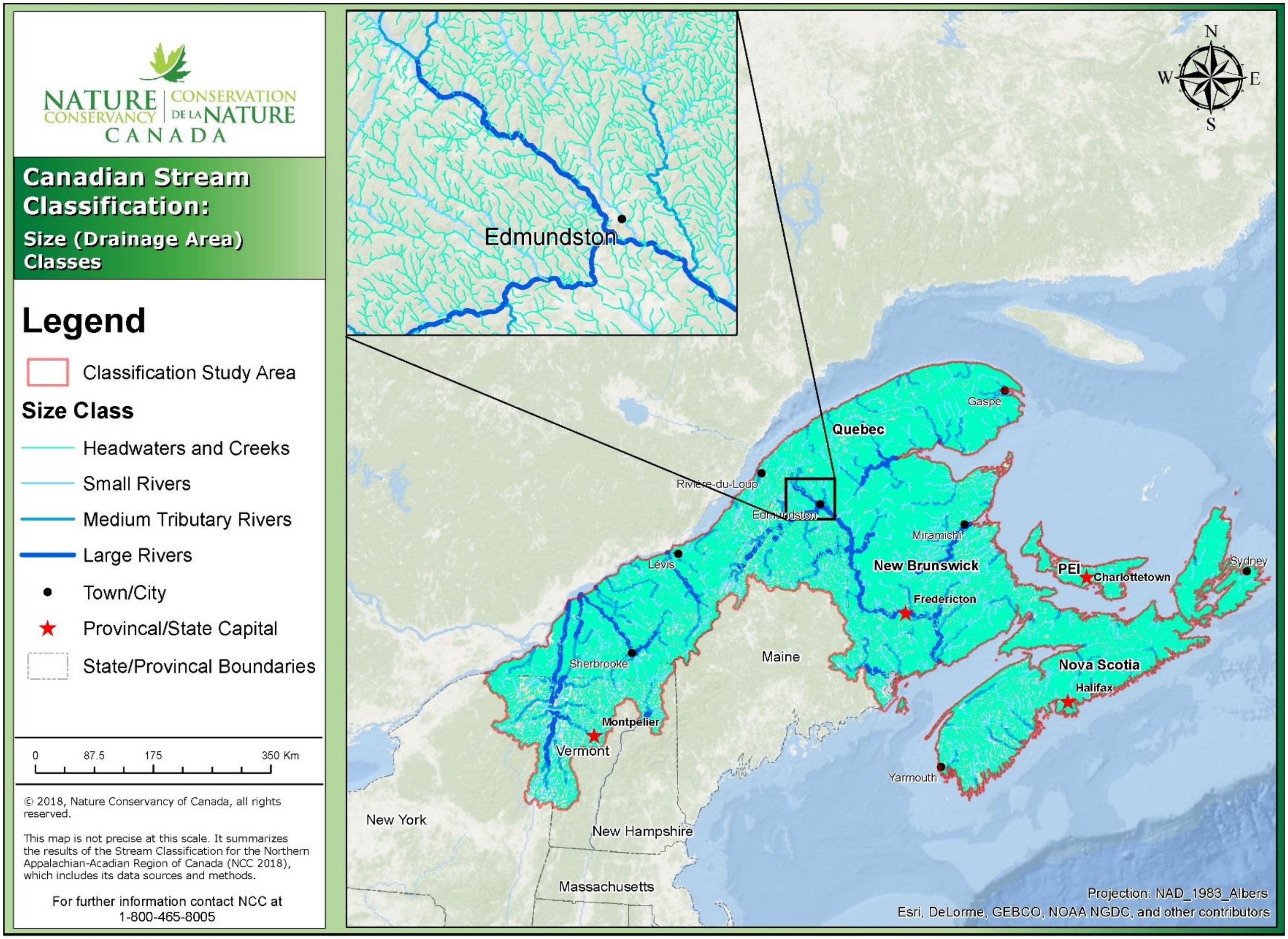


Figure 3.2: Stream and river size classes.

Gradient

Stream gradient has a strong influence on aquatic communities because it determines such factors as stream shape, water velocity, and streambed substrate (Rosgen 1994; Montgomery and Buffington 1997). For example, very high gradient streams tend to have fast-flowing water over substrates of cobble or bedrock in confined channels. In contrast, very low gradient systems tend to have slow-flowing water over substrates of sand and silt with seasonal connections to adjacent floodplains (Rosgen 1996; Allan 1995).

Gradient was determined using *percent slope,* which is a unitless ratio calculated as the change in elevation divided by distance. Percent slope was already calculated for the U.S. hydrography layer. Calculating the percent slope for each flowline in the Canadian base hydrography involved the following steps:

1. DEM elevations were determined for the start and end points of each flowline using the "isectlinerst" tool in the Geospatial Modelling Environment[1];
2. change in elevation for each flowline was calculated; and
3. change in elevation was divided by length for each flowline.

Once percent slope was calculated for each flowline, gradient class thresholds were developed. To maintain consistency across the Canada-U.S. border, gradient class thresholds were adopted from the adjacent U.S. freshwater classification (Olivero and Anderson 2008). These thresholds were chosen by comparing the classes with stream gradients at known locations and with Rosgen's (1994) slope classes, and by examining the distribution of freshwater species across different watercourse gradients. The results of the gradient classification highlight three primary classes (Table 3.2; Figure 3.3); however, the classification is not limited to these three (see Chapter 4) and can be modified to meet the user's needs.

Table 3.2. Stream and river gradient classes

Description	Stream channel slope (%)	Total length in region (km)
Low Gradient	< 0.1	26,783
Moderate Gradient	≥ 0.1 and < 2	117,200
High Gradient	≥ 2	82,006

As with the size class analysis, statistical analysis was used to explore how biota respond to changes in gradient. Benthic species data were obtained from the CABIN (2017) dataset, and

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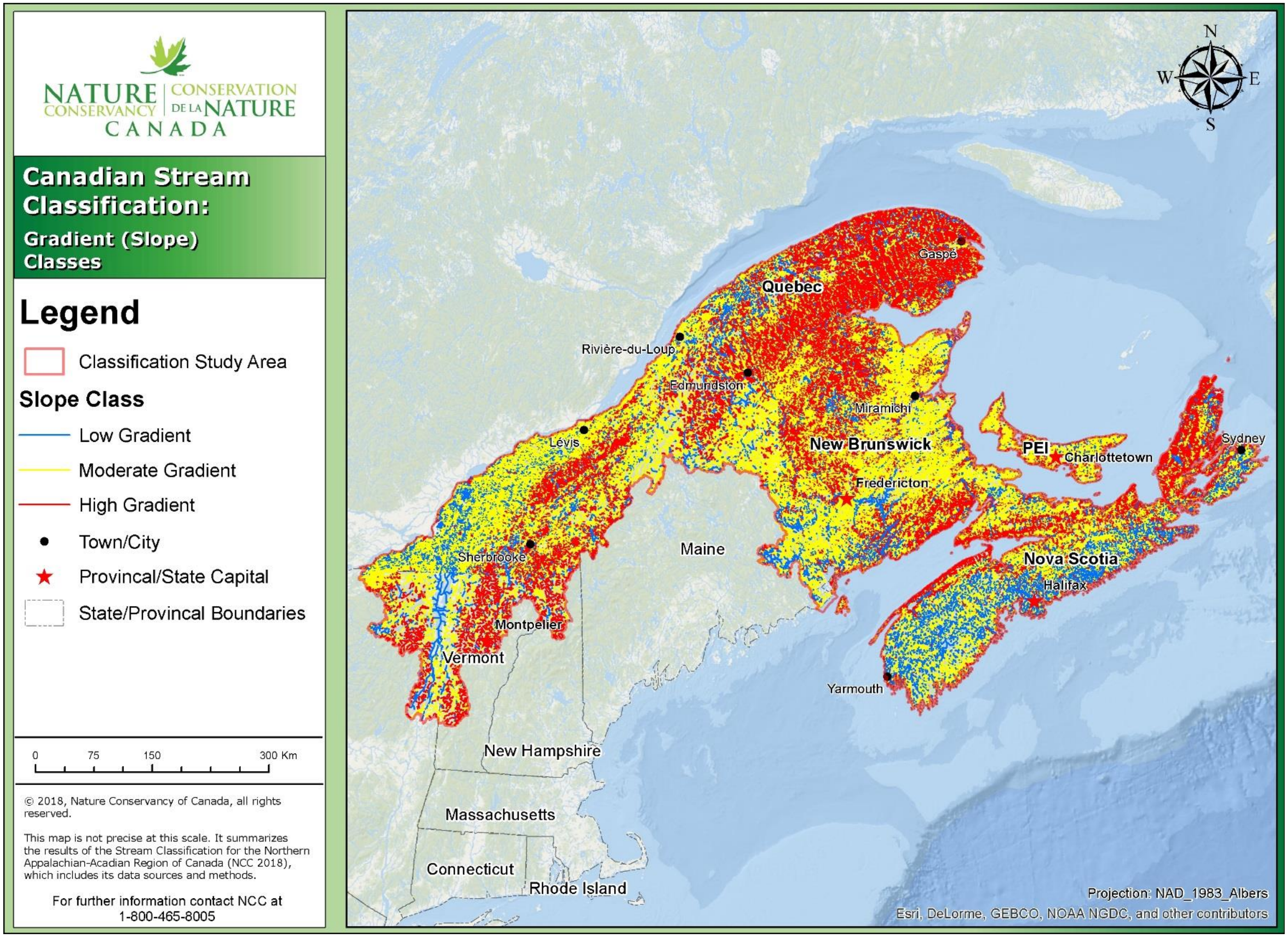
[1] See http://www.spatialecology.com/gme/

statistical analysis included a TITAN analysis (TITAN2, Baker and King 2010), which used indicator species to detect changes in species distribution and abundance across different stream gradients (for a detailed explanation of this analysis, please see Appendix C). Results highlighted 52 benthic taxonomic families whose distribution and abundance responded significantly to the expected changes in gradient. By studying the resultant plots and significant change points, taxa were found to be strongly associated with the specific gradient classes.



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For further information contact NCC at 1-800-465-8005

Figure 3.3: Stream and river gradient classes.

Temperature

Stream temperature has a strong influence on aquatic communities because it sets physiological limits beyond which many freshwater organisms cannot survive (Smith and Lavis 1975). Many fish and aquatic invertebrates are commonly differentiated as cold- or warm-water species, reflecting their habitat preferences (Halliwell et al. 1999; Stamp et al. 2010). For example, brook trout require cold water and are relatively intolerant of even small increases in temperature (Wehrly et al. 2007), whereas redbreast sunfish require warm water for nesting and spawning (Magnuson et al. 1979).

Although numerous temperature variables affect aquatic communities, mean summer temperature is most often used for freshwater classification purposes (see Olivero-Sheldon and Anderson 2015; McManamay et al. 2017; Deweber and Wagner 2015). To maintain consistency with the adjacent U.S. classification (Olivero and Anderson 2008), mean summer temperature was adopted for this classification as well. Water temperature data for June, July, and August between 1990 and 2016 were taken from four sources: (1) RivTemp (2016) from Institut national de la recherché scientifique; (2) Water Quality Database (2016) from the Community Based Environmental Monitoring Network; (3) Long-term freshwater quality monitoring data for the Maritime Coastal Basin from Environment and Climate Change Canada (2016); and (4) Surface Water Quality Data (2016) of the New Brunswick Department of Environment and Local Government. Figure 3.4 shows the final map of temperature data points (n=684).

To extrapolate the data points into a temperature layer, the Random Forest statistical package was used (Liaw and Wiener 2002). Random Forest is a machine learning technique that builds decision trees to assess the relationships between a response variable and potential predictor variables, extrapolating those relationships into a continuous layer. The final temperature layer explained 66.0% of the variance in the mean summer temperature data points using 20 predictor variables related to climate, soils, and topography, the most important of which were maximum air temperature of the warmest month and mean air temperature of the warmest three months. Once the final layer was completed, temperature values were assigned to all flowlines of the base hydrography in the Canadian portion of the study area (Figure 3.5). Current stream temperature data for the U.S. portion of the study area are lacking: the adjacent U.S. freshwater classification (Olivero and Anderson 2008) used a temperature dataset now considered outdated (see discussion for more details).

Once the temperature values were assigned to each flowline, temperature class thresholds were developed. These classes were based on (1) a commonly applied approach to distinguish freshwater systems in various state and provincial programs; (2) a TITAN analysis using fish species in the U.S portion of the Northern Appalachian–Acadian ecoregion (Y.-P. Tsang, unpublished data), and (3) a similar analysis investigating the association of CABIN (2017) data with stream temperature in Canada. The results of the temperature classification highlight three primary classes (Table 3.3; Figure 3.6); however, as with the previous classification variables, the number of classes can be modified depending on the user's needs.

Table 3.3. Stream and river temperature classes

Description	Stream temperature (°C)	Total length in region (km)*
Cold	≤ 18	123,157
Cool	19–21	71,467
Warm	≥ 22	8,305

*Values are for the Canadian portion of the study area only.

To verify the three temperature classes, the original temperature data points were compared with the reclassified Random Forest layer. More than 87% of the points were classified into the correct category; the Cold class had the highest accuracy at 96%, and Cool and Warm had comparably high accuracy, at 81% and 80%, respectively. In addition, benthic species data from the CABIN (2017) dataset were included in TITAN analysis (TITAN2, Baker and King 2010; for a detailed explanation of this analysis, please see Appendix C). Forty-nine taxonomic families showed significant response along the temperature gradient. Many species clearly declined or increased in abundance at the class breaks of 18 and 21, confirming the three temperature classes. The results also aligned with a study of fish species in the U.S. portion of the Northern Appalachian–Acadian ecoregion (Y.-P. Tsang, unpublished data).

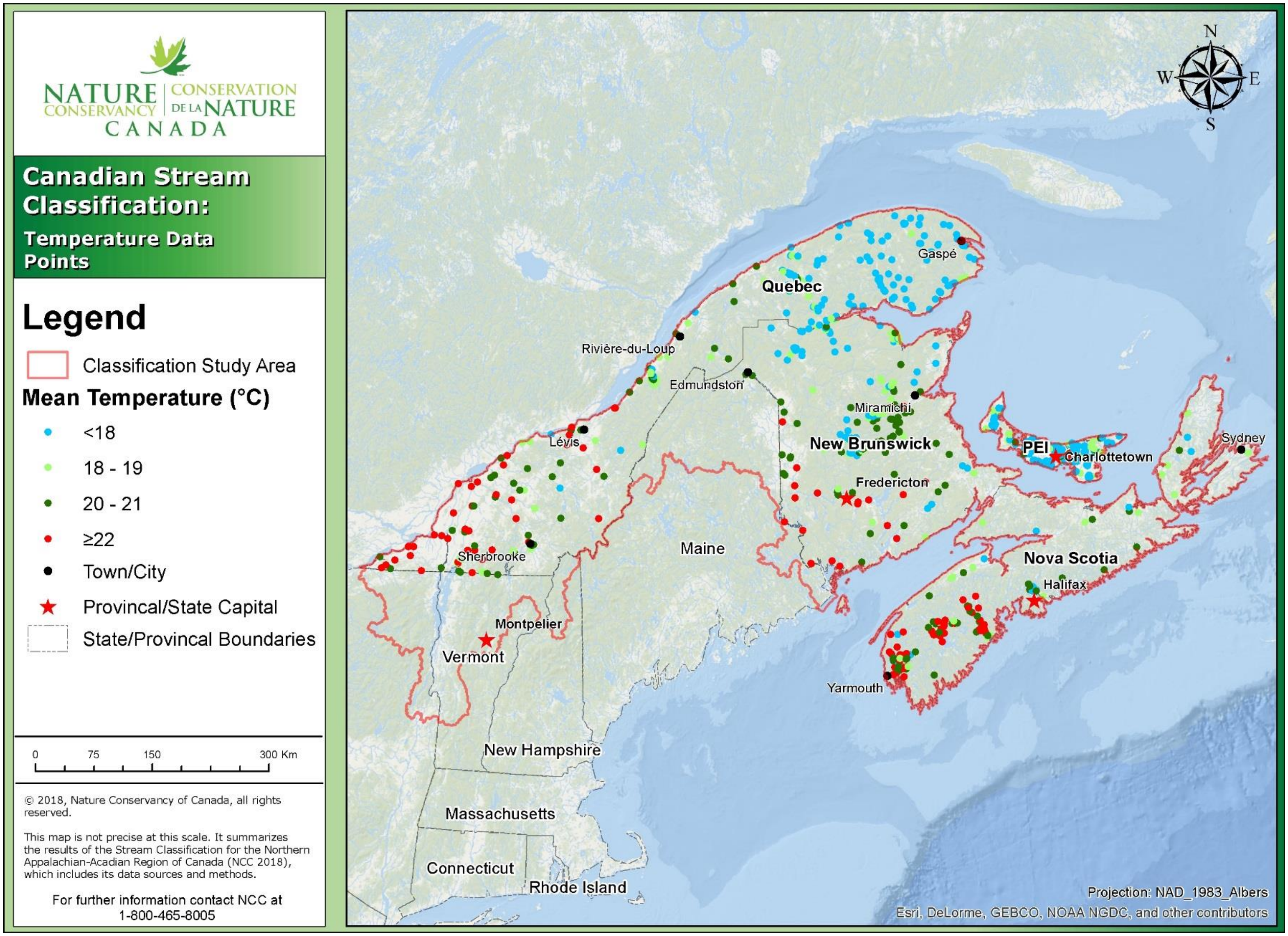


Figure 3.4: Mean summer temperature data points for the Canadian portion of the study area.

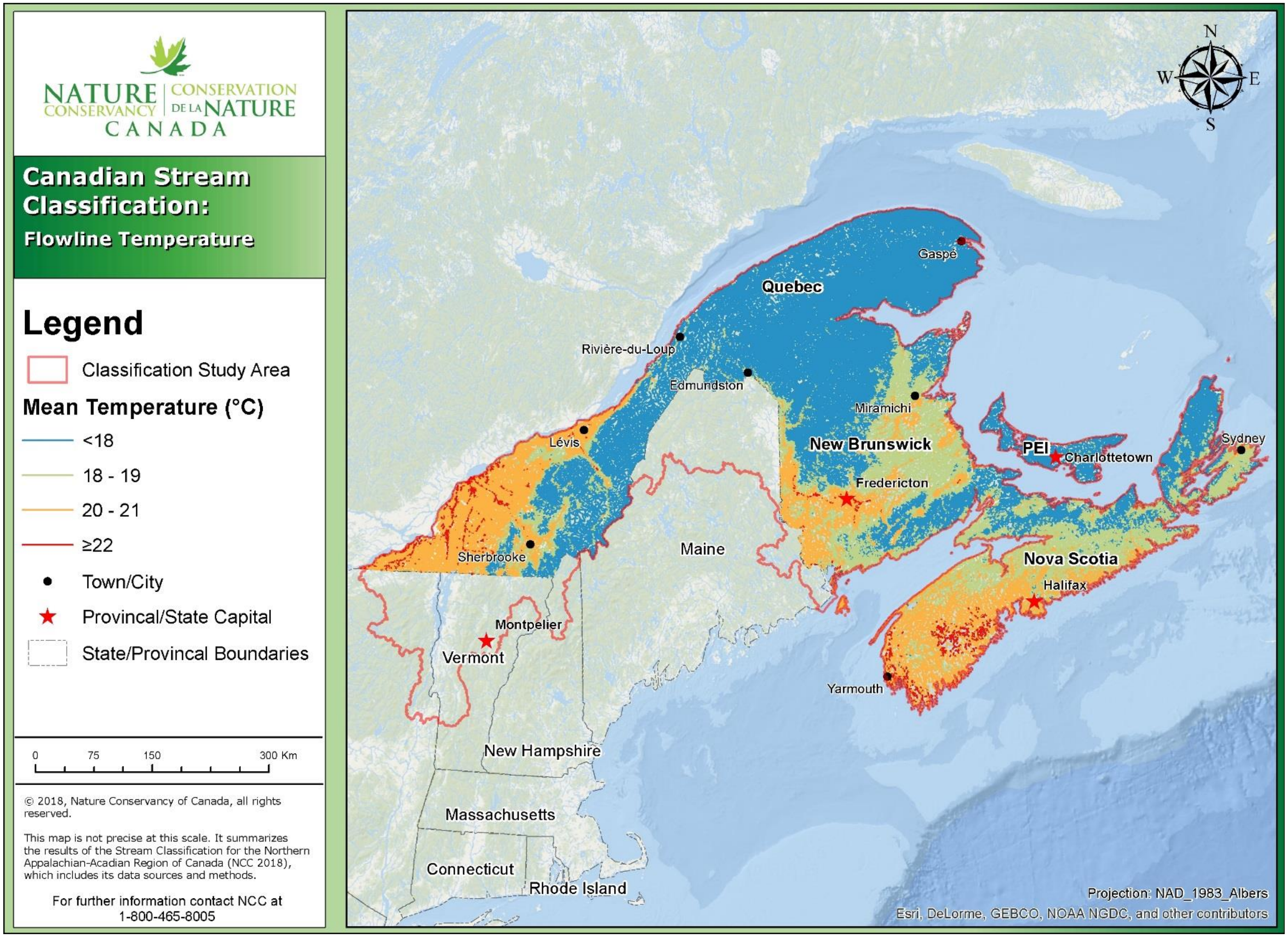
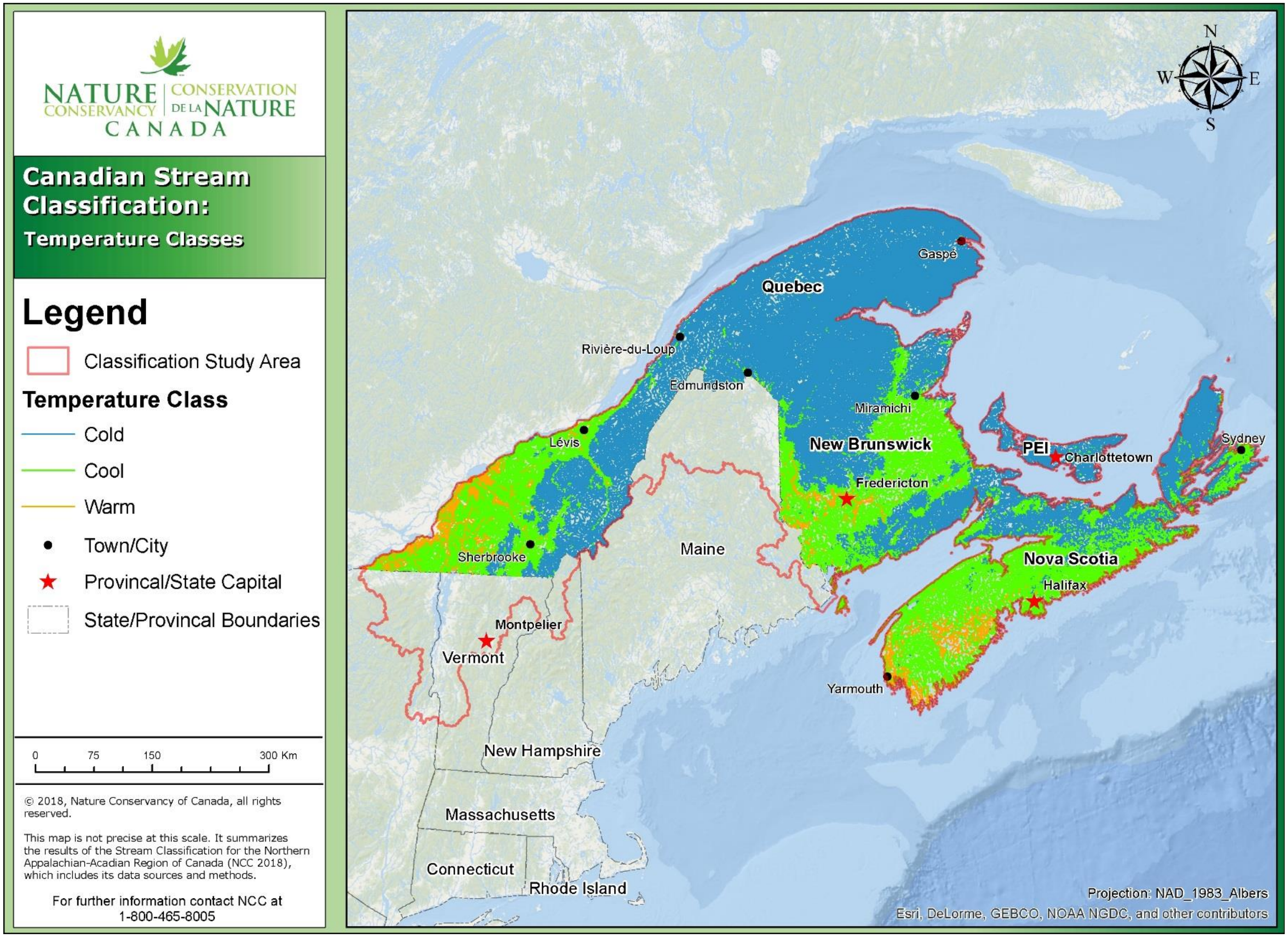


Figure 3.5: Mean summer flowline temperature for the Canadian portion of the study area.



Canadian Stream Classification: Temperature Classes

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Figure 3.6: Stream and river temperature classes for the Canadian portion of the study area.

Alkalinity

In freshwater ecology, alkalinity refers to the ability of a stream or river to neutralize acid; it is sometimes called "buffering capacity." Many aquatic organisms require water pH to remain within a particular range for optimal growth and reproduction. For example, streams with a pH of 5.0 or lower will not support many species of fish and other aquatic life (Allan 1995), yet some aquatic species, such as frogs, can withstand a much lower pH (USEPA 2015). Stream alkalinity is influenced by the composition of the soil and bedrock through which the water passes: streams flowing through regions of granite-based soils will have low alkalinity, whereas those in limestone regions will have high alkalinity (Hendrey et al. 1980).

Alkalinity data were obtained from five published sources: (1) National Rivers and Streams Assessment 2008–2009 of the U.S. Environmental Protection Agency (2016); (2) Water Quality Database (2017) of the Community Based Environmental Monitoring Network; (3) Long-term freshwater quality monitoring data for the Maritime Coastal Basin (2016) from Environment and Climate Change Canada; (4) Atlas interactif de la qualité des eaux de surface et des écosystèmes aquatiques from the Quebec Ministry of Sustainable Development and Fight Against Climate Change, Environment and Parks (2017); and (5) Surface Water Quality Data (2016) of the New Brunswick Department of Environment and Local Government. The analysis also drew from two unpublished studies (S. McLeod; C. Crane). The final map of alkalinity data points (n=616) can be seen in Figure 3.7.

As with the temperature analysis, the Random Forest statistical package was used (Liaw and Wiener 2002) to extrapolate the data points into an alkalinity layer. The final alkalinity layer explained 68.3% of the variance in the alkalinity data points using 13 predictor variables related to soils, the most important of which was soil surface cation exchange capacity. Once the final layer was completed, alkalinity values were assigned to all flowlines of the base hydrography (Figure 3.8). Alkalinity class thresholds were based on Olivero et al. (2015) and the U.S. Environmental Protection Agency (2017). The results of the alkalinity classification highlight three primary classes (Table 3.4; Figure 3.9); however, as with the previous classification variables, the number of classes can be modified depending on the user's needs.

Table 3.4. Stream and river alkalinity classes

Description	Alkalinity (mg/L of $CaCO_3$)	Total length in region (km)
Low Alkalinity	≤ 20	109,899
Moderate Alkalinity	21–50	85,329
High Alkalinity	≥ 51	30,691

To verify the three alkalinity classes, the original alkalinity data points were compared with the reclassified Random Forest layer. More than 95% of the points were classified into the correct category; the High Alkalinity class had the highest accuracy, at 99%, and Low and Medium Alkalinity had 95% and 86% accuracy, respectively. Benthic species data from the CABIN (2017) dataset were included in a threshold indicator taxa analysis (TITAN2, Baker and King 2010; for a detailed explanation of this analysis, please see Appendix C), the results of which supported the three alkalinity classes. Although one set of benthic species in the TITAN analysis responded to an alkalinity threshold ~10 mg/L, the expert team chose to lump this "very low" alkalinity group into the Low Alkalinity class, as was done in other classifications (Olivero-Sheldon et al. 2015, Olivero and Anderson 2008). In the Moderate Alkalinity class, the number of benthic taxa increased beyond 20 mg/L, whereas the High Alkalinity class had only a small set of taxa that preferred the most highly buffered habitats.

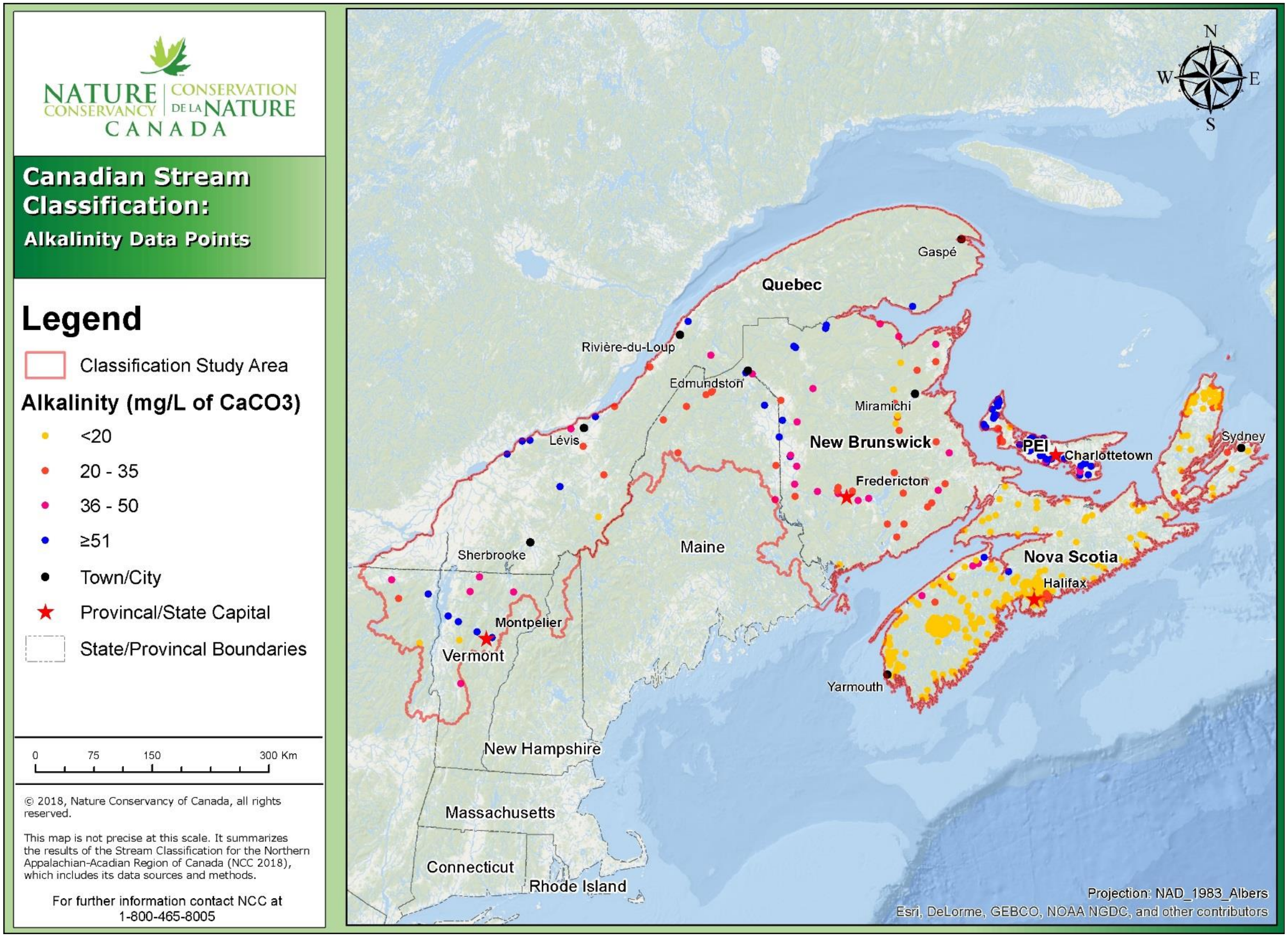
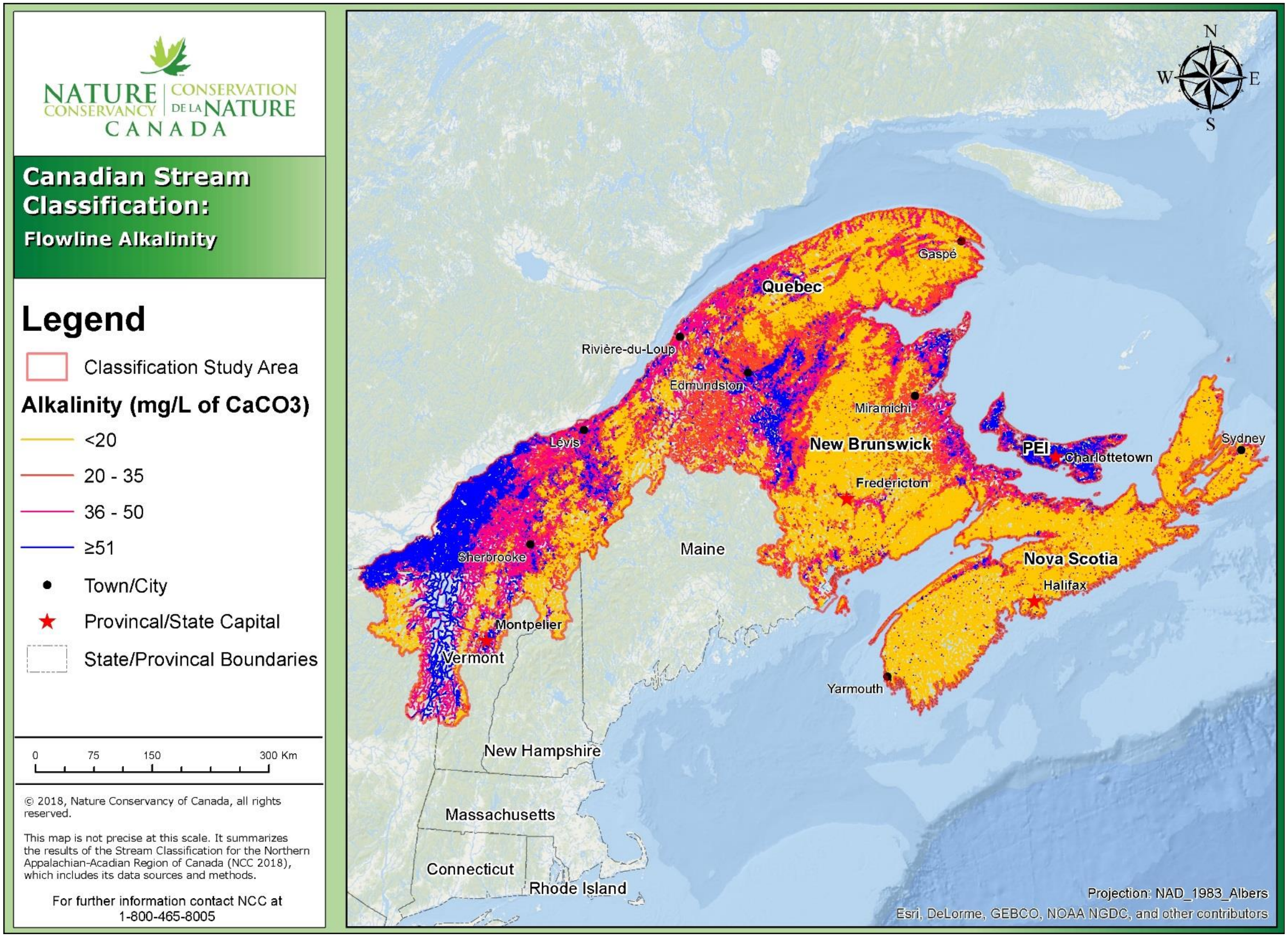


Figure 3.7: Alkalinity data points.



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Projection: NAD_1983_Albers

Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors

Figure 3.8: Flowline alkalinity.

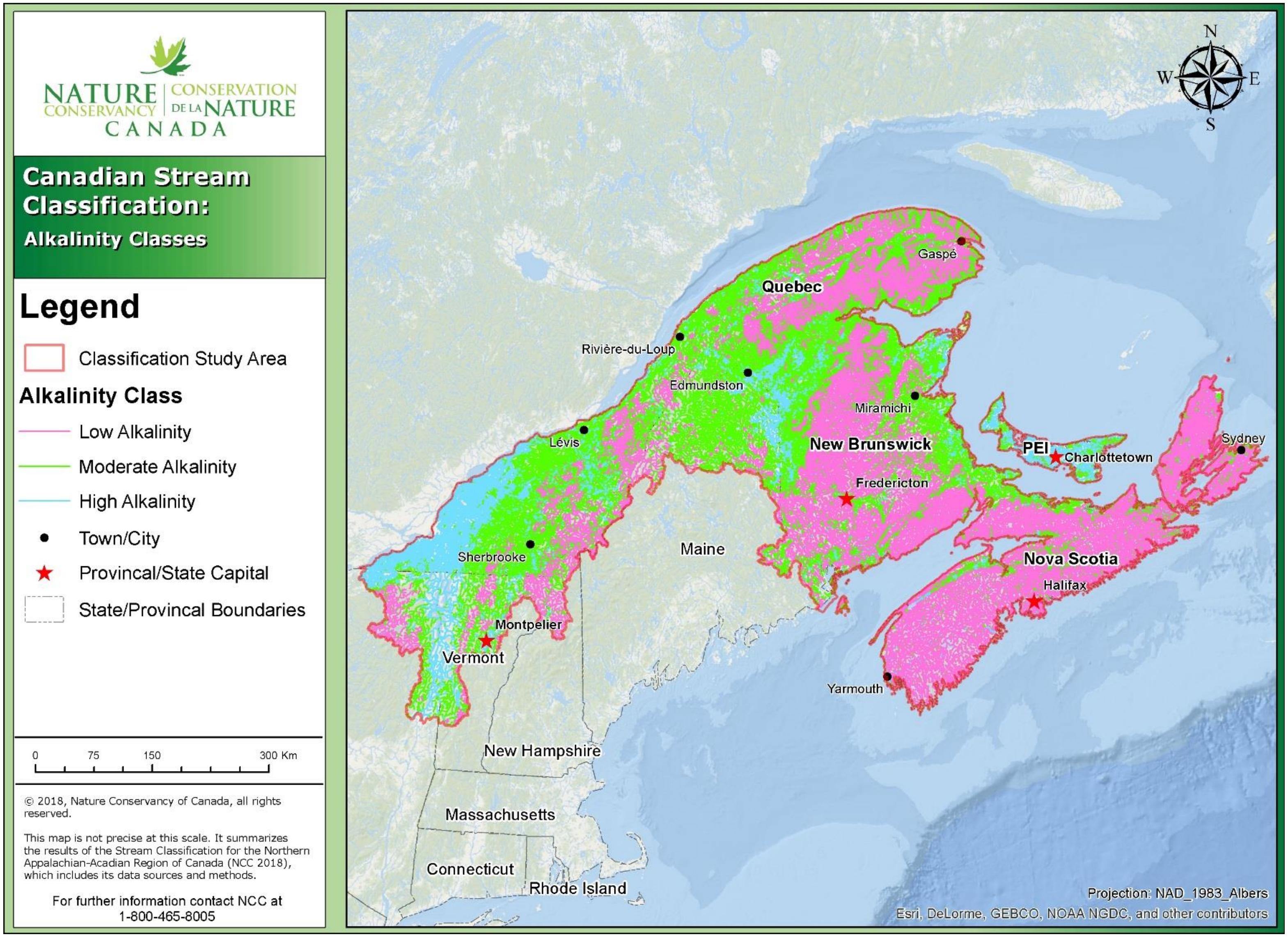


Figure 3.9: Stream and river alkalinity classes.

Tidal Influence

Streams and rivers that connect directly to the ocean or to estuaries are often strongly influenced by tidal forces. Both the flow of water and the concentration of dissolved salt (i.e., salinity) can fluctuate greatly as tides come in and go out, creating a gradient of freshwater, brackish, and saline conditions within the tidal zone. These conditions affect the abundance and distribution of aquatic communities, many of which are uniquely suited to a specific range of tidally influenced conditions (Olivero and Anderson 2008).

Because salinity data for rivers and streams in eastern Canada are incomplete, the tidal influence analysis is less robust than in the adjacent U.S. classification (Olivero and Anderson 2008). However, an interim analysis was completed using tidal height, the results of which are included as a placeholder in the classification until the required salinity data become available. Tidal height was determined using hydrolographic vertical separation surfaces (HyVSEPs), which are bathymetric products from the Canadian Hydrographic Service and the Canadian Geodetic Survey (Robin et al. 2016). HyVSEPs capture high and low tide height information across multiple data points, which can then be spatially extrapolated to define the tidal range (Figure 3.10). Selecting all flowlines within the base hydrography that overlapped with the tidal range layer yielded an approximation of tidally influenced streams and rivers (Figure 3.11). The approach greatly underestimates the total number and length of tidally influenced streams and rivers, but a simple binary definition must suffice until a more robust tidal influence analysis can be used to update the classification (Table 3.5).

Table 3.5. Stream and river tidal influence class definitions.

Description	Total Length in Region (km)
Tidally Influenced	4,070
Not Tidally Influenced	221,918

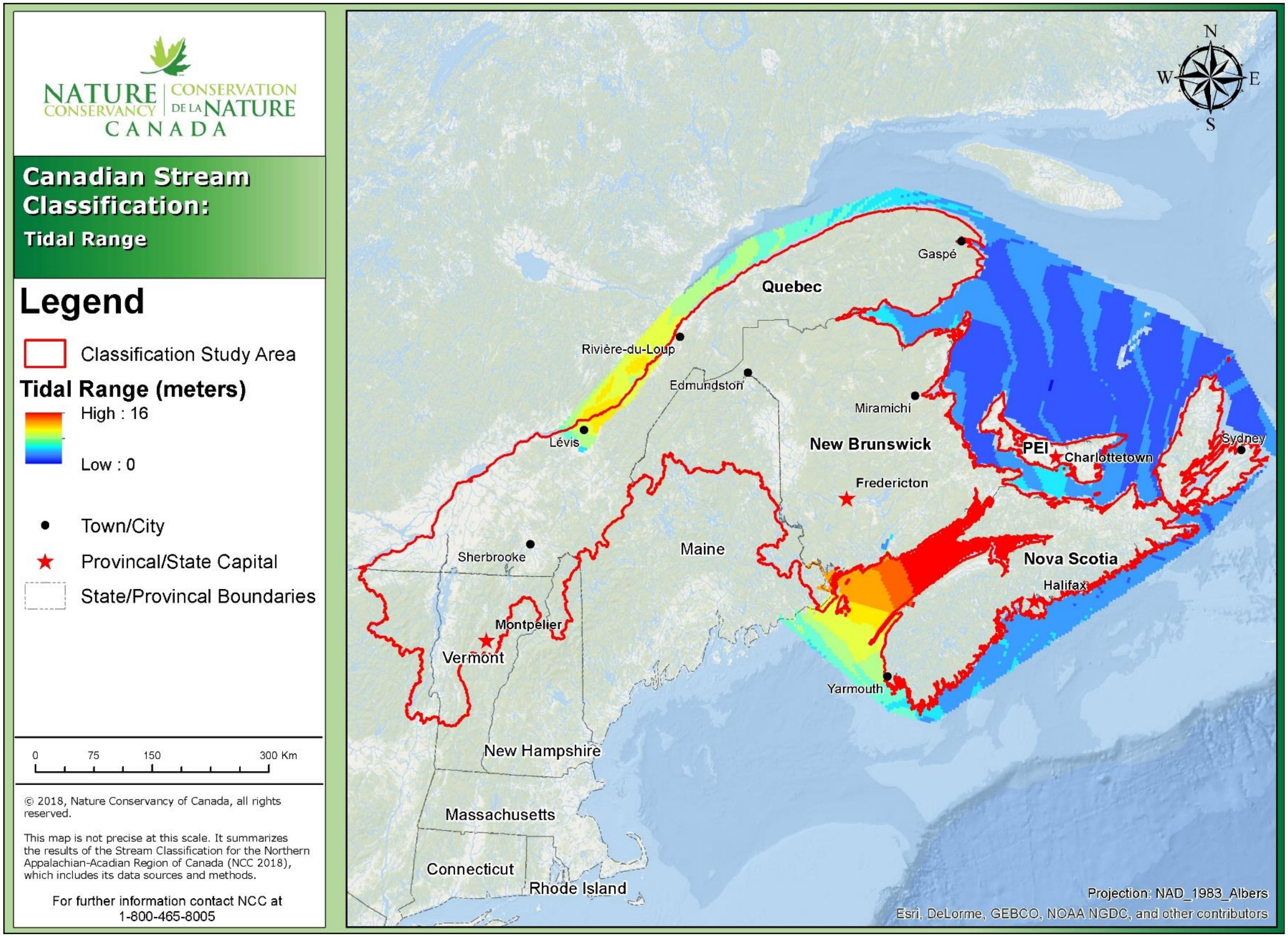


Figure 3.10: HyVSEP-derived Tidal Range.

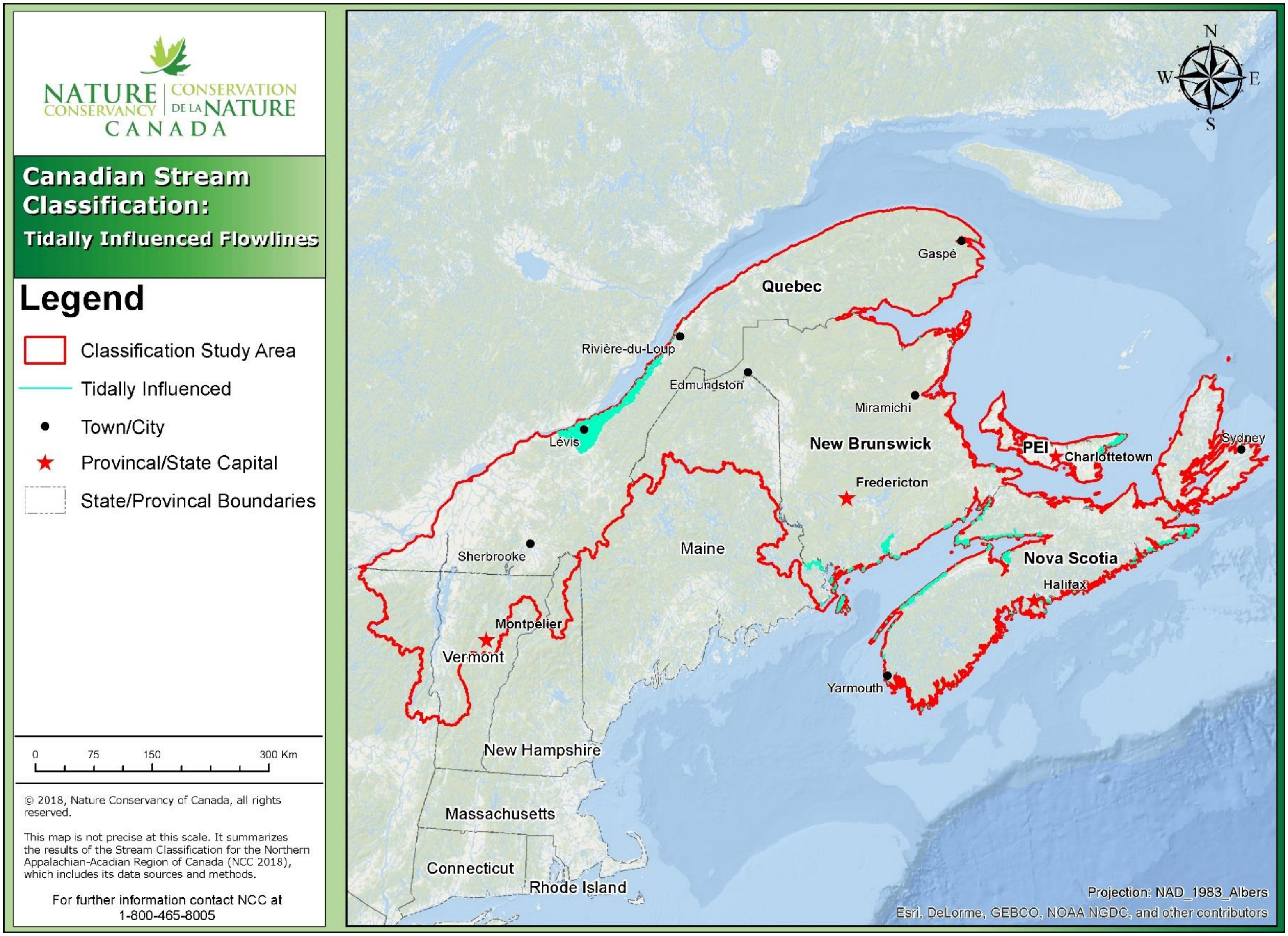


Figure 3.11: Tidally Influenced Flowlines.

4. Variable Combinations

Variable combinations refer to individual variables or combinations of variables that can be used to analyze the classification data, depending on the level of complexity preferred. Not all variables and classes will be relevant to all users, and for this reason, 10 taxonomies were developed to allow flexibility in symbolizing and classifying streams and rivers. These taxonomies are included in the GIS data as "layers," which collapse or expand the variable classes according to the combination chosen. Although users can develop their own taxonomies, the 10 taxonomies described below provide ready-made combinations that are both practical and ecologically relevant.

Individual Variables

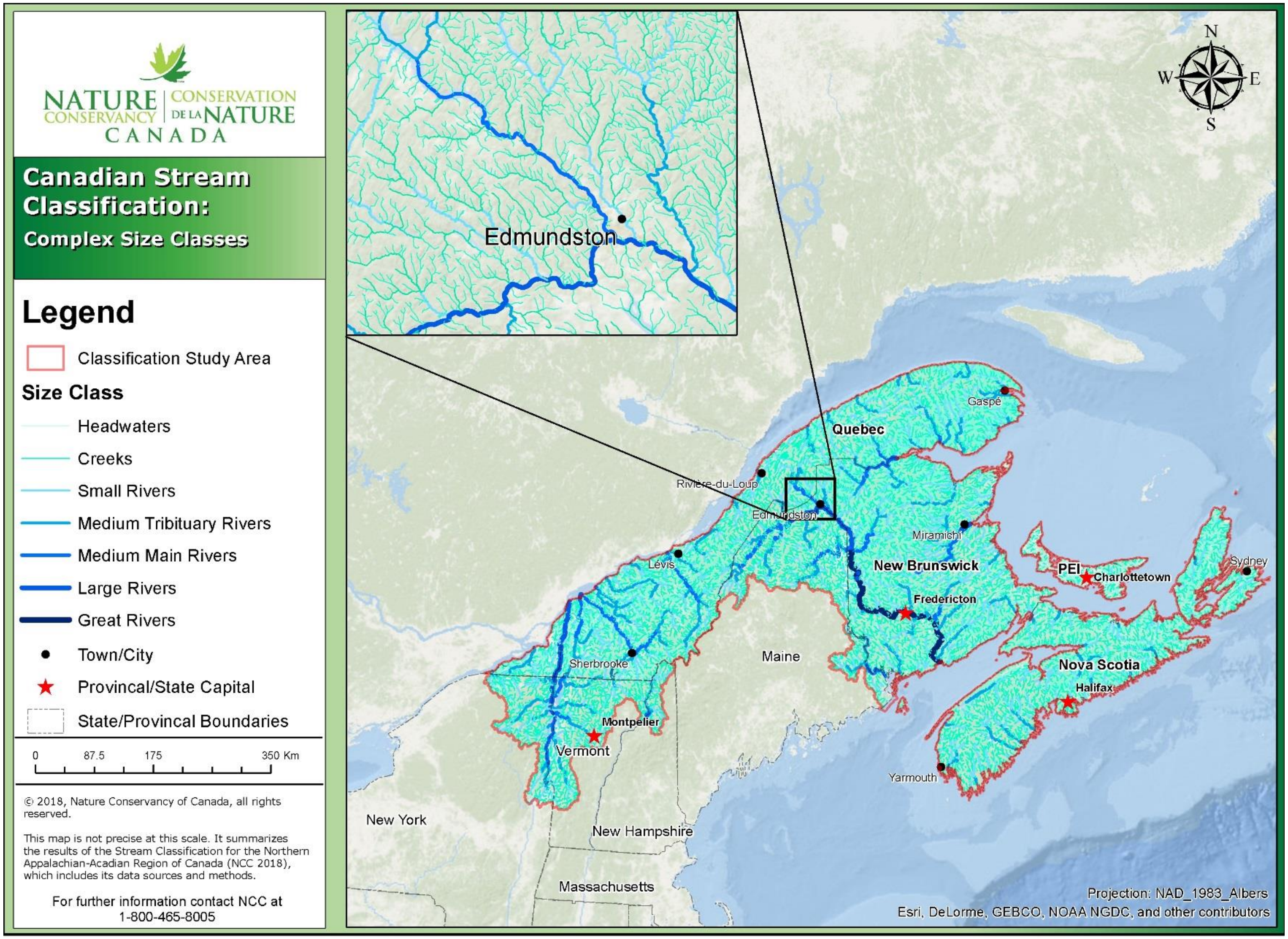
In the previous chapter, five variables were used to classify streams and rivers: size, gradient, temperature, alkalinity, and tidal influence. However, because size and gradient are particularly relevant to aquatic biodiversity (Vannote et al. 1980; Higgins et al. 2005; Rosgen 1994; Montgomery and Buffington 1997), a more complex taxonomy was created for both size (Table 4.1; Figure 4.1) and gradient (Table 4.2; Figure 4.2) so that users can analyze these variables in greater detail.

Table 4.1. "Complex" stream and river size class definitions.

Description	Upstream Drainage Area (km^2)	Total Length in region (km)
Headwaters	< 10	151,312
Creeks	≥ 10 & < 100	53,245
Small Rivers	≥ 100 & < 518	13,961
Medium Tributary Rivers	≥ 518 & < 2,590	5,377
Medium Main-stem Rivers	≥ 2,590 & < 10,000	1,379
Large Rivers	≥ 10,000 & < 25,000	391
Great Rivers	≥ 25,000	322

Table 4.2. "Complex" stream and river gradient class definitions.

Description	Stream Channel Slope (%)	Total Length in region (km)
Very Low Gradient	< 0.02%	19,441
Low Gradient	≥ 0.02% & < 0.1%	7,393
Moderate-Low Gradient	≥ 0.1% & < 0.5%	40,427
Moderate-High Gradient	≥ 0.5% & < 2%	76,770
High Gradient	≥ 2% & < 5%	47,571
Very High Gradient	≥ 5%	34,441



Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors

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Figure 4.1: Complex stream and river size classes.

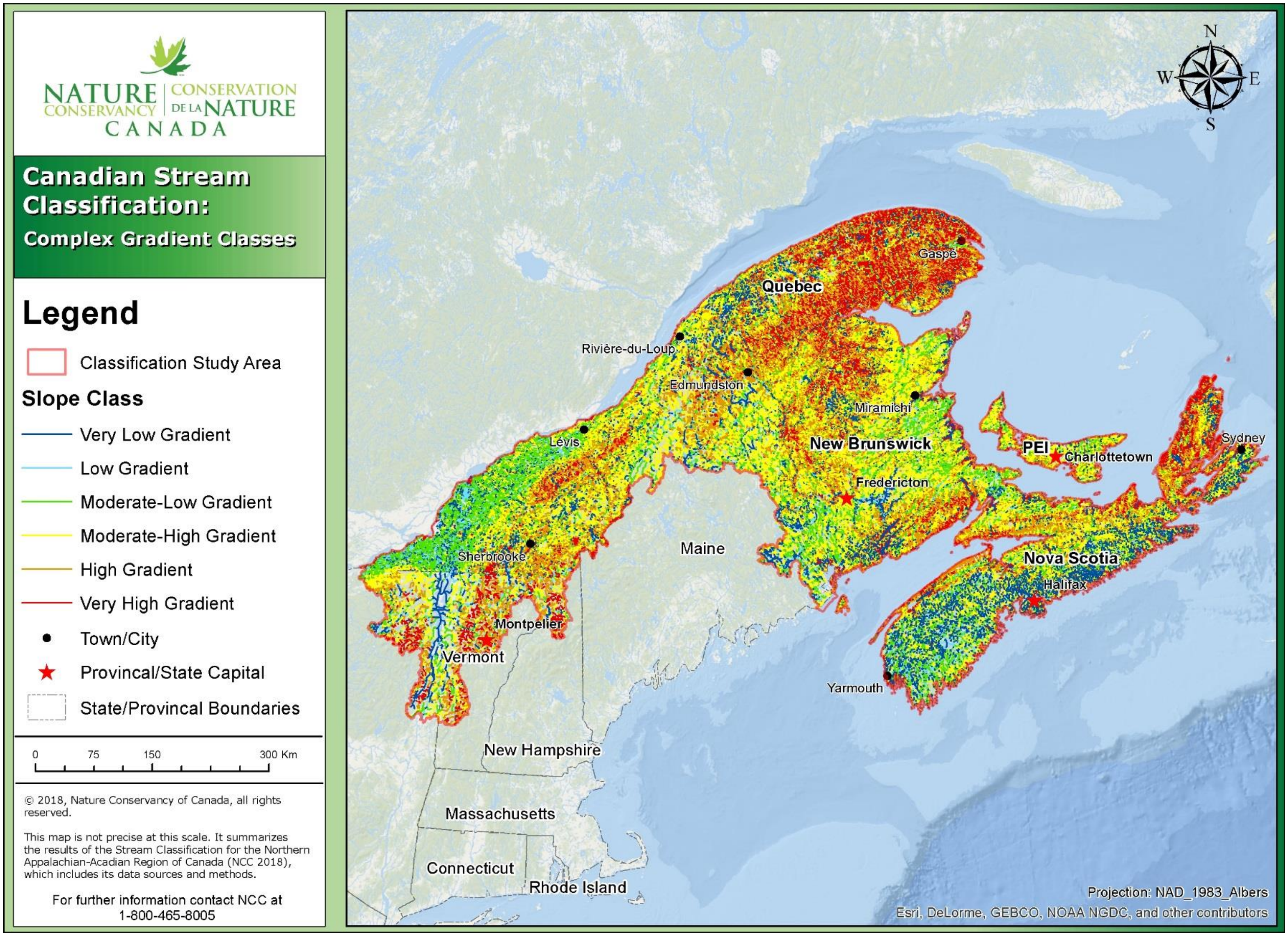

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Figure 4.2: Complex stream and river gradient classes.

Simple Combination

The simple variable combination aligns with the U.S. simplified habitat classification, which was developed with guidance from state-level freshwater ecologists (Olivero and Anderson 2008). This variable combination, best suited for general users, simplifies the alkalinity classes for headwaters through large rivers, and simplifies the gradient and temperature classes for medium to large rivers (Olivero and Anderson 2008). The simple combination resulted in 23 stream types, making it seamless with the U.S classification (Figure 4.3[2]; Appendix D).

Intermediate Combination

The intermediate variable combination provides a flexible set of stream and river types for planners and managers across the region, and it offers an appropriate level of detail for regional or provincial habitat guides. It is based on four size classes combined with the variables most likely to be ecologically relevant:

1. Headwaters and Creeks, and Small Rivers are defined by gradient (low, moderate, and high classes), temperature (cold, cool, and warm classes), and alkalinity (low, moderate, and high classes).
2. Medium Rivers and Large Rivers are defined by gradient (low, moderate, and high classes) and temperature (cold, cool, and warm classes).

This taxonomy resulted in 75 stream types (Figure 4.4[2]; Appendix D). Similar to the Simple Combination, tidal influence was only combined with the size class variables; stream and river types that have a tidally influenced version are identified in Appendix D.

Complex Combination

In total, the five class variables resulted in 216 possible combinations of size (4), gradient (3), temperature (3), alkalinity (3), and tidal range (2). However, many combinations do not exist in reality. For example, although large rivers may occasionally have stretches with high gradients, such as waterfalls, at the scale of the classification, any "high-gradient large rivers" are likely to be an error originating from the DEM. For this reason, the complex taxonomy yields only 166 of the 216 possible combinations (Figure 4.5[2]; Appendix D). Moreover, many of the 166 combinations occur only in very short segments, which again may reflect errors in the classification rather than habitats that are truly rare or unique. Although no combinations will be deleted from the classification without supporting ground-truthed evidence, it is

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[2] Because the temperature analysis could not be completed for the US portion of the study area, the combination maps only illustrate Canadian streams and rivers.

important that managers and planners recognize the possibility of error and treat as suspicious any combination less than 10km long at the regional scale.

To verify the combined classes, statistical analyses were conducted to compare the relationship between predicted class combinations and known benthic taxa data. Generally, there was a strong correlation between the combined classes and benthic taxa, with temperature and gradient proving the strongest predictor variables. For a full description of the statistical analyses, see Appendix E.

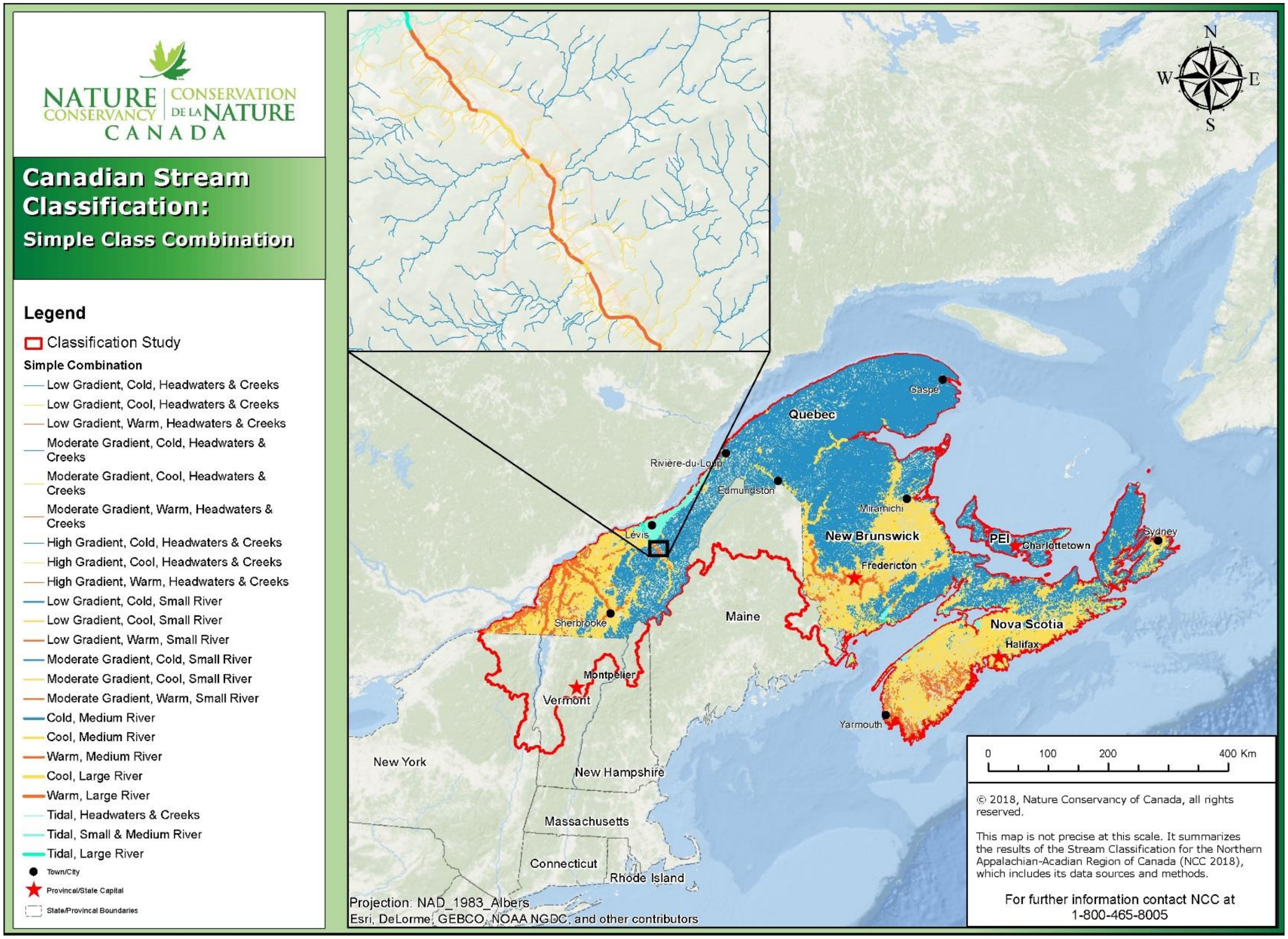

Figure 4.3: Simple combination classes.

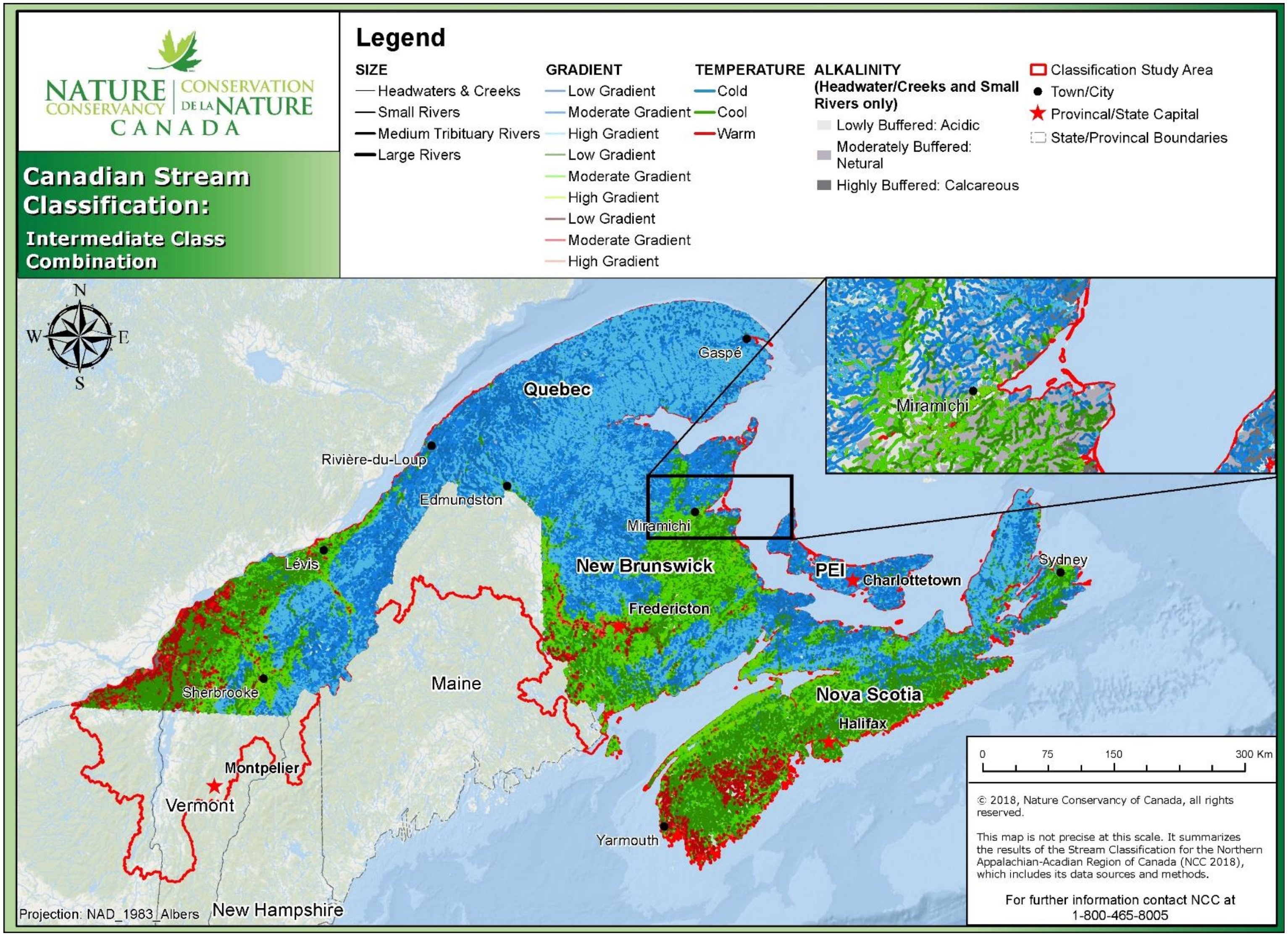

Figure 4.4: Intermediate combination classes.

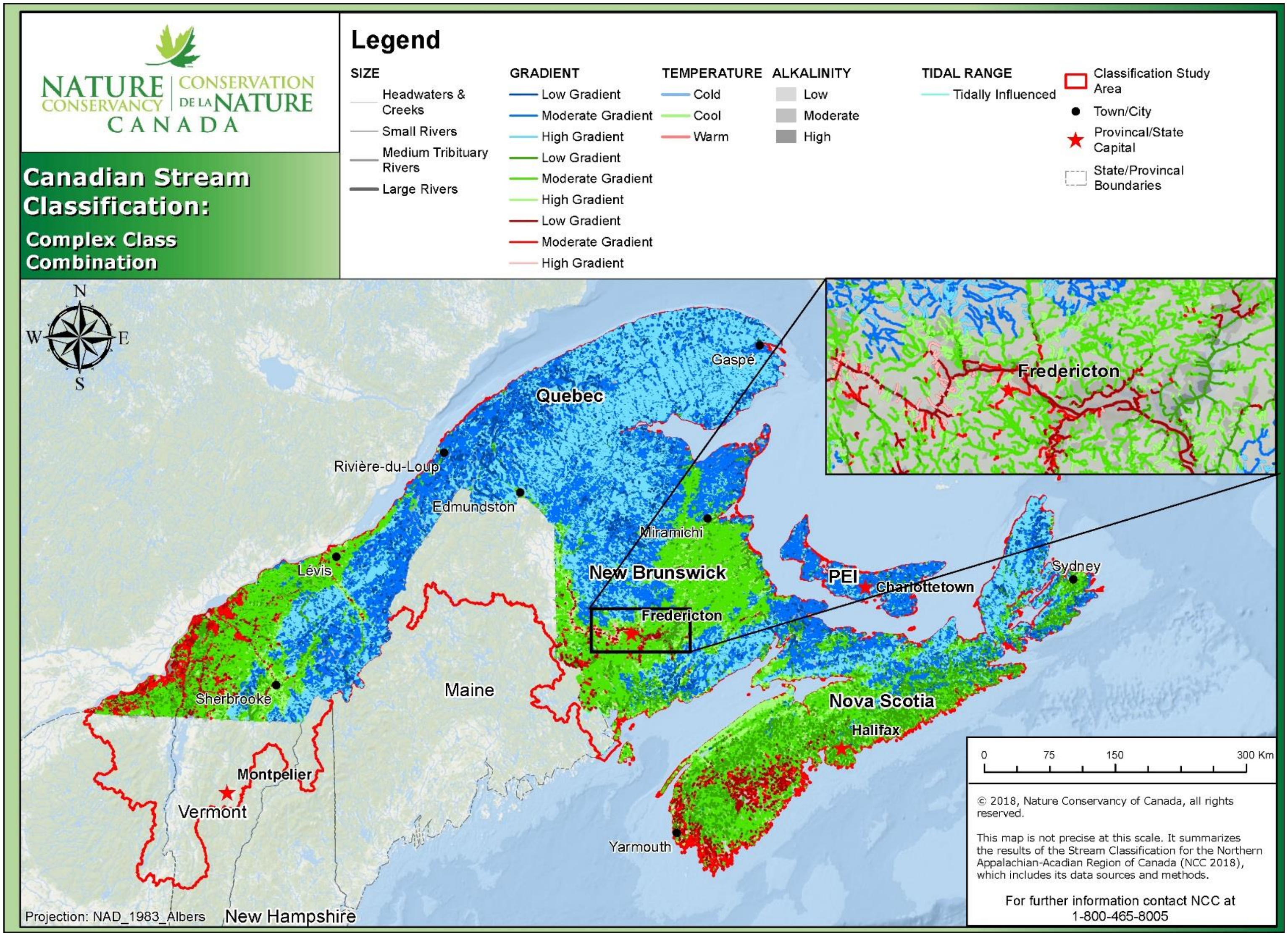

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Figure 4.5: Complex combination classes.

5. Discussion

As statistician George Box (Box and Draper 1987) observed, “All models are wrong, but some are useful.” It must be acknowledged that as a modelling exercise, this classification is a simplification of the ecological complexity of stream and river systems. However, it is also a useful tool to identify these systems and allow land-use planners and managers to better understand how the systems interact with the surrounding landscape. Eastern Canada has had a considerable aquatic data gap, and this classification represents the first comprehensive attempt to identify and map stream and river ecosystems across the region. Because the methods are adapted from an earlier U.S. classification, this effort allows for comparison of streams and rivers across the Northern Appalachian–Acadian ecoregion. That said, the classification should be treated not as a definitive source on freshwater taxonomy and distribution, but as a guide that will be improved over time.

Utility of Results

Stream and river ecosystems are dynamic, and therefore the relationships between local land-use decisions and downstream consequences can be difficult to define and trace. The ability to establish these relationships is an important aspect of responsible freshwater management: it allows land use planners and managers to make informed decisions. Additionally, planners and managers need to identify freshwater ecosystems that are unique, rare, or threatened to guide conservation and restoration activities, both locally and at the regional scale. The social and environmental value of comprehensive aquatic planning is massive: more than 225,000 kilometers of streams and rivers run through the region, providing food, fresh water, energy, and recreation for people, while also supporting an incredible diversity of wildlife.

This classification supports freshwater planning and management throughout the region at various spatial scales. At the local scale, watershed groups can use the classification as a decision-support tool when choosing to protect or restore freshwater habitats. Municipal land-use planners can use it to help communities develop nature-based solutions to mitigate the consequences of climate change and to identify areas important for maintaining drinking water supply and quality. Researchers can use it to support studies on landscape-scale patterns that alter regional and local freshwater ecosystems, as well as to determine the thresholds of human influence that compromise freshwater health. Lastly, government agencies can use it to identify cost-saving opportunities for natural storm-water and floodwater storage and retention (i.e., “green infrastructure”), as well as provincial-scale climate change adaptation measures. The widespread adoption of the U.S. stream classifications by U.S. organizations indicates the high potential for the Canadian classification to be applied, and we view it as a tool that will strengthen collaboration and knowledge sharing across the region.

Limitations

As with all projects of this size and complexity, issues of data availability and resolution resulted in several limitations. The traditional spatial tools for delineating watersheds were not sufficient for this regional-scale analysis, which highlights the need for higher-resolution digital elevation models in future analyses. To remedy this problem, other watershed delineation tools were explored, and one in particular greatly improved the quality of the watershed delineations (see Appendix B). However, an advanced level of GIS knowledge was needed to use this tool, and the resulting trade-off means that the delineation process is difficult to replicate.

It is also important to note that the base hydrography is not free of error. As illustrated in Appendix A, errors in the base hydrography layer required fixing. Although automated processes greatly improved our ability to address them, many could only be fixed by time-consuming manual editing. Inevitably, some errors were missed. However, as we progress with subsequent analyses, the base hydrography will be corrected and updated.

Another challenge was acquiring spatial data that could be combined across the four Canadian provinces and between Canada and the United States. Some data gaps could only be filled with coarse-resolution data of different coverages, time periods, or collection protocols. The tidal influence analysis was greatly limited by a lack of data on river salinity, and as a result, distinguishing among freshwater, brackish, and estuarine systems was not possible. Acquiring salinity data is a high priority for future work. Additionally, the temperature dataset used in the U.S. classification (Olivero and Anderson 2008) is now outdated by almost 10 years, and as a result, the U.S. and Canadian temperature layers are not comparable. Any updates to the U.S. classification will be used to update the Canadian classification as well, allowing for a seamless temperature layer across the border.

Lastly, although lakes and ponds are important components of freshwater ecosystems in the region, they lay beyond the scope of this analysis. Classifying lakes and ponds based on their biophysical characteristics would involve a very different approach than was taken for streams and rivers, and integrating the two classifications would require considerable time and effort. However, this is a high priority, and a spatial layer of waterbodies larger than 2 hectares has already been developed as a foundation for a future lake and pond classification.

Next Steps

In addition to addressing the limitations described above, the Nature Conservancy of Canada will build upon the stream classification by developing a Freshwater Conservation Blueprint for the region, comprising three main elements: (1) an aquatic connectivity analysis, (2) a watershed stress index, and (3) a watershed prioritization analysis, each of which are detailed below. Additionally, a separate but related tool called the "active river area" will be developed to spatially identify lands adjacent to streams and rivers that directly impact their health. These tools will allow individuals and organizations to set conservation and restoration priorities at multiple spatial scales throughout the Canadian portion of the Northern Appalachian–Acadian region.

Maintaining stream connectivity within a watershed provides multiple benefits to both people and wildlife. Once identified and mapped, potential barriers (e.g., dams, culverts, causeways) to free-flowing water can be prioritized, whether for stream restoration to promote freshwater biodiversity, or for maintenance of critical transportation infrastructure. The aquatic connectivity tool will be developed to achieve both outcomes, allowing for stronger collaboration in freshwater conservation and restoration throughout the region. Furthermore, spatially identifying these barriers in a GIS database allows for their cumulative effects across watersheds to be assessed, which in turn will allow governments to better understand the landscape-scale consequences of climate change–induced flooding and other human impacts, and to design mitigation strategies accordingly.

Identifying watershed stressors and designing an index to measure their effects on freshwater health is critical to setting conservation and restoration priorities. Stressors are defined as any physical, chemical, or biological entity that can cause an adverse effect (USEPA 2017). Stressors that influence watersheds can come from a variety of human activities, including man-made barriers, improper agricultural practices, point-source pollution, and development of impervious surfaces. Once a suitable set of watershed stressors is identified and mapped, a quantitative index can be developed, which will allow for consistent comparison of the relative stress across watersheds.

Using both the watershed stress index and the findings from the classification regarding rare and unique freshwater habitats, a prioritization analysis will highlight those watersheds that are high priority for conservation (high ecological value and low stress) or restoration (high ecological value and high stress). This analysis will allow conservation groups throughout the region to strengthen their planning and implementation by focusing on the highest-priority areas for aquatic biodiversity. The results of this analysis will be integrated into Nature Conservancy of Canada's core business planning to ensure that limited conservation dollars are spent in areas that are most in need of intervention.

Lastly, the Active River Area (ARA) assessment will spatially identify lands that directly influence aquatic systems, including floodplains, terraces, and riparian wetlands. This framework will allow land-use planners to identify where current infrastructure is vulnerable and where future development is at risk. It will also identify areas that provide high-value ecosystem services, such as storm-water storage areas, which if conserved or restored could reduce future downstream damage from flooding. Furthermore, riparian systems have high biodiversity value, and by spatially identifying these systems, conservation groups can focus efforts in these areas.

The completed Freshwater Conservation Blueprint will be a freely accessible suite of robust freshwater planning tools for individuals and organizations of all sizes and sectors. By identifying and prioritizing freshwater systems that provide value to both people and wildlife, we envision these aquatic tools promoting collaborative efforts in guiding sustainable development and conserving freshwater biodiversity throughout the region.

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Appendix A. Hydrography Edits

Disconnected Flowlines

The hydrography initially showed many tributary reaches not connected to their mainstream river (Figure A1). This error prevented them and their attributes from being included in the geometrically correct hydrography layer. The misalignments were manually corrected for the entire base hydrography layer, however, errors still likely exist and will be corrected wherever they are found.

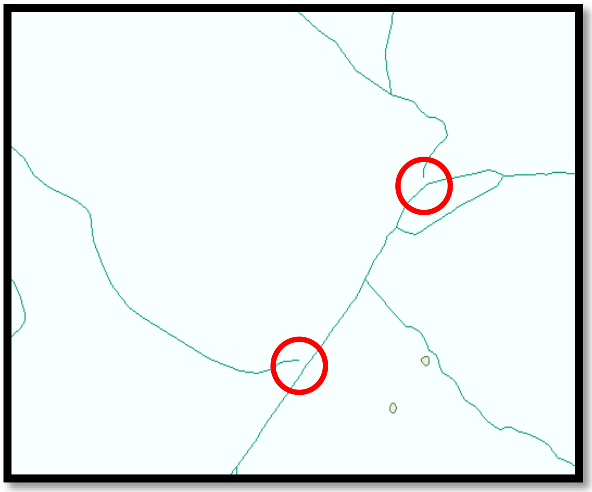

Figure A1. Disconnected flowlines

Conflicting Flow Direction

Even when properly connected, many flowlines had conflicting direction errors. The Barrier Analysis Toolkit (BAT)[3] helped identify most of these errors, and the remainder were identified via visual inspection. Correcting flow direction errors required selecting each segment and either manually reversing its vertices or, if the segment appeared to be a "dangle" (see below), manually deleting it and merging the two remaining segments (Figure A2).

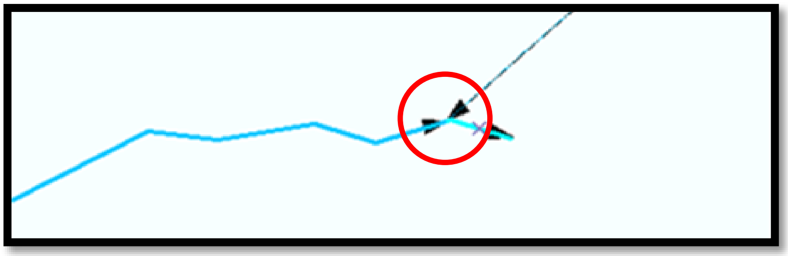

Figure A2. Conflicting flow direction

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[3] https://www.conservationgateway.org/News/Pages/connectivity-analysis-too.aspx

Dangles

A dangle is a short continuation of a flowline rather than an actual segment of stream (Figure A3). Most dangles in our hydrography dataset were found at the edge of waterbody polygons as a result of DEM resolution errors. All dangles that would have resulted in an incorrect catchment delineation were manually removed from the hydrography layer.

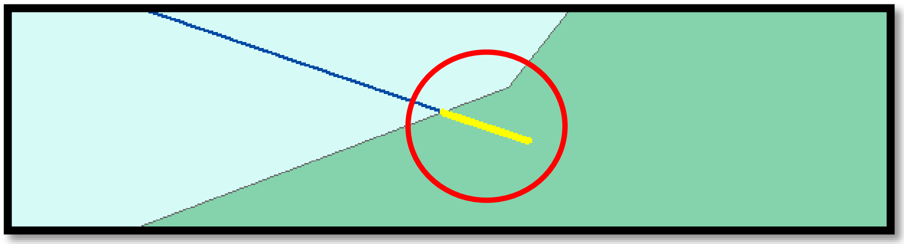


Figure A3. Erroneous flowlines or "Dangles"

Duplicate Node IDs

With the BAT tool, the base hydrography layer was analyzed for duplicate node IDs, which are flowlines that share the same *from* and *to* points; that is, they form a loop (Figure A4). All flowlines identified as having duplicate node IDs were deleted.

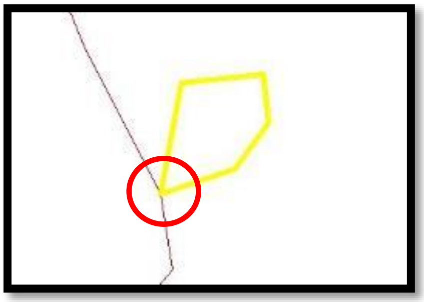


Figure A4. Duplicate node IDs

Simple Bifurcation Errors

The BAT tool identified simple bifurcation errors, which are areas where a node's downstream polylines both flow away from the same point. Bifurcation errors create problems with several of the automated tools used to develop the classification and were therefore removed. Where these errors occurred, aerial imagery was used to select the true channel and then delete the secondary flowlines.

Braided Stream Networks

Braided streams occur where rivers split into many small divergent channels, most often in tidally influenced areas where watercourses enter estuaries. These braided networks do not have true "catchments" relevant to the classification. Braided stream networks create problems with several of the automated tools used to develop the classification and were therefore removed. Where these errors occurred, aerial imagery as used to select the true channel and then delete the secondary flowlines.

Incorporation of Waterbodies

Although lakes and ponds were not classified as part of this analysis, they strongly influence river and stream systems. To capture changes between inflow and outflow, we split stream and river flowlines where they intersected a waterbody. In the preliminary gradient analysis flowline gradients were much more generalized than expected. However, once flowlines were split by waterbody polygons, gradient results were much more precise because they reflected more accurate elevations at waterbody inlets and outlets.

Manual Edge Matching Process

Because Canadian and U.S. hydrography use different scales (1:50,000 and 1:100,000, respectively), the two layers could not be seamlessly joined. To match edges, we manually appended the different layers across the Canada-U.S. border (Figure A5). Tributary flowlines that were missing because of the difference in scales were manually digitized (shown as purple lines) based on aerial imagery.

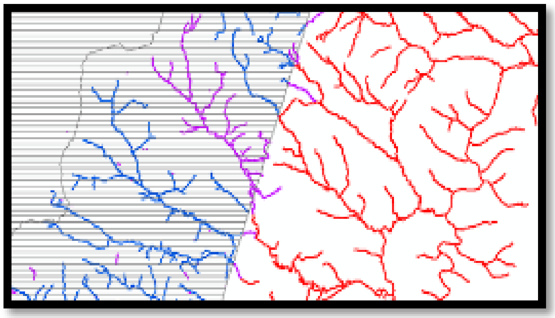


Figure A5. Hydrography edge matching.

Appendix B. DEM Reconditioning

Because of the coarse resolution of the digital elevation model (DEM) data used in this analysis, a DEM reconditioning process was carried out to improve the precision of the classification results. Although DEM reconditioning is possible in the ArcGIS ArcHydro extension, a tool designed in an older programming language was found to produce better results, given the size and scale of data used in this classification. The AGREE.AML tool increased the degree of agreement between the base hydrography and flow directions derived from the elevation values. Its reconditioning function modifies a DEM by imposing the base hydrography onto it, "burning in" the stream network (Figure B1).

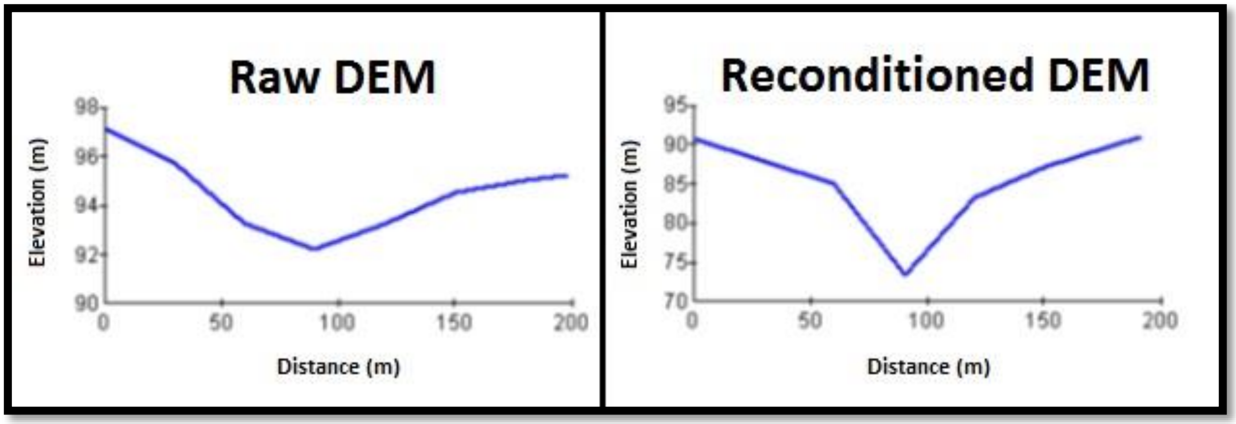
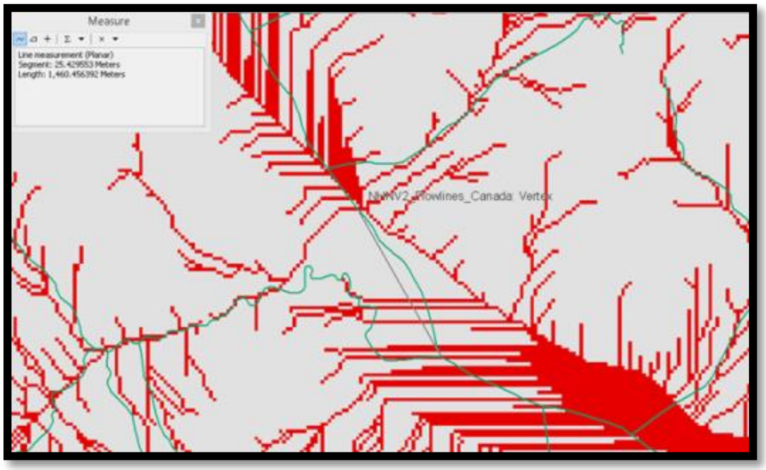


Figure B1. Example of DEM reconditioning of stream elevation

AGREE.AML uses a "stream buffer" parameter to dictate the spatial extent of surface reconditioning (i.e., the area around the stream that will alter DEM elevation values to form a stream bed). The buffer distance is set approximately equal to or slightly larger than the spatial scale of alignment error between the base hydrography and the raster-predicted streams derived from flow accumulation models. As shown in Figure B2, the disagreement between the base hydrography and the raster-predicted streams was significant, with the DEM's flow accumulation picking up many artificial flowlines, likely because of the coarse 30m resolution. The discrepancies guided where to begin experimenting with the stream buffer parameter.



Line measurement (Planar)
Segment: 25.429553 Meters
Length: 1,460.456392 Meters

Figure B2: Base hydrology (green) vs. raster-predicted streams (red)

Within the AGREE.AML tool, the "smooth drop/raise" parameter is the amount that the river or stream will be dropped or extruded (i.e., the depth of the stream bed). This creates a distinct profile along streams and is the value used to interpolate the DEM into the buffered area. The following formula was used to calculate the smooth drop/raise parameter:

(Mean Area Slope Inside Buffer) * (Buffer Distance) * (Forcing Factor)

where Mean Area Slope Inside Buffer is the average slope inside the stream buffer (discussed above), Buffer Distance is the width of the stream buffer, and Forcing Factor is a parameter that controls the magnitude of the alteration, with 0.0 being close to the original slope and 0.5 corresponding to a doubling of the slope. The "sharp drop/raise" parameter controls how much the river or stream will be dropped or extruded (i.e. height of buffer distance) after the initial smooth modified elevation grid is computed (i.e. smooth drop/raise parameter). This essentially digs a trench/raises a wall around the river or stream to help reinforce the initial smooth distance parameter (Hellweger 1997)

After experimenting with several AGREE.AML parameter values, we found that the most realistic catchments were produced with the following values:

Buffer Distance (Stream Buffer Distance): 120 meters
Smooth Distance (Smooth Drop/Raise Distance): 200 meters
Sharp Distance (Sharp Drop/Raise Distance) : –50,000 meters

Once the DEM reconditioning parameters were determined, the DEM needed to be "filled" to ensure that any small imperfections were smoothed over.

Appendix C. Threshold Indicator Taxa Analysis

We used statistical analysis of benthic species distribution and abundance to explore patterns in how taxa were associated with changes in four environmental variables: size, gradient, temperature, and alkalinity. Benthic taxa counts came from the CABIN (2017) dataset for the project area. The data covered all four provinces but were limited in geographic distribution, with fewer samples available in Quebec, particularly the Gaspe Bay peninsula. Nevertheless, CABIN had the most consistent, best available data across the full study area (Figure C1).

The CABIN dataset used a standardized subsampling method to estimate a complete count of each taxon's abundance in a given sampling event. The database for our study area contained 23,478 records of site-taxa abundance information collected between June 1 and September 30 between 2002 and 2016 and included 656 unique site-date sampling events. These 656 events fell on 307 reaches. Our smallest classification unit is the reach, so we summarized the average "CompleteCount" for each taxon at the family level (total complete count / # site-date samples) for each reach. Family-level taxonomy was chosen because many samples were not keyed out to the genus and species level, whereas family information was consistently available for all biota samples. This allowed comparison and analysis across all the provinces and samples. We then removed families that did not occur in at least four catchments; by eliminating these rare taxa, we met the statistical requirements for TITAN analysis. The remaining 119 families were used in further analysis.

The benthic samples covered a wide range of our modeled environmental variables. The 307 stream reaches with biotic samples represented all gradient, temperature, and alkalinity classes, and they included samples in six of our seven size classes (the largest, Great River, was not represented). The input reaches with biotic data specifically ranged from 0.198km^2 to 17,387km^2, with a mean of 500 and standard deviation of 2,431. For gradient, they ranged from 0.00001 to 20.84, with a mean of 1.40 and standard deviation of 2.36. For temperature, they ranged from 13.46°C to 23.75°C, with a mean of 19.23 and standard deviation of 2.01. For alkalinity, they ranged from –1.83 mg/l $CaCO_3$ to 114.15 mg/l $CaCO_3$, with a mean of 18.84, and standard deviation of 17.68. Although we might have desired more even coverage in the number of samples in each class and across the range of values found in our mapped variables, TITAN was still a valid exploratory nonparametric analysis approach, and we were pleased that a full range of the mapped environmental variables were also represented in our biotic sample data locations. Future work should attempt to integrate additional biotic samples in the several variable classes that had fewer samples, such as larger rivers and very low gradient streams. Future work would also benefit from analysis at the genus and species level for watersheds where these data are available, and from consistently keying all animals to the genus or species level.

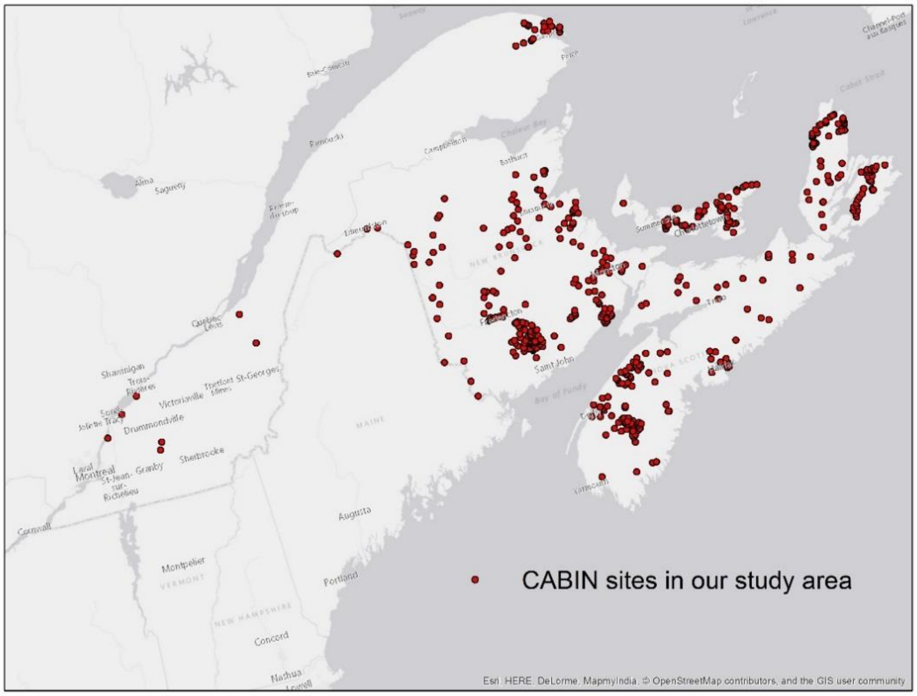


Figure C1. CABIN sample sites

We used Threshold Indicator Taxa Analysis (TITAN2, Baker and King 2010) to explore whether the environmental changes significantly correlated with changing distribution and abundance of taxa. TITAN uses indicator species scores across binary partitions of a sample set to detect congruence in taxon-specific changes in abundance and occurrence frequency along the range of environmental variables. Ecological transition points (or zones of rapid change) are identified in the biological data in response to small, continuous increases in an environmental variable (Baker and King 2010). These are the points or values at which significant changes in a taxon's abundance are apparent. Similar to ordinations, this analysis is exploratory, but TITAN has significant advantages: it distinguishes the strength and direction of species response (increasing or decreasing below or above a change point), is nonparametric and is available in R, and the output is shown on a standard graph.

The TITAN taxon change point plots for each variable (Figures C2–C6) display the change points at which a taxon's abundance increases as a measured environmental variable decreases or increases as the variable increases. Only significant taxa are shown. The individual taxa and their change point values and other relevant statistics are also presented in tabular form in Tables C1–C4.

We used recommended default parameters: a minimum of five observations on either side of an environmental change point, 250 random permutations of the taxa data, and 500 bootstraps or new datasets generated by resampling the paired environmental and taxa datasets to calculate the uncertainty and Z scores. Results indicate significant taxa whose change threshold could be identified. We used the default recommendations from Baker and King (2010) to define "significant" taxa as those with an indicator p-value <0.05, purity >0.95, and reliability >0.95. Purity and reliability are measures that assess the quality of the indicator response. Purity is the proportion of the bootstrap replicates that have the same direction response (i.e., negative or positive) as the observed response. Reliability indicates the proportion of the bootstrap replicates with p-values for the indicator value score at <0.05.

The taxon's response to environmental change is summarized in the change point plots. Although some taxa had longer confidence intervals than others, the figures indicate that taxa respond to these important environmental variables. Of the 119 families, 30 significantly responded to size, 52 to gradient, 49 to temperature, and 48 to alkalinity. The figures show which benthic taxa are found at different points in the range of the environmental variable. Some taxa show a very narrow distribution along the range of a variable, with a distinct, drastic threshold above which they totally disappear. Longer confidence intervals characterize taxa that have a larger environmental niche, a greater tolerance for the variable, and a longer linear response around a change point. Longer confidence interval lines may also be due to the family level of the analysis: the response of particular genera and species within the family may vary. Individual taxa histograms of the taxon-specific change points are available for those who wish to study detailed patterns of response. These plots distinguish taxa whose bootstrapped change point distributions are clearly unimodal from those that are more uniform or multimodal, and thus they indicate particular genera or species that respond at different or multiple values. Time constraints precluded further study of taxon-specific histogram shapes; however, researchers are encouraged to explore these plots and the finer taxonomic patterns in the CABIN data. We also encourage the collection and analysis of other biotic datasets that may improve our understanding of the response of other freshwater biota, such as fish or aquatic plants, to environmental variables.

In Figures C2 (size), C3 and C4 (gradient), C5 (temperature), and C6 (alkalinity), solid black circles represent change points for taxa associated with increasing abundance with smaller values (negative response), and open circles represent species associated with increasing abundance with increasing values (positive response). Dots are sized in proportion to the strength (Z score) of their threshold. Horizontal lines (solid for decreasing species, dotted for increasing species) correspond to the 90% confidence intervals of the change point. Longer horizontal lines represent uncertainty about the existence of a distinct threshold because of gradual increases in frequency and abundance. Thus large dots with short confidence intervals show the strongest change point; however, all taxa shown had significant change points.

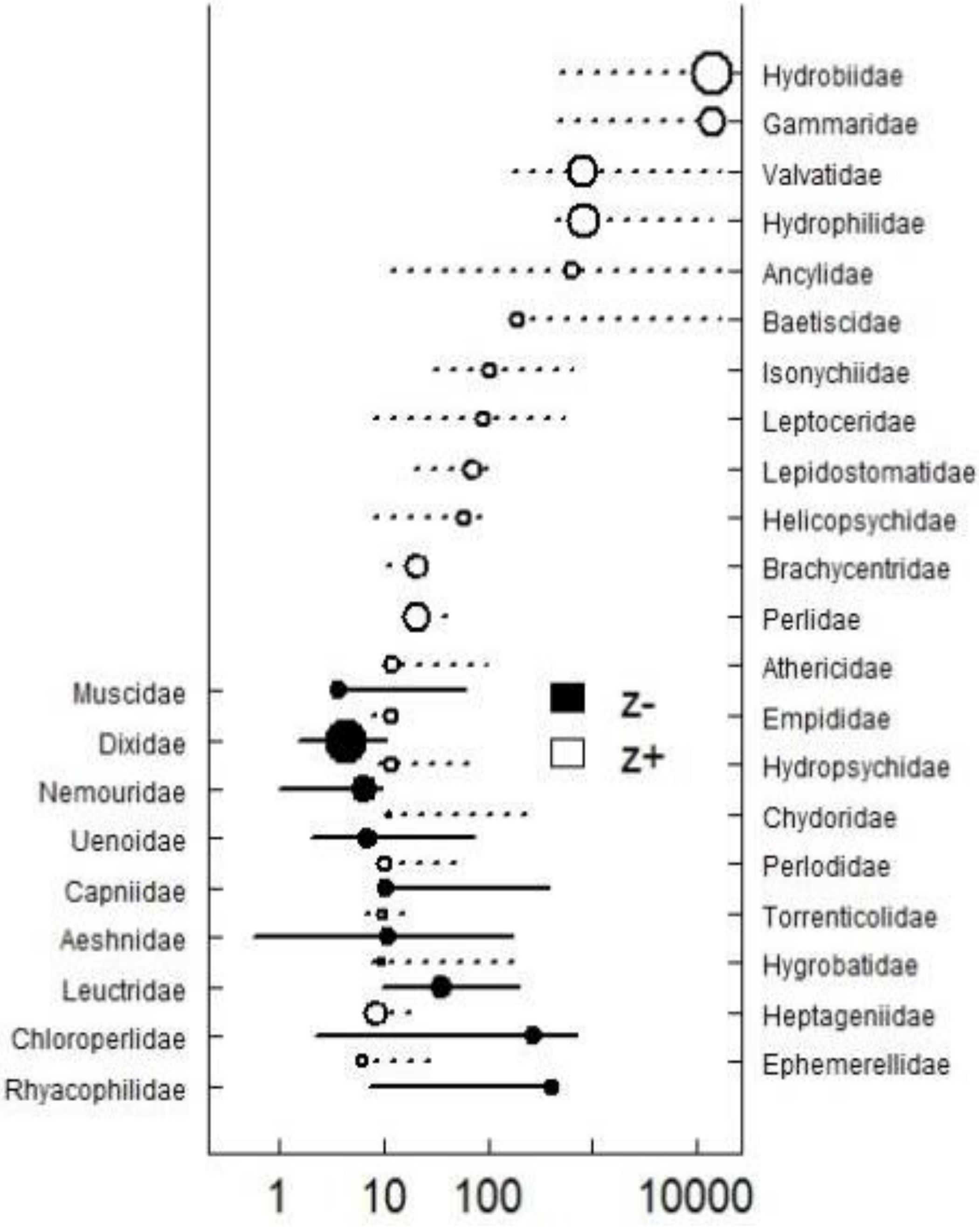


Figure C2. Significant indicator taxa change points in relation to stream size (drainage area in km^2)

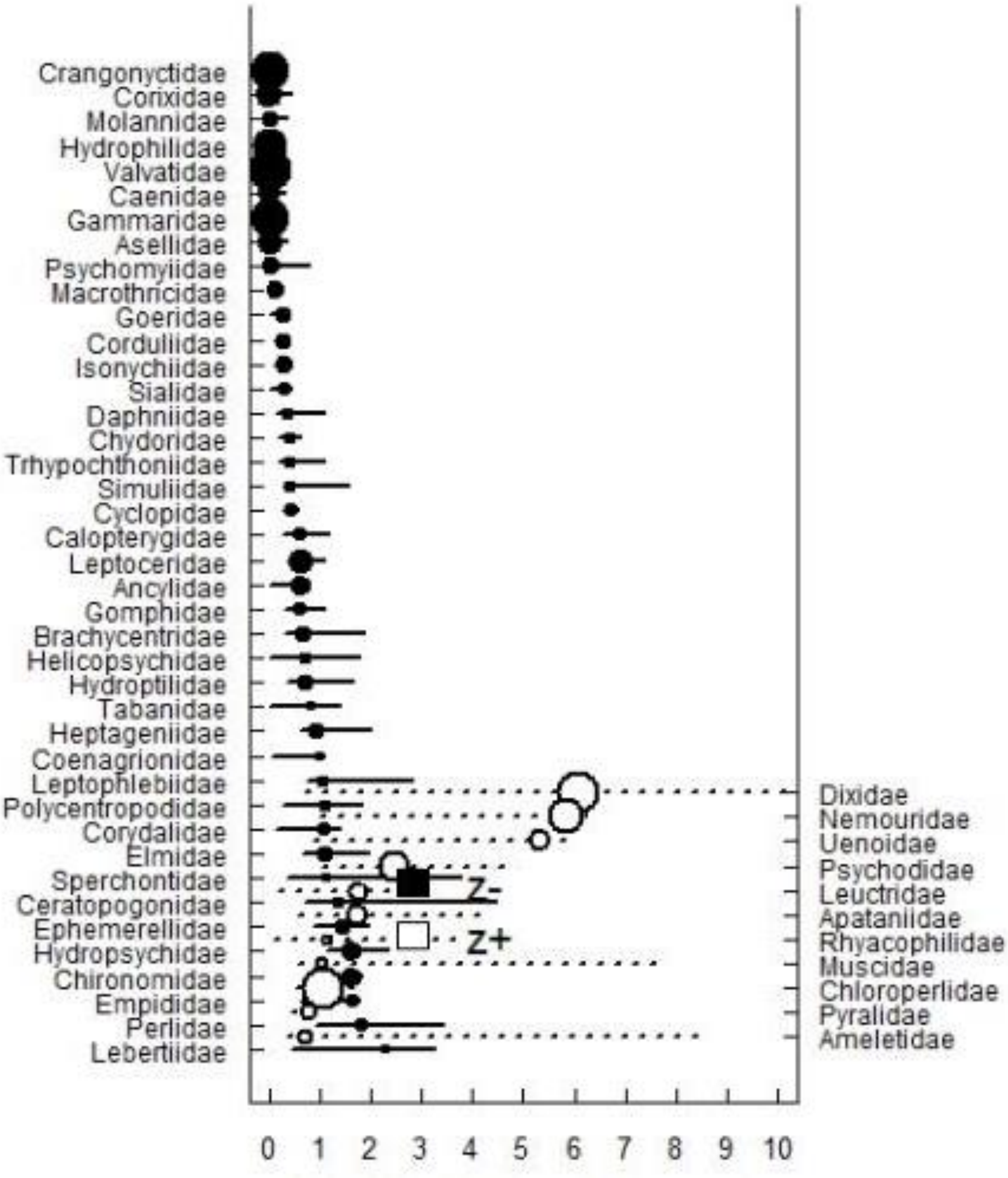


Figure C3. Significant indicator taxa change points in relation to stream gradient (0–10%)

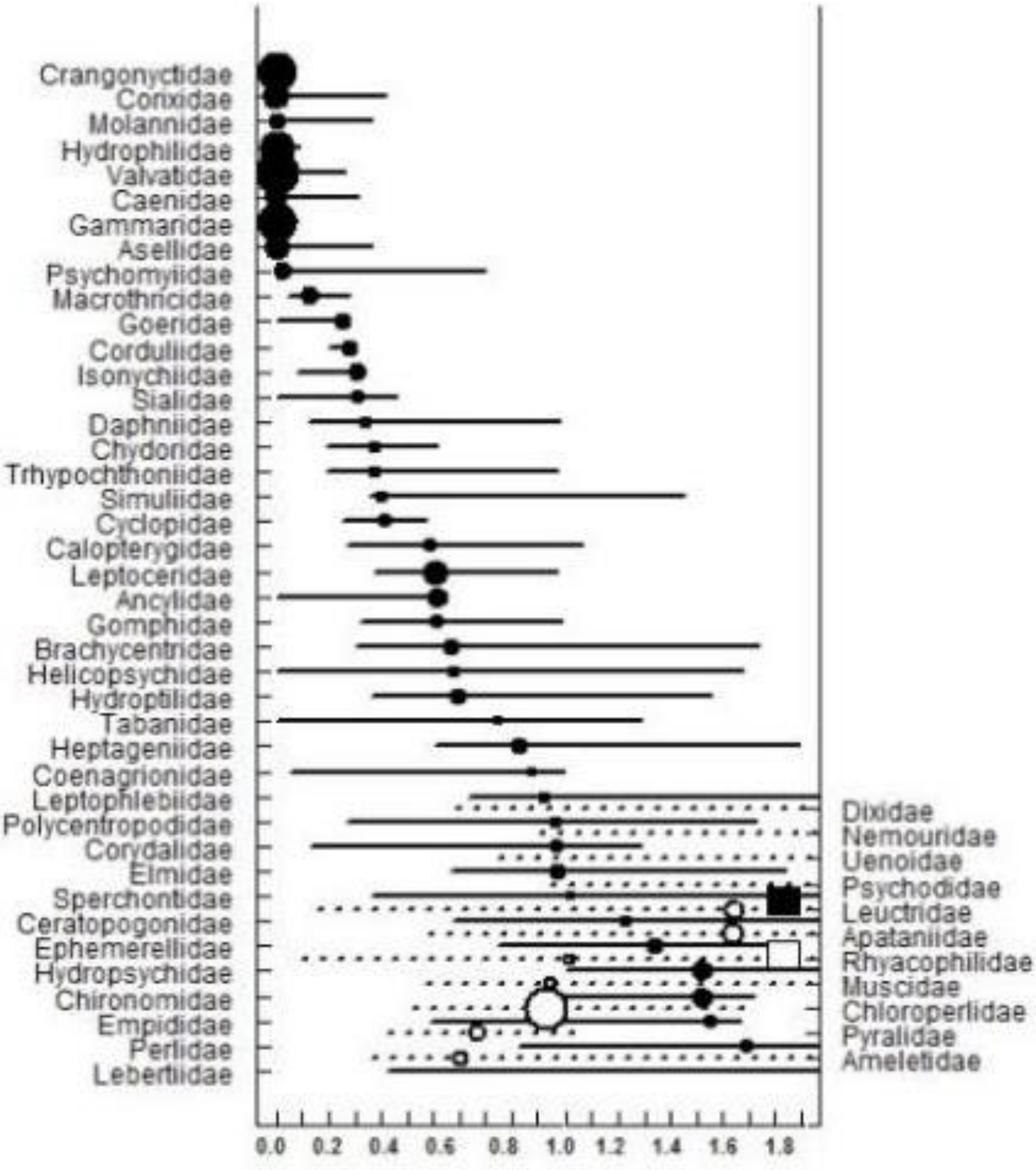


Figure C4. Significant indicator taxa change points in relation to gradient (<2%)

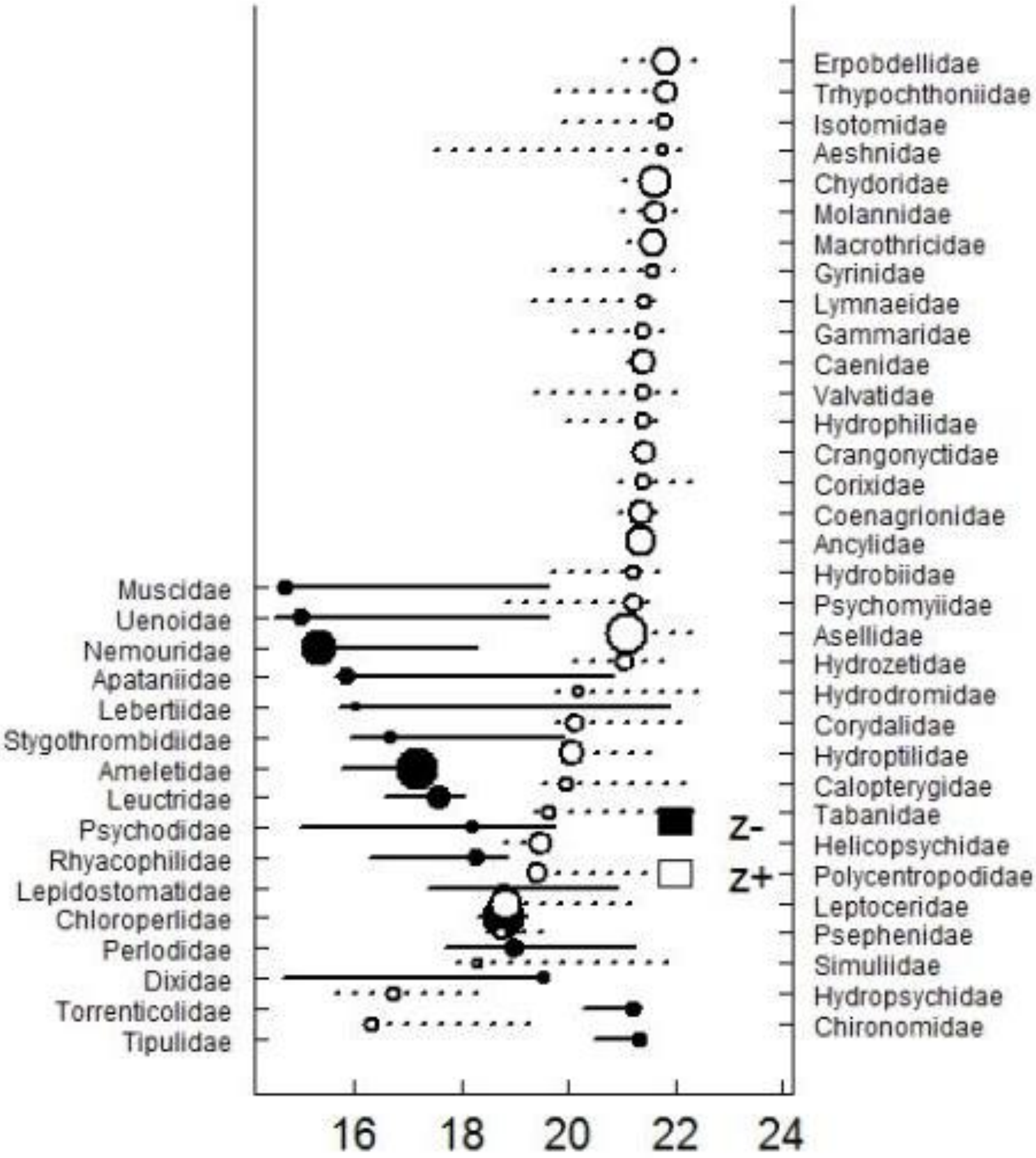


Figure C5. Significant indicator taxa change points in relation to stream temperature (°C)

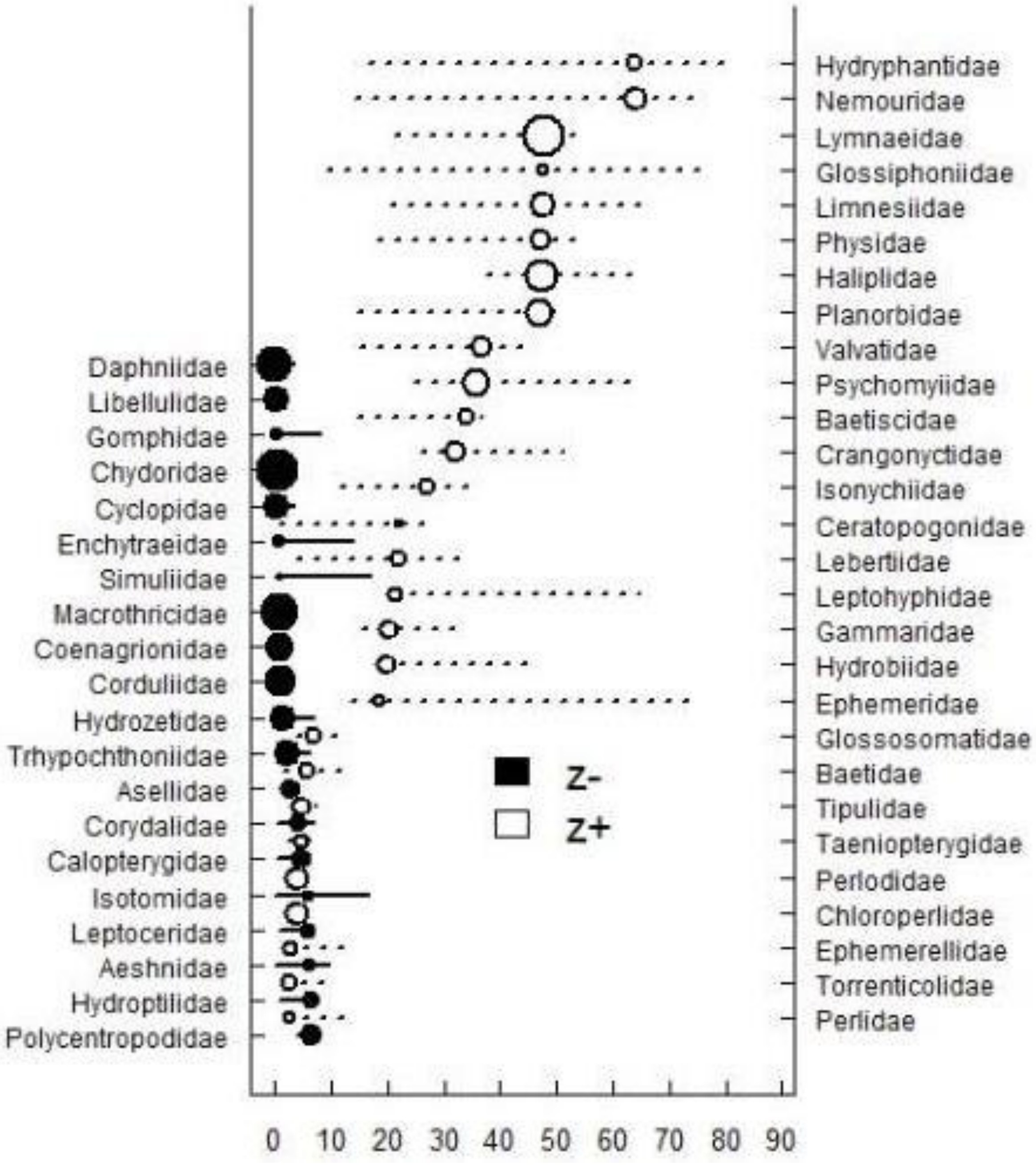


Figure C6. Significant indicator taxa change points in relation to alkalinity (mg/l $CaCO_3$)

Threshold values for indicator taxa are given in Tables C1 (size), C2 (gradient), C3 (temperature), and C4 (alkalinity), where:

- *Env.cp* is the environmental change point value for each taxon.
- *Freq* is the number of nonzero abundance values per taxon.
- *GRP* is the direction of change: 1 indicates a negative response and 2 indicates a positive response.
- *IndVal* is the indicator species analysis value, which uses the IndVal statistics from Dufrene and Legendre (1997). The value is scaled from 0 to 100%, with 100% being the highest possible indicator.
- *Pval* is the probability that an equal or larger indicator value could be obtained from random data, calculated as (number of random Ind Vals > observed IndVal) / number of permutations.
- *Z* is the standardization of IndVal as z scores (mean of individual indicator value / standard deviation of indicator values of permuted samples).
- *CI* (5%, 10%, 50%, 90%, 95%) is the change point quantiles among bootstrap replicates.
- *Purity* is a measure of the quality of the indicator response. This is the proportion of bootstrap replicates with the same direction response (i.e., negative or positive) as the observed response.
- *Reliability* is a measure of the quality of the indicator response. This is the proportion of the bootstrap replicates with p-values for the indicator value score (IndVal) at <0.05.

Table C1. TITAN summary data for size class threshold values

Class	*Scientific name*	*Common name*	*Env.Cp*	*Freq*	*GRP*	*IndVal*	*Pval*	*Z*	*Ci 0.05*	*Ci 0.1*	*Ci 0.5*	*Ci 0.9*	*Ci 0.95*	*Purity*	*Reliability*
Headwater	Muscidae	Stable flies	3.76	11	1	8.940	0.020	4.40	3.12	3.35	4.75	24.88	61.20	0.95	0.98
Headwater	Dixidae	Nematoceran flies	4.19	12	1	16.580	0.004	10.42	1.53	2.17	4.00	6.58	10.47	0.99	1.00
Headwater	Nemouridae	Stoneflies	6.61	31	1	19.440	0.004	6.42	0.96	1.66	5.18	6.64	9.57	1.00	1.00
Headwater	Uenoidae	Caddisflies	6.73	15	1	9.110	0.008	4.62	1.98	3.09	7.35	32.60	72.38	1.00	0.99
Headwater	Ephemerellidae	Mayflies	6.06	277	2	81.710	0.004	6.18	5.27	5.56	11.46	25.14	27.97	1.00	1.00
Headwater	Heptageniidae	Mayflies	8.19	262	2	72.850	0.004	10.70	7.39	7.62	8.11	18.36	20.12	1.00	1.00
Creek	Capniidae	Stoneflies	10.62	215	1	52.140	0.004	4.50	9.44	10.50	24.09	289.13	385.22	0.99	0.99
Creek	Aeshnidae	Dragon/damselflies	11.15	43	1	15.410	0.004	4.27	0.55	6.85	13.16	27.97	172.54	0.95	0.96
Creek	Leuctridae	Stoneflies	36.15	160	1	46.230	0.004	5.37	9.42	13.08	40.61	149.34	194.45	1.00	1.00
Creek	Torrenticolidae	Water mites	9.44	173	2	49.440	0.004	5.54	6.63	7.39	9.82	18.06	20.24	1.00	1.00
Creek	Hygrobatidae	Water mites	9.44	166	2	43.630	0.004	4.31	7.63	8.36	9.51	34.18	187.09	0.95	0.98
Creek	Perlodidae	Stoneflies	9.94	194	2	53.390	0.004	6.58	9.29	9.66	10.33	41.31	50.29	0.99	1.00
Creek	Chydoridae	Waterfleas	10.85	14	2	7.110	0.016	2.85	9.76	9.89	11.07	126.56	278.78	0.99	0.98
Creek	Hydropsychidae	Caddisflies	11.26	278	2	69.870	0.004	7.15	8.45	9.26	12.37	45.47	62.42	1.00	1.00
Creek	Empididae	Dance flies	11.46	203	2	58.650	0.004	6.88	7.41	7.84	10.75	13.16	14.38	1.00	1.00
Creek	Athericidae	Watersnipe flies	12.09	89	2	33.950	0.004	8.40	9.28	11.15	12.72	40.71	96.28	1.00	1.00
Creek	Perlidae	Stoneflies	20.13	153	2	57.860	0.004	12.66	16.62	17.48	19.82	38.75	44.13	1.00	1.00
Creek	Brachycentridae	Caddisflies	20.59	139	2	52.660	0.004	11.25	10.51	11.76	20.05	27.61	28.23	1.00	1.00
Creek	Helicopsychidae	Caddisflies	56.53	71	2	31.110	0.004	7.30	7.84	8.08	71.21	96.05	107.22	1.00	1.00
Creek	Lepidostomatidae	Caddisflies	68.69	228	2	73.020	0.004	9.33	18.90	20.04	23.86	78.74	103.42	1.00	1.00
Creek	Leptoceridae	Caddisflies	86.25	158	2	48.900	0.004	6.93	7.84	8.08	85.88	501.41	520.33	0.99	1.00
Small	Chloroperlidae	Stoneflies	267.60	155	1	45.690	0.004	4.52	2.17	5.13	271.55	468.19	695.48	1.00	1.00
Small	Rhyacophilidae	Caddisflies	392.34	213	1	58.930	0.004	3.68	7.07	7.95	191.56	410.76	429.82	0.98	0.99
Small	Isonychiidae	Mayflies	100.91	20	2	15.160	0.004	7.49	29.59	31.66	96.24	140.14	648.88	0.98	1.00
Small	Baetiscidae	Mayflies	187.74	7	2	9.540	0.004	7.58	172.29	175.11	190.52	6579.52	16788.94	0.99	0.95
Medium	Ancylidae	Freshwater snails	655.19	28	2	28.170	0.004	7.85	11.36	17.89	553.05	9343.43	16780.40	1.00	1.00
Medium	Hydrophilidae	Water mites	820.36	12	2	28.970	0.004	15.01	437.96	467.32	904.09	11125.8	13953.12	0.97	0.99
Medium	Valvatidae	Freshwater snails	820.36	17	2	36.860	0.004	14.12	169.19	439.56	794.13	16780.4	16781.80	1.00	1.00
Large river	Hydrobiidae	Freshwater snails	13953.12	30	2	90.330	0.004	19.42	492.68	735.11	1903.66	16780.4	16781.80	0.98	1.00
Large river	Gammaridae	Scuds	13953.12	28	2	81.600	0.004	13.02	467.31	764.89	7162.46	16780.4	16788.94	0.97	1.00

Table C2. TITAN summary data for gradient class threshold values

Class	*Scientific name*	*Common name*	*Env. Cp*	*Freq*	*GRP*	*IndVal*	*Pval*	*Z*	*Ci 0.05*	*Ci 0.1*	*Ci 0.5*	*Ci 0.9*	*Ci 0.95*	*Purity*	*Relia-bility*
Very Low	Valvatidae	Freshwater Snails	0.00	17	1	32.980	0.004	17.26	0.00	0.00	0.00	0.09	0.26	0.98	1.00
Very low	Crangonyctidae	Amphipod	0.00	6	1	22.590	0.004	15.72	0.00	0.00	0.00	0.04	0.07	1.00	0.98
Very low	Gammaridae	Scuds	0.00	28	1	42.170	0.004	14.89	0.00	0.00	0.00	0.06	0.08	0.96	1.00
Very low	Hydrophilidae	Water mites	0.00	12	1	34.990	0.004	13.93	0.00	0.00	0.00	0.07	0.08	1.00	0.99
Very low	Corixidae	Water boatmen	0.00	9	1	18.420	0.004	10.46	0.00	0.00	0.03	0.08	0.42	1.00	0.98
Very low	Asellidae	Isopods	0.00	35	1	44.510	0.004	10.02	0.00	0.00	0.05	0.34	0.36	1.00	1.00
Very low	Caenidae	Mayflies	0.00	23	1	32.460	0.004	9.25	0.00	0.00	0.03	0.13	0.31	0.96	0.98
Very low	Molannidae	Caddisflies	0.00	10	1	12.750	0.004	6.57	0.00	0.00	0.01	0.35	0.36	0.97	0.99
Low	Psychomyiidae	Caddisflies	0.03	29	1	24.210	0.004	7.48	0.00	0.00	0.00	0.18	0.80	1.00	0.99
Low	Macrothricidae	Water fleas	0.13	6	1	8.370	0.004	7.22	0.05	0.05	0.13	0.28	0.28	1.00	0.98
Low-mod	Goeridae	Caddisflies	0.25	5	1	5.620	0.004	6.50	0.00	0.00	0.24	0.26	0.27	1.00	0.95
Low-mod	Corduliidae	Dragon/damselflies	0.28	8	1	6.980	0.004	5.91	0.20	0.25	0.27	0.29	0.30	1.00	0.97
Low-mod	Isonychiidae	Mayflies	0.31	20	1	13.660	0.004	7.02	0.08	0.12	0.29	0.31	0.33	1.00	1.00
Low-mod	Sialidae	Alderflies	0.31	37	1	17.430	0.004	5.22	0.00	0.00	0.28	0.34	0.46	1.00	0.99
Low-mod	Daphniidae	Waterfleas	0.34	16	1	9.330	0.004	4.27	0.12	0.17	0.34	0.65	1.08	1.00	0.99
Low-mod	Chydoridae	Waterfleas	0.37	14	1	9.000	0.004	4.84	0.19	0.23	0.38	0.60	0.61	1.00	0.99
Low-mod	Trhypochthoniidae	Water mites	0.37	43	1	15.890	0.004	4.24	0.19	0.22	0.37	1.03	1.08	0.97	0.96
Low-mod	Simuliidae	Black fly	0.40	180	1	58.400	0.004	4.85	0.36	0.37	0.45	0.67	1.56	1.00	1.00
Low-mod	Cyclopidae	Copepod	0.42	18	1	10.770	0.004	5.33	0.25	0.29	0.42	0.56	0.57	1.00	0.99
Mod-high	Calopterygidae	Dragon/damselflies	0.59	50	1	19.780	0.004	5.59	0.27	0.37	0.58	0.91	1.17	1.00	1.00
Mod-high	Leptoceridae	Caddisflies	0.61	158	1	54.700	0.004	10.25	0.37	0.43	0.61	1.03	1.07	1.00	1.00
Mod-high	Ancylidae	Freshwater snails	0.61	28	1	16.850	0.004	8.47	0.00	0.00	0.46	0.61	0.65	1.00	1.00
Mod-high	Gomphidae	Dragon/damselflies	0.61	105	1	31.330	0.004	5.43	0.32	0.37	0.83	1.08	1.09	1.00	1.00
Mod-high	Brachycentridae	Caddisflies	0.67	139	1	43.750	0.004	6.70	0.30	0.43	0.67	1.66	1.84	1.00	1.00
Mod-high	Helicopsychidae	Caddisflies	0.68	71	1	25.170	0.004	4.88	0.00	0.12	0.54	1.70	1.78	1.00	1.00
Mod-high	Hydroptilidae	Caddisflies	0.69	163	1	46.890	0.004	6.09	0.37	0.53	0.66	1.08	1.66	1.00	1.00
Mod-high	Tabanidae	Horse fly	0.84	21	1	9.210	0.016	3.56	0.00	0.04	0.42	1.22	1.39	1.00	0.99
Mod-high	Heptageniidae	Mayflies	0.93	262	1	59.140	0.004	6.38	0.61	0.66	1.03	1.78	2.00	0.99	1.00
Mod-high	Coenagrionidae	Dragon/damselflies	0.98	33	1	13.450	0.004	3.80	0.05	0.26	0.80	1.08	1.10	1.00	0.99
Mod-high	Leptophlebiidae	Mayflies	1.02	273	1	75.630	0.004	4.56	0.74	0.96	1.06	2.03	2.82	1.00	1.00
Mod-high	Polycentropodidae	Caddisflies	1.06	150	1	44.300	0.004	4.93	0.27	0.31	1.01	1.19	1.83	1.00	1.00
Mod-high	Elmidae	Riffle beetles	1.08	263	1	70.890	0.004	5.99	0.67	0.70	1.07	1.67	1.95	1.00	1.00
Mod-high	Corydalidae	Dobsonflies	1.08	84	1	30.750	0.004	5.08	0.13	0.41	1.08	1.20	1.39	1.00	1.00
Mod-high	Sperchontidae	Water mites	1.13	156	1	37.180	0.012	3.17	0.36	0.45	1.12	3.70	3.77	0.98	0.98
Mod-high	Ceratopogonidae	Biting midges	1.33	199	1	48.360	0.008	4.26	0.68	1.09	1.54	4.28	4.44	0.95	1.00

Mod-high	Ephemerellidae	Mayflies	1.45	277	1	76.340	0.004	5.87	0.85	0.99	1.12	1.72	1.94	1.00	1.00
Mod-high	Chironomidae	Nonbiting midges	1.62	304	1	82.940	0.004	8.09	1.08	1.09	1.58	1.72	1.83	1.00	1.00
Mod-high	Hydropsychidae	Caddisflies	1.62	278	1	78.040	0.004	7.95	1.11	1.15	1.66	1.92	2.35	1.00	1.00
Mod-high	Empididae	Dance flies	1.66	203	1	57.180	0.004	5.39	0.59	0.61	1.53	1.69	1.77	1.00	1.00
Mod-high	Perlidae	Stoneflies	1.80	153	1	45.060	0.004	5.30	0.93	1.00	2.03	3.00	3.42	1.00	1.00
Mod-high	Ameletidae	Mayflies	0.71	27	2	12.650	0.004	4.12	0.36	0.37	1.22	5.59	8.55	0.99	0.99
Mod-high	Pyralidae	Grass moths	0.77	12	2	7.310	0.004	4.64	0.42	0.43	0.77	1.10	1.14	1.00	0.99
Mod-high	Chloroperlidae	Stoneflies	1.03	155	2	54.920	0.004	11.34	0.52	0.55	1.08	1.71	1.78	1.00	1.00
Mod-high	Muscidae	Stable flies	1.05	11	2	6.660	0.004	3.42	0.57	0.59	0.81	1.52	7.77	1.00	0.98
Mod-high	Rhyacophilidae	Caddisflies	1.12	213	2	50.600	0.016	2.88	0.10	0.12	0.99	2.51	3.64	1.00	0.99
Mod-high	Apataniidae	Caddisflies	1.75	36	2	18.950	0.004	6.04	0.58	0.95	1.83	3.61	4.28	0.98	0.98
Mod-high	Leuctridae	Stoneflies	1.75	160	2	49.920	0.004	5.36	0.16	0.34	1.86	2.26	2.49	0.98	0.99
High	Lebertiidae	Water mites	2.32	143	1	40.390	0.008	3.45	0.42	1.00	2.32	3.09	3.25	0.98	1.00
High	Psychodidae	Water penny beetle	2.47	22	2	20.460	0.004	8.70	1.05	1.08	2.40	3.41	4.74	0.99	1.00
Very high	Uenoidae	Caddisflies	5.33	15	2	19.140	0.008	6.10	0.85	0.96	1.66	5.98	6.06	0.98	0.99
Very high	Nemouridae	Stoneflies	5.86	31	2	36.910	0.004	9.82	1.01	1.02	2.72	5.95	6.23	1.00	1.00
Very high	Dixidae	Nematoceran flies	6.06	12	2	34.200	0.004	11.62	0.68	1.10	6.15	10.14	10.88	1.00	1.00

Table C3. TITAN summary data for temperature class threshold values

Class	*Scientific name*	*Common name*	*Env.Cp*	*Freq*	*GRP*	*IndVal*	*Pval*	*Z*	*Ci 0.05*	*Ci 0.1*	*Ci 0.5*	*Ci 0.9*	*Ci 0.95*	*Purity*	*Relia-bility*
Cold	Muscidae	Stable flies	14.68	11	1	27.330	0.012	5.77	14.61	14.61	15.88	19.64	19.64	1.00	0.96
Cold	Uenoidae	Caddisflies	15.01	15	1	27.260	0.004	6.66	14.49	14.59	16.42	19.31	19.64	1.00	0.98
Cold	Nemouridae	Stoneflies	15.34	31	1	44.490	0.004	13.28	15.01	15.16	16.35	18.29	18.30	1.00	1.00
Cold	Apataniidae	Caddisflies	15.88	36	1	28.200	0.004	6.51	15.63	15.65	15.92	18.17	20.86	0.97	1.00
Cold	Lebertiidae	Water mites	16.03	143	1	45.040	0.008	3.16	15.71	16.03	17.93	21.81	21.91	0.99	1.00
Cold	Stygothrombidiida	Water mites	16.66	9	1	8.660	0.004	5.06	15.89	16.54	16.70	19.89	19.92	0.99	0.96
Cold	Ameletidae	Mayflies	17.14	27	1	35.040	0.004	16.10	15.75	15.94	16.71	17.42	17.53	1.00	1.00
Cold	Leuctridae	Stoneflies	17.55	160	1	63.400	0.004	9.09	16.54	16.61	17.47	17.63	18.04	1.00	1.00
Cold	Chironomidae	Nonbiting midges	16.32	304	2	82.360	0.004	5.31	16.27	16.30	16.53	18.28	19.35	1.00	1.00
Cold	Hydropsychidae	Caddisflies	16.72	278	2	74.930	0.004	5.78	15.63	15.70	16.72	18.27	18.30	1.00	1.00
Cool	Psychodidae	Water penny beetle	18.22	22	1	12.610	0.004	5.05	14.96	17.71	18.22	19.30	19.75	0.97	0.98
Cool	Rhyacophilidae	Caddisflies	18.30	213	1	63.310	0.004	7.00	16.29	16.32	18.30	18.81	18.87	1.00	1.00
Cool	Lepidostomatidae	Caddisflies	18.76	228	1	58.120	0.004	4.60	17.37	17.48	18.83	20.33	20.91	0.99	1.00
Cool	Chloroperlidae	Stoneflies	18.79	155	1	66.160	0.004	15.63	18.28	18.35	18.72	19.04	19.21	1.00	1.00
Cool	Perlodidae	Stoneflies	19.00	194	1	56.070	0.004	7.53	17.69	17.91	19.13	20.56	21.26	1.00	1.00
Cool	Dixidae	Nematoceran flies	19.57	12	1	7.890	0.004	5.21	14.66	16.69	19.48	19.62	19.64	1.00	1.00
Cool	Simuliidae	Black fly	18.30	180	2	56.240	0.004	4.06	17.90	18.30	19.74	21.74	21.88	1.00	1.00

Cool	Psephenidae	Water penny beetle	18.72	86	2	32.280	0.004	5.25	18.44	18.49	18.70	19.21	19.59	0.98	1.00
Cool	Leptoceridae	Caddisflies	18.81	158	2	59.650	0.004	12.10	18.48	18.65	19.25	19.96	21.27	1.00	1.00
Cool	Polycentropodidae	Caddisflies	19.44	150	2	52.450	0.004	8.34	19.44	19.51	19.77	20.05	21.76	1.00	1.00
Cool	Helicopsychidae	Caddisflies	19.45	71	2	33.220	0.004	9.16	18.78	19.29	19.50	19.74	19.75	1.00	1.00
Cool	Tabanidae	Horse fly	19.65	21	2	11.810	0.004	5.52	19.35	19.38	21.16	22.47	22.52	0.96	1.00
Cool	Calopterygidae	Dragon/damselflies	19.94	50	2	20.410	0.004	5.92	19.52	19.75	20.90	21.59	22.21	0.98	1.00
Cool	Hydroptilidae	Caddisflies	20.06	163	2	58.030	0.004	9.48	19.84	19.93	20.05	21.53	21.60	1.00	1.00
Cool	Corydalidae	Dobsonflies	20.13	84	2	35.070	0.004	7.47	19.74	19.79	19.96	21.59	22.14	1.00	1.00
Cool	Hydrodromidae	Water mites	20.19	11	2	7.490	0.004	4.39	19.75	19.82	20.23	22.52	22.58	1.00	0.98
Warm	Torrenticolidae	Water mites	21.22	173	1	55.310	0.004	5.48	20.29	20.45	21.20	21.37	21.39	1.00	1.00
Warm	Tipulidae	Crane fly	21.33	239	1	67.020	0.004	5.99	20.48	20.92	21.24	21.38	21.45	0.99	1.00
Warm	Hydrozetidae	Water mites	21.06	67	2	34.840	0.004	7.43	20.09	20.31	21.08	21.79	21.80	0.97	1.00
Warm	Asellidae	Isopods	21.08	35	2	41.860	0.004	15.31	20.94	20.98	21.14	21.83	22.33	1.00	1.00
Warm	Psychomyiidae	Caddisflies	21.20	29	2	19.030	0.004	6.91	18.81	20.96	21.08	21.58	21.61	1.00	0.99
Warm	Hydrobiidae	Freshwater snails	21.20	30	2	20.540	0.004	5.84	19.65	19.86	21.20	21.48	21.95	1.00	1.00
Warm	Ancylidae	Freshwater snails	21.37	28	2	26.780	0.004	10.93	21.07	21.12	21.29	21.42	21.47	1.00	1.00
Warm	Coenagrionidae	Dragon/damselflies	21.37	33	2	27.680	0.004	9.22	20.92	20.98	21.37	21.59	21.64	1.00	1.00
Warm	Corixidae	Water boatmen	21.39	9	2	9.900	0.008	6.07	20.93	21.28	21.53	22.29	22.32	0.98	0.96
Warm	Caenidae	Mayflies	21.42	23	2	23.580	0.004	9.37	21.08	21.19	21.39	21.45	21.47	1.00	1.00
Warm	Crangonyctidae	Amphipod	21.42	6	2	10.720	0.004	9.12	21.19	21.23	21.39	21.46	21.52	1.00	0.98
Warm	Valvatidae	Freshwater snails	21.42	17	2	15.090	0.004	6.76	19.36	19.86	21.42	21.96	22.07	1.00	1.00
Warm	Hydrophilidae	Water mites	21.42	12	2	12.740	0.004	6.63	19.95	19.95	21.02	21.50	21.91	1.00	1.00
Warm	Gammaridae	Scuds	21.42	28	2	21.300	0.004	6.28	20.07	21.33	21.42	21.49	21.91	1.00	0.99
Warm	Lymnaeidae	Freshwater snails	21.42	37	2	23.960	0.004	5.67	19.31	21.20	21.39	21.48	21.62	0.98	0.97
Warm	Macrothricidae	Water fleas	21.59	6	2	13.100	0.004	10.76	21.08	21.14	21.53	21.69	21.86	1.00	0.99
Warm	Gyrinidae	Whirligig beetles	21.59	6	2	7.400	0.008	5.45	19.65	19.72	21.49	21.80	21.98	1.00	0.95
Warm	Chydoridae	Waterfleas	21.59	14	2	24.160	0.004	11.63	20.99	21.27	21.58	21.78	21.80	1.00	1.00
Warm	Molannidae	Caddisflies	21.59	10	2	12.520	0.004	8.70	20.98	21.16	21.81	22.14	22.19	0.97	0.99
Warm	Aeshnidae	Dragon/damselflies	21.79	43	2	25.950	0.004	4.79	17.48	17.95	21.75	21.95	22.16	1.00	1.00
Warm	Trhypochthoniidae	Water mites	21.80	43	2	36.840	0.004	8.87	19.75	19.85	21.16	21.80	21.86	0.99	1.00
Warm	Isotomidae	Springtails	21.80	34	2	24.760	0.008	6.04	19.86	20.39	21.54	21.86	22.04	0.97	0.97
Warm	Erpobdellidae	Leeches	21.82	15	2	21.320	0.004	10.70	21.02	21.22	21.82	22.32	22.44	0.99	0.99

Table C4. TITAN summary data for alkalinity class threshold values

Class	*Scientific name*	*Common name*	*Env.Cp*	*Freq*	*GRP*	*IndVal*	*Pval*	*Z*	*Ci 0.05*	*Ci 0.1*	*Ci 0.5*	*Ci 0.9*	*Ci 0.95*	*Purity*	*Relia-bility*
Low	Daphniidae	Waterfleas	0.01	16	1	40.490	0.004	20.53	-0.17	0.05	0.46	1.25	3.24	0.99	1.00

Class	*Scientific name*	*Common name*	*Env.Cp*	*Freq*	*GRP*	*IndVal*	*Pval*	*Z*	*Ci 0.05*	*Ci 0.1*	*Ci 0.5*	*Ci 0.9*	*Ci 0.95*	*Purity*	*Relia-bility*
Low	Libellulidae	Dragon/damselflies	0.05	8	1	32.400	0.004	14.46	-0.09	0.05	1.11	1.48	2.07	0.97	0.99
Low	Gomphidae	Dragon/damselflies	0.20	105	1	60.860	0.004	7.23	-0.53	-0.51	0.44	6.58	7.81	1.00	1.00
Low	Chydoridae	Waterfleas	0.37	14	1	62.350	0.004	24.08	0.01	0.05	0.37	0.92	1.49	1.00	1.00
Low	Cyclopidae	Copepod	0.37	18	1	42.330	0.004	14.72	-0.32	-0.17	0.37	1.38	3.32	1.00	1.00
Low	Enchytraeidae	Pot worm	0.44	107	1	70.110	0.004	8.01	0.31	0.40	0.73	3.61	13.78	0.96	1.00
Low	Simuliidae	Black fly	0.44	180	1	72.780	0.004	4.04	-0.09	-0.05	3.20	16.04	16.89	0.98	0.97
Low	Macrothricidae	Water fleas	0.56	6	1	31.580	0.004	20.92	0.27	0.40	0.56	1.11	1.23	0.99	0.99
Low	Coenagrionidae	Dragon/damselflies	0.71	33	1	51.950	0.004	16.01	0.03	0.08	0.73	1.70	2.19	0.96	1.00
Low	Corduliidae	Dragon/damselflies	0.98	8	1	28.980	0.004	17.50	0.37	0.44	0.89	1.24	1.40	0.98	1.00
Low	Hydrozetidae	Water mites	1.40	67	1	70.220	0.004	15.29	1.24	1.39	3.60	5.72	6.74	1.00	1.00
Low	Trhypochthoniid	Water mites	2.07	43	1	48.650	0.004	15.11	0.08	0.27	1.78	5.73	6.21	1.00	1.00
Low	Asellidae	Isopods	2.42	35	1	39.600	0.004	11.85	1.22	1.38	2.70	4.00	4.16	1.00	1.00
Low	Corydalidae	Dobsonflies	4.15	84	1	46.830	0.004	9.87	0.40	0.84	4.10	6.71	6.87	1.00	1.00
Low	Calopterygidae	Dragon/damselflies	4.62	50	1	36.500	0.004	11.90	0.20	0.44	3.96	5.79	6.04	1.00	1.00
Low	Leptoceridae	Caddisflies	5.68	158	1	53.930	0.004	8.60	0.63	0.73	1.05	5.99	6.18	1.00	1.00
Low	Isotomidae	Springtails	5.68	34	1	20.880	0.004	6.46	-0.32	0.01	5.73	11.04	16.59	1.00	1.00
Low	Aeshnidae	Dragon/damselflies	5.99	43	1	23.450	0.004	7.98	0.01	0.13	6.04	8.13	9.70	0.99	1.00
Low	Hydroptilidae	Caddisflies	6.45	163	1	57.500	0.004	9.58	0.79	1.24	3.20	6.66	6.81	1.00	1.00
Low	Polycentropodid	Caddisflies	6.57	150	1	70.160	0.004	12.38	3.84	4.11	6.38	7.20	7.39	1.00	1.00
Low	Torrenticolidae	Water mites	2.64	173	2	57.310	0.004	5.76	1.47	1.85	3.85	6.34	10.73	1.00	1.00
Low	Ephemerellidae	Mayflies	2.64	277	2	83.540	0.004	5.36	1.83	2.11	2.64	6.35	12.52	1.00	1.00
Low	Perlidae	Stoneflies	2.64	153	2	47.550	0.004	4.61	1.78	2.00	2.64	11.51	11.86	1.00	1.00
Low	Chloroperlidae	Stoneflies	3.85	155	2	56.440	0.004	8.46	3.67	3.80	4.05	5.79	5.99	1.00	1.00
Low	Perlodidae	Stoneflies	3.91	194	2	65.740	0.004	8.21	3.05	3.67	4.12	5.73	5.90	1.00	1.00
Low	Taeniopterygidae	Stoneflies	4.41	115	2	38.820	0.008	4.93	2.29	2.88	4.65	5.68	6.37	1.00	1.00
Low	Tipulidae	Crane fly	4.62	239	2	67.660	0.004	7.09	3.61	4.05	5.73	6.80	7.25	1.00	1.00
Low	Baetidae	Mayflies	5.74	260	2	67.000	0.004	5.95	1.39	1.40	5.87	10.26	12.97	0.99	1.00
Low	Glossosomatidae	Leeches	6.73	136	2	43.740	0.004	5.97	3.83	3.91	6.38	11.42	11.82	1.00	1.00
Low	Ephemeridae	Mayflies	18.59	25	2	13.110	0.008	4.25	13.55	15.46	21.21	64.38	74.49	1.00	1.00
Low	Hydrobiidae	Freshwater snails	19.76	30	2	20.690	0.004	6.89	18.70	19.69	31.54	45.28	46.31	1.00	1.00
Low	Gammaridae	Scuds	20.21	28	2	17.200	0.004	6.61	15.27	15.58	20.97	31.54	32.25	1.00	1.00
Low	Leptohyphidae	Mayflies	21.30	6	2	5.660	0.004	5.04	20.74	21.21	22.09	38.28	64.82	1.00	0.96
Low	Lebertiidae	Water mites	21.80	143	2	42.870	0.004	6.22	3.71	3.91	22.09	30.79	33.58	1.00	1.00
Low	Ceratopogonidae	Biting midges	21.80	199	2	44.720	0.012	3.14	0.56	1.13	7.88	23.44	26.16	0.99	1.00
Medium	Isonychiidae	Mayflies	26.97	20	2	13.410	0.004	6.34	11.55	12.17	25.62	32.25	35.40	1.00	1.00
Medium	Crangonyctidae	Amphipod	32.17	6	2	7.650	0.004	7.37	25.83	26.32	37.07	49.41	51.15	1.00	0.98

Class	*Scientific name*	*Common name*	*Env.Cp*	*Freq*	*GRP*	*IndVal*	*Pval*	*Z*	*Ci 0.05*	*Ci 0.1*	*Ci 0.5*	*Ci 0.9*	*Ci 0.95*	*Purity*	*Relia-bility*
Medium	Baetiscidae	Mayflies	34.05	7	2	6.870	0.004	5.70	14.40	25.29	26.83	35.56	36.62	1.00	0.97
Medium	Psychomyiidae	Caddisflies	35.56	29	2	25.870	0.004	9.94	24.60	25.01	35.19	51.30	64.38	0.99	1.00
Medium	Valvatidae	Freshwater snails	36.62	17	2	15.510	0.004	7.32	14.96	23.54	34.69	45.26	45.94	1.00	1.00
Medium	Planorbidae	Freshwater snails	46.68	30	2	31.390	0.004	9.64	14.68	15.03	46.11	50.52	51.32	1.00	1.00
Medium	Haliplidae	Crawling water beetles	47.23	6	2	17.890	0.004	11.54	37.47	38.44	45.78	52.44	63.04	0.99	0.99
Medium	Physidae	Freshwater snails	47.23	45	2	38.490	0.004	7.42	18.13	19.81	47.23	52.73	54.24	1.00	1.00
Medium	Lymnaeidae	Freshwater snails	47.50	37	2	47.410	0.004	14.40	21.21	26.37	48.55	51.81	54.02	1.00	1.00
Medium	Limnesiidae	Water mites	47.50	6	2	13.450	0.004	8.85	20.33	21.19	35.56	48.51	64.66	1.00	0.98
Medium	Glossiphoniidae	Leeches	47.50	16	2	13.020	0.016	4.40	9.24	9.93	38.12	65.30	75.39	1.00	0.97
High	Nemouridae	Stoneflies	63.88	31	2	48.870	0.004	8.58	14.28	14.95	63.21	71.13	75.36	0.99	0.97
High	Hydryphantidae	Water mites	63.88	40	2	47.730	0.004	5.63	16.41	33.57	63.04	73.77	80.28	0.96	0.95

Appendix D. Variable Combinations

The following tables list the various habitat classes in the simple (Table D1), intermediate (Table D2), and complex (Table D3) variable combinations discussed in Chapter 4.

Table D1. Number of flowlines and length (km) for simple combination classes

	Class	Flowlines (n)	Length (km)
1	Low Gradient, Cold, Headwaters & Creeks	11,459	2,181
2	Low Gradient, Cool, Headwaters & Creeks	15,142	5,599
3	Low Gradient, Warm, Headwaters & Creeks	1,948	1,131
4	Moderate Gradient, Cold, Headwaters & Creeks	35,919	46,681
5	Moderate Gradient, Cool, Headwaters & Creeks	30,241	40,932
6	Moderate Gradient, Warm, Headwaters & Creeks	1,914	3,023
7	High Gradient, Cold, Headwaters & Creeks	62,394	64,215
8	High Gradient, Cool, Headwaters & Creeks	9,887	9,622
9	High Gradient, Warm, Headwaters & Creeks	274	295
10	Low Gradient, Cold, Small Rivers	1,355	959
11	Low Gradient, Cool, Small Rivers	1,885	1,668
12	Low Gradient, Warm, Small Rivers	342	399
13	Moderate Gradient, Cold, Small Rivers	3,165	3,798
14	Moderate Gradient, Cool, Small Rivers	2,479	3,435
15	Moderate Gradient, Warm, Small Rivers	292	485
16	Cold, Medium Tributary Rivers	1,373	1,267
17	Cool, Medium Tributary Rivers	1,431	1,575
18	Warm, Medium Tributary Rivers	619	755
19	Cool, Large Rivers	637	609
20	Warm, Large Rivers	664	668
21	Tidally Influenced, Headwaters & Creeks	2,916	3,542
22	Tidally Influenced, Small and Medium Rivers	212	316
23	Tidally Influenced, Large Rivers	51	55

Table D2. Tidal influence, number of flowlines, and length (km) for intermediate combination classes

	Class	Flowlines (n)	Length (km)
1	Low Gradient, Cold, Low Alkalinity, Headwaters & Creeks	4,757	734
2	Low Gradient, Cold, Moderate Alkalinity, Headwaters & Creeks	4,974	1,166
3	Low Gradient, Cold, High Alkalinity, Headwaters & Creeks	1,728	282
4	Low Gradient, Cold, Low Alkalinity, Small Rivers	362	247
5	Low Gradient, Cold, Moderate Alkalinity, Small Rivers	798	585
6	Low Gradient, Cold, High Alkalinity, Small Rivers	195	127
7	Moderate Gradient, Cold, Low Alkalinity, Headwaters & Creeks	17,196	23,260
8	Moderate Gradient, Cold, Moderate Alkalinity, Headwaters & Creeks	14,506	18,640
9	Moderate Gradient, Cold, High Alkalinity, Headwaters & Creeks	4,217	4,781
10	Moderate Gradient, Cold, Low Alkalinity, Small Rivers	1,071	1,376
11	Moderate Gradient, Cold, Moderate Alkalinity, Small Rivers	1,375	1,731
12	Moderate Gradient, Cold, High Alkalinity, Small Rivers	288	389
13	High Gradient, Cold, Low Alkalinity, Headwaters & Creeks	35,341	38,545
14	High Gradient, Cold, Moderate Alkalinity, Headwaters & Creeks	23,239	22,370
15	High Gradient, Cold, High Alkalinity, Headwaters & Creeks	3,814	3,300
16	High Gradient, Cold, Low Alkalinity, Small Rivers	219	211
17	High Gradient, Cold, Moderate Alkalinity, Small Rivers	187	83
18	High Gradient, Cold, High Alkalinity, Small Rivers	25	9
19	Low Gradient, Cool, Low Alkalinity, Headwaters & Creeks	7,690	1,378
20	Low Gradient, Cool, Moderate Alkalinity, Headwaters & Creeks	3,831	1,537
21	Low Gradient, Cool, High Alkalinity, Headwaters & Creeks	3,621	2,684
22	Low Gradient, Cool, Low Alkalinity, Small Rivers	598	587
23	Low Gradient, Cool, Moderate Alkalinity, Small Rivers	859	776
24	Low Gradient, Cool, High Alkalinity, Small Rivers	428	305
25	Moderate Gradient, Cool, Low Alkalinity, Headwaters & Creeks	14,571	20,194
26	Moderate Gradient, Cool, Moderate Alkalinity, Headwaters & Creeks	10,035	13,322
27	Moderate Gradient, Cool, High Alkalinity, Headwaters & Creeks	5,635	7,415

28	Moderate Gradient, Cool, Low Alkalinity, Small Rivers	1,049	1,640
29	Moderate Gradient, Cool, Moderate Alkalinity, Small Rivers	868	1,226
30	Moderate Gradient, Cool, High Alkalinity, Small Rivers	344	380
31	High Gradient, Cool, Low Alkalinity, Headwaters & Creeks	4,938	4,927
32	High Gradient, Cool, Moderate Alkalinity, Headwaters & Creeks	3,740	3,759
33	High Gradient, Cool, High Alkalinity, Headwaters & Creeks	1,209	936
34	High Gradient, Cool, Low Alkalinity, Small Rivers	88	101
35	High Gradient, Cool, Moderate Alkalinity, Small Rivers	88	73
36	High Gradient, Cool, High Alkalinity, Small Rivers	42	15
37	Low Gradient, Warm, Low Alkalinity, Headwaters & Creeks	840	225
38	Low Gradient, Warm, Moderate Alkalinity, Headwaters & Creeks	339	117
39	Low Gradient, Warm, High Alkalinity, Headwaters & Creeks	769	789
40	Low Gradient, Warm, Low Alkalinity, Small Rivers	71	72
41	Low Gradient, Warm, Moderate Alkalinity, Small Rivers	87	91
42	Low Gradient, Warm, High Alkalinity, Small Rivers	184	235
43	Moderate Gradient, Warm, Low Alkalinity, Headwaters & Creeks	501	825
44	Moderate Gradient, Warm, Moderate Alkalinity, Headwaters & Creeks	253	348
45	Moderate Gradient, Warm, High Alkalinity, Headwaters & Creeks	1,160	1,850
46	Moderate Gradient, Warm, Low Alkalinity, Small Rivers	63	154
47	Moderate Gradient, Warm, Moderate Alkalinity, Small Rivers	77	127
48	Moderate Gradient, Warm, High Alkalinity, Small Rivers	133	183
49	High Gradient, Warm, Low Alkalinity, Headwaters & Creeks	103	123
50	High Gradient, Warm, Moderate Alkalinity, Headwaters & Creeks	93	101
51	High Gradient, Warm, High Alkalinity, Headwaters & Creeks	78	71
52	High Gradient, Warm, Low Alkalinity, Small Rivers	8	9
53	High Gradient, Warm, Moderate Alkalinity, Small Rivers	6	6
54	High Gradient, Warm, High Alkalinity, Small Rivers	5	5
55	Low Gradient, Cold, Medium Tributary Rivers	702	479
56	Low Gradient, Cool, Medium Tributary Rivers	889	889
57	Low Gradient, Warm, Medium Tributary Rivers	435	481
58	Low Gradient, Cold, Large Rivers	138	116
59	Low Gradient, Cool, Large Rivers	377	338
60	Low Gradient, Warm, Large Rivers	518	515

61	Moderate Gradient, Cold, Medium Tributary Rivers	597	748
62	Moderate Gradient, Cool, Medium Tributary Rivers	493	648
63	Moderate Gradient, Warm, Medium Tributary Rivers	174	260
64	Moderate Gradient, Cold, Large Rivers	44	57
65	Moderate Gradient, Cool, Large Rivers	68	88
66	Moderate Gradient, Warm, Large Rivers	139	146
67	High Gradient, Cold, Medium Tributary Rivers	74	39
68	High Gradient, Cool, Medium Tributary Rivers	49	38
69	High Gradient, Warm, Medium Tributary Rivers	10	14
70	High Gradient, Cold, Large Rivers	2	4
71	High Gradient, Cool, Large Rivers	8	6
72	High Gradient, Warm, Large Rivers	7	7
73	Tidally Influenced, Headwaters & Creeks	2,916	3,542
74	Tidally Influenced, Large Rivers	51	55
75	Tidally Influenced, Small and Medium Rivers	212	316

Table D3. Number of flowlines and length (km) for complex combination classes

	Class	Flowlines (n)	Length (km)
1	Low Gradient, Cold, High Alkalinity, Headwaters & Creeks	1,728	282
2	Low Gradient, Cold, High Alkalinity, Large Rivers	15	15
3	Low Gradient, Cold, High Alkalinity, Medium Tributary Rivers	70	45
4	Low Gradient, Cold, High Alkalinity, Small Rivers	195	127
5	Low Gradient, Cold, Low Alkalinity, Headwaters & Creeks	4,757	734
6	Low Gradient, Cold, Low Alkalinity, Large Rivers	5	4
7	Low Gradient, Cold, Low Alkalinity, Medium Tributary Rivers	160	80
8	Low Gradient, Cold, Low Alkalinity, Small Rivers	362	247
9	Low Gradient, Cold, Moderate Alkalinity, Headwaters & Creeks	4,974	1,166
10	Low Gradient, Cold, Moderate Alkalinity, Large Rivers	118	97
11	Low Gradient, Cold, Moderate Alkalinity, Medium Tributary Rivers	472	354
12	Low Gradient, Cold, Moderate Alkalinity, Small Rivers	798	585

13	Low Gradient, Cool, High Alkalinity, Headwaters & Creeks	3,621	2,684
14	Low Gradient, Cool, High Alkalinity, Large Rivers	44	42
15	Low Gradient, Cool, High Alkalinity, Medium Tributary Rivers	206	180
16	Low Gradient, Cool, High Alkalinity, Small Rivers	428	305
17	Low Gradient, Cool, Low Alkalinity, Headwaters & Creeks	7,690	1,378
18	Low Gradient, Cool, Low Alkalinity, Large Rivers	55	52
19	Low Gradient, Cool, Low Alkalinity, Medium Tributary Rivers	188	237
20	Low Gradient, Cool, Low Alkalinity, Small Rivers	598	587
21	Low Gradient, Cool, Moderate Alkalinity, Headwaters & Creeks	3,831	1,537
22	Low Gradient, Cool, Moderate Alkalinity, Large Rivers	278	245
23	Low Gradient, Cool, Moderate Alkalinity, Medium Tributary Rivers	495	473
24	Low Gradient, Cool, Moderate Alkalinity, Small Rivers	859	776
25	Low Gradient, Warm, High Alkalinity, Headwaters & Creeks	769	789
26	Low Gradient, Warm, High Alkalinity, Large Rivers	252	226
27	Low Gradient, Warm, High Alkalinity, Medium Tributary Rivers	235	224
28	Low Gradient, Warm, High Alkalinity, Small Rivers	184	235
29	Low Gradient, Warm, Low Alkalinity, Headwaters & Creeks	840	225
30	Low Gradient, Warm, Low Alkalinity, Large Rivers	26	30
31	Low Gradient, Warm, Low Alkalinity, Medium Tributary Rivers	46	107
32	Low Gradient, Warm, Low Alkalinity, Small Rivers	71	72
33	Low Gradient, Warm, Moderate Alkalinity, Headwaters & Creeks	339	117
34	Low Gradient, Warm, Moderate Alkalinity, Large Rivers	240	259
35	Low Gradient, Warm, Moderate Alkalinity, Medium Tributary Rivers	154	149
36	Low Gradient, Warm, Moderate Alkalinity, Small Rivers	87	91
37	Moderate Gradient, Cold, High Alkalinity, Headwaters & Creeks	4,217	4,781
38	Moderate Gradient, Cold, High Alkalinity, Large Rivers	4	6
39	Moderate Gradient, Cold, High Alkalinity, Medium Tributary Rivers	40	51
40	Moderate Gradient, Cold, High Alkalinity, Small Rivers	288	389
41	Moderate Gradient, Cold, Low Alkalinity, Headwaters & Creeks	17,196	23,260
42	Moderate Gradient, Cold, Low Alkalinity, Medium Tributary Rivers	180	255
43	Moderate Gradient, Cold, Low Alkalinity, Small Rivers	1071	1,376
44	Moderate Gradient, Cold, Moderate Alkalinity, Headwaters & Creeks	14,506	18,640
45	Moderate Gradient, Cold, Moderate Alkalinity, Large Rivers	40	51

46	Moderate Gradient, Cold, Moderate Alkalinity, Medium Tributary Rivers	377	442
47	Moderate Gradient, Cold, Moderate Alkalinity, Small Rivers	1,375	1,731
48	Moderate Gradient, Cool, High Alkalinity, Headwaters & Creeks	5,635	7,415
49	Moderate Gradient, Cool, High Alkalinity, Large Rivers	18	23
50	Moderate Gradient, Cool, High Alkalinity, Medium Tributary Rivers	89	113
51	Moderate Gradient, Cool, High Alkalinity, Small Rivers	344	380
52	Moderate Gradient, Cool, Low Alkalinity, Headwaters & Creeks	14,571	20,194
53	Moderate Gradient, Cool, Low Alkalinity, Large Rivers	9	12
54	Moderate Gradient, Cool, Low Alkalinity, Medium Tributary Rivers	146	211
55	Moderate Gradient, Cool, Low Alkalinity, Small Rivers	1,049	1,640
56	Moderate Gradient, Cool, Moderate Alkalinity, Headwaters & Creeks	10,035	13,322
57	Moderate Gradient, Cool, Moderate Alkalinity, Large Rivers	41	54
58	Moderate Gradient, Cool, Moderate Alkalinity, Medium Tributary Rivers	258	324
59	Moderate Gradient, Cool, Moderate Alkalinity, Small Rivers	868	1,226
60	Moderate Gradient, Warm, High Alkalinity, Headwaters & Creeks	1,160	1,850
61	Moderate Gradient, Warm, High Alkalinity, Large Rivers	68	71
62	Moderate Gradient, Warm, High Alkalinity, Medium Tributary Rivers	80	93
63	Moderate Gradient, Warm, High Alkalinity, Small Rivers	133	183
64	Moderate Gradient, Warm, Low Alkalinity, Headwaters & Creeks	501	825
65	Moderate Gradient, Warm, Low Alkalinity, Large Rivers	2	3
66	Moderate Gradient, Warm, Low Alkalinity, Medium Tributary Rivers	56	103
67	Moderate Gradient, Warm, Low Alkalinity, Small Rivers	63	154
68	Moderate Gradient, Warm, Moderate Alkalinity, Headwaters & Creeks	253	348
69	Moderate Gradient, Warm, Moderate Alkalinity, Large Rivers	69	73
70	Moderate Gradient, Warm, Moderate Alkalinity, Medium Tributary Rivers	38	64
71	Moderate Gradient, Warm, Moderate Alkalinity, Small Rivers	77	127
72	High Gradient, Cold, High Alkalinity, Headwaters & Creeks	3,814	3,300
73	High Gradient, Cold, High Alkalinity, Medium Tributary Rivers	5	3
74	High Gradient, Cold, High Alkalinity, Small Rivers	25	9
75	High Gradient, Cold, Low Alkalinity, Headwaters & Creeks	35,341	38,545
76	High Gradient, Cold, Low Alkalinity, Medium Tributary Rivers	24	12
77	High Gradient, Cold, Low Alkalinity, Small Rivers	219	211
78	High Gradient, Cold, Moderate Alkalinity, Headwaters & Creeks	23,239	22,370

79	High Gradient, Cold, Moderate Alkalinity, Large Rivers	2	4
80	High Gradient, Cold, Moderate Alkalinity, Medium Tributary Rivers	45	24
81	High Gradient, Cold, Moderate Alkalinity, Small Rivers	187	83
82	High Gradient, Cool, High Alkalinity, Headwaters & Creeks	1,209	936
83	High Gradient, Cool, High Alkalinity, Large Rivers	1	0
84	High Gradient, Cool, High Alkalinity, Medium Tributary Rivers	6	2
85	High Gradient, Cool, High Alkalinity, Small Rivers	42	15
86	High Gradient, Cool, Low Alkalinity, Headwaters & Creeks	4,938	4,927
87	High Gradient, Cool, Low Alkalinity, Large Rivers	3	3
88	High Gradient, Cool, Low Alkalinity, Medium Tributary Rivers	22	19
89	High Gradient, Cool, Low Alkalinity, Small Rivers	88	101
90	High Gradient, Cool, Moderate Alkalinity, Headwaters & Creeks	3,740	3,759
91	High Gradient, Cool, Moderate Alkalinity, Large Rivers	4	4
92	High Gradient, Cool, Moderate Alkalinity, Medium Tributary Rivers	21	16
93	High Gradient, Cool, Moderate Alkalinity, Small Rivers	88	73
94	High Gradient, Warm, High Alkalinity, Headwaters & Creeks	78	71
95	High Gradient, Warm, High Alkalinity, Large Rivers	6	7
96	High Gradient, Warm, High Alkalinity, Medium Tributary Rivers	2	1
97	High Gradient, Warm, High Alkalinity, Small Rivers	5	5
98	High Gradient, Warm, Low Alkalinity, Headwaters & Creeks	103	123
99	High Gradient, Warm, Low Alkalinity, Medium Tributary Rivers	5	8
100	High Gradient, Warm, Low Alkalinity, Small Rivers	8	9
101	High Gradient, Warm, Moderate Alkalinity, Headwaters & Creeks	93	101
102	High Gradient, Warm, Moderate Alkalinity, Large Rivers	1	0
103	High Gradient, Warm, Moderate Alkalinity, Medium Tributary Rivers	3	5
104	High Gradient, Warm, Moderate Alkalinity, Small Rivers	6	6
105	Tidally Influenced, High Gradient, Cold, High Alkalinity, Headwaters & Creeks	33	33
106	Tidally Influenced, High Gradient, Cold, High Alkalinity, Medium Tributary Rivers	1	8
107	Tidally Influenced, High Gradient, Cold, Low Alkalinity, Headwaters & Creeks	143	219
108	Tidally Influenced, High Gradient, Cold, Low Alkalinity, Small Rivers	4	2
109	Tidally Influenced, High Gradient, Cold, Moderate Alkalinity, Headwaters & Creeks	101	136
110	Tidally Influenced, High Gradient, Cold, Moderate Alkalinity, Medium Tributary Rivers	1	1
111	Tidally Influenced, High Gradient, Cold, Moderate Alkalinity, Small Rivers	1	1

112	Tidally Influenced, High Gradient, Cool, High Alkalinity, Headwaters & Creeks	39	42
113	Tidally Influenced, High Gradient, Cool, High Alkalinity, Medium Tributary Rivers	2	3
114	Tidally Influenced, High Gradient, Cool, Low Alkalinity, Headwaters & Creeks	270	368
115	Tidally Influenced, High Gradient, Cool, Low Alkalinity, Small Rivers	4	6
116	Tidally Influenced, High Gradient, Cool, Moderate Alkalinity, Headwaters & Creeks	155	155
117	Tidally Influenced, High Gradient, Cool, Moderate Alkalinity, Medium Tributary Rivers	2	0
118	Tidally Influenced, High Gradient, Cool, Moderate Alkalinity, Small Rivers	3	15
119	Tidally Influenced, High Gradient, Warm, High Alkalinity, Medium Tributary Rivers	1	0
120	Tidally Influenced, High Gradient, Warm, Moderate Alkalinity, Headwaters & Creeks	9	7
121	Tidally Influenced, High Gradient, Warm, Moderate Alkalinity, Large Rivers	2	0
122	Tidally Influenced, High Gradient, Warm, Moderate Alkalinity, Medium Tributary Rivers	2	1
123	Tidally Influenced, Low Gradient, Cold, High Alkalinity, Headwaters & Creeks	13	9
124	Tidally Influenced, Low Gradient, Cold, Low Alkalinity, Headwaters & Creeks	24	2
125	Tidally Influenced, Low Gradient, Cold, Low Alkalinity, Small Rivers	1	0
126	Tidally Influenced, Low Gradient, Cold, Moderate Alkalinity, Headwaters & Creeks	35	22
127	Tidally Influenced, Low Gradient, Cold, Moderate Alkalinity, Medium Tributary Rivers	12	16
128	Tidally Influenced, Low Gradient, Cool, High Alkalinity, Headwaters & Creeks	118	41
129	Tidally Influenced, Low Gradient, Cool, High Alkalinity, Large Rivers	1	7
130	Tidally Influenced, Low Gradient, Cool, High Alkalinity, Medium Tributary Rivers	10	18
131	Tidally Influenced, Low Gradient, Cool, High Alkalinity, Small Rivers	24	23
132	Tidally Influenced, Low Gradient, Cool, Low Alkalinity, Headwaters & Creeks	137	20
133	Tidally Influenced, Low Gradient, Cool, Low Alkalinity, Small Rivers	6	9
134	Tidally Influenced, Low Gradient, Cool, Moderate Alkalinity, Headwaters & Creeks	187	116
135	Tidally Influenced, Low Gradient, Cool, Moderate Alkalinity, Large Rivers	1	0
136	Tidally Influenced, Low Gradient, Cool, Moderate Alkalinity, Medium Tributary Rivers	10	9
137	Tidally Influenced, Low Gradient, Cool, Moderate Alkalinity, Small Rivers	11	12
138	Tidally Influenced, Low Gradient, Warm, High Alkalinity, Headwaters & Creeks	3	0
139	Tidally Influenced, Low Gradient, Warm, High Alkalinity, Large Rivers	2	1
140	Tidally Influenced, Low Gradient, Warm, High Alkalinity, Medium Tributary Rivers	15	13
141	Tidally Influenced, Low Gradient, Warm, Low Alkalinity, Headwaters & Creeks	3	0
142	Tidally Influenced, Low Gradient, Warm, Moderate Alkalinity, Headwaters & Creeks	18	6
143	Tidally Influenced, Low Gradient, Warm, Moderate Alkalinity, Large Rivers	18	14
144	Tidally Influenced, Low Gradient, Warm, Moderate Alkalinity, Medium Tributary Rivers	14	12

145	Tidally Influenced, Low Gradient, Warm, Moderate Alkalinity, Small Rivers	1	7
146	Tidally Influenced, Moderate Gradient, Cold, High Alkalinity, Headwaters & Creeks	82	115
147	Tidally Influenced, Moderate Gradient, Cold, High Alkalinity, Small Rivers	1	6
148	Tidally Influenced, Moderate Gradient, Cold, Low Alkalinity, Headwaters & Creeks	50	85
149	Tidally Influenced, Moderate Gradient, Cold, Low Alkalinity, Small Rivers	1	3
150	Tidally Influenced, Moderate Gradient, Cold, Moderate Alkalinity, Headwaters & Creeks	142	252
151	Tidally Influenced, Moderate Gradient, Cold, Moderate Alkalinity, Medium Tributary Rivers	1	3
152	Tidally Influenced, Moderate Gradient, Cold, Moderate Alkalinity, Small Rivers	1	2
153	Tidally Influenced, Moderate Gradient, Cool, High Alkalinity, Headwaters & Creeks	242	305
154	Tidally Influenced, Moderate Gradient, Cool, High Alkalinity, Medium Tributary Rivers	17	20
155	Tidally Influenced, Moderate Gradient, Cool, High Alkalinity, Small Rivers	18	40
156	Tidally Influenced, Moderate Gradient, Cool, Low Alkalinity, Headwaters & Creeks	196	244
157	Tidally Influenced, Moderate Gradient, Cool, Low Alkalinity, Small Rivers	5	4
158	Tidally Influenced, Moderate Gradient, Cool, Moderate Alkalinity, Headwaters & Creeks	879	1,308
159	Tidally Influenced, Moderate Gradient, Cool, Moderate Alkalinity, Medium Tributary Rivers	15	38
160	Tidally Influenced, Moderate Gradient, Cool, Moderate Alkalinity, Small Rivers	11	18
161	Tidally Influenced, Moderate Gradient, Warm, High Alkalinity, Large Rivers	5	4
162	Tidally Influenced, Moderate Gradient, Warm, High Alkalinity, Medium Tributary Rivers	7	8
163	Tidally Influenced, Moderate Gradient, Warm, Low Alkalinity, Headwaters & Creeks	1	1
164	Tidally Influenced, Moderate Gradient, Warm, Moderate Alkalinity, Headwaters & Creeks	36	55
165	Tidally Influenced, Moderate Gradient, Warm, Moderate Alkalinity, Large Rivers	22	28
166	Tidally Influenced, Moderate Gradient, Warm, Moderate Alkalinity, Medium Tributary Rivers	10	16

Appendix E. Complex Combination Statistical Analysis

To identify the relationship between benthic taxa and the combined classification variables (complex combination), catchments were clustered on their benthic taxa, lumping together those with similar species composition. We then explored the relationship between the clusters and the environmental variables. We ran a flexible beta hierarchical clustering analysis of the species data in R (R Core Team 2016), using the cluster package (Maechler et al. 2016) with the Bray-Curtis dissimilarity and a beta linkage of –0.25. To keep the number of clusters manageable, we limited the groups to 10. The flexible beta linkage method was chosen because it is compatible with the Bray Curtis dissimilarity and conserves space (Lance and Williams 1967; McCune and Grace 2002). Mantel tests were used to select the cluster group level that minimized within-group variance and maximized among-group variance. For the Mantel tests, the Bray-Curtis dissimilarity was used for the species data, and simple Euclidean distance was used for individual cluster group levels. All Mantel tests were conducted in R, using the vegan package (Oksanen et al. 2016).

To understand how the catchments sorted in multidimensional space, we ran a nonmetric multidimensional scaling (NMDS) ordination of the species data in R using a step-down procedure. The objective of NMDS is to project multidimensional data onto a lower-dimensional ordination space while preserving the relative distances among objects in the original space (Legendre and Legendre 1998). NMDS is particularly appropriate for ecological analyses because data do not have to meet the statistical assumptions of multinormality (McCune and Grace 2002). The initial NMDS run was made using the Bray-Curtis dissimilarity measure, starting with a six-dimensional solution and stepping down to a one-dimensional solution. Multiple NMDS runs were used to ensure that the solution was stable and the stress converged. The dimensionality of the dataset was determined by plotting stress against the number of dimensions in a scree plot. A three-dimensional (3-D) solution was used for the final NMDS runs because additional dimensions provided minimal reductions in stress. A Shepard plot of NMDS ordination distances against the original Bray Curtis dissimilarities was used as a diagnostic of ordination quality. To examine the relationship between the hierarchical cluster groups and the environmental variables (size, gradient, temperature, and alkalinity), 3-D vector fitting was used. This step identified the direction in the ordination space in which the environmental vectors changed most rapidly and to which they were most correlated. All NMDS analyses were conducted in R using the labdsv (Roberts 2016) and vegan packages.

The hierarchical clustering analysis had a good agglomerative coefficient (AC = .90) as values closer to 1 indicate a strong clustering structure. The results of the cluster analysis are shown in a dendogram (Figure E1). The cluster group level was then plotted against Mantel test statistic (r) to identify the "shoulder" in the graph where the increases in the r statistic start to level out. A cluster level of five groups was selected because cluster levels beyond five groups resulted in a significant decrease in the r statistic (Table E1). That is, within-group variance was minimized and among-group variance was maximized at five group clusters. The cluster groups were plotted against the four ancillary environmental variables calculated for each catchment (Figure E2).

For the final 3-D NMDS solution, the stress was a reasonable 12.32. The location of plots in the 3-D NMDS ordination space is shown in Figure E3, where point (i.e., catchment) color reflects cluster group and 3-D vectors show environmental variables that are significantly correlated with the ordination. NMDS promotes an intuitive interpretation: catchments near each other have more species in common, and more distant catchments have fewer species in common. The NMDS plot and Figure E2 reveal several trends. Catchments primarily sort in species composition space along temperature and gradient axes. The temperature and gradient vectors distinguish the warm-temperature and low-gradient sites from the cooler catchments with higher-gradient streams. Catchment size and alkalinity do not drive species composition patterns among the catchments as strongly as temperature and gradient, but they do play a role in how catchments sort in species space. For example, few large drainages have species that prefer streams with warm temperatures and low gradients. Figure E4 shows the Shepard plot where the nonmetric fit is based on stress *S*, defined as *sqrt (1-S^2).* The correlation between the ordination distances and the fitted values is denoted as the linear fit in the Shepard diagram.

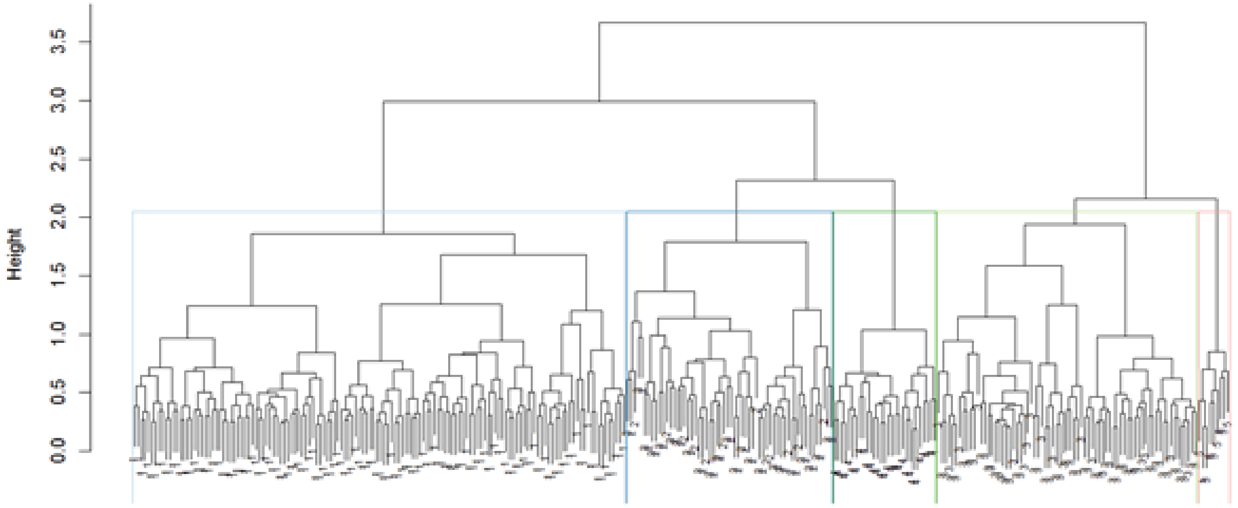


Figure E1. Dendogram from hierarchical cluster analysis of species data for all catchments. The y-axis indicates sites' similarity in species composition when merged into a cluster. The colours of the brackets that indicate the clustering correspond to the cluster group colours used in subsequent figures.

Table E1. Number of catchments per cluster

Cluster group	Catchments (n)
1	138
2	58
3	73
4	29
5	9

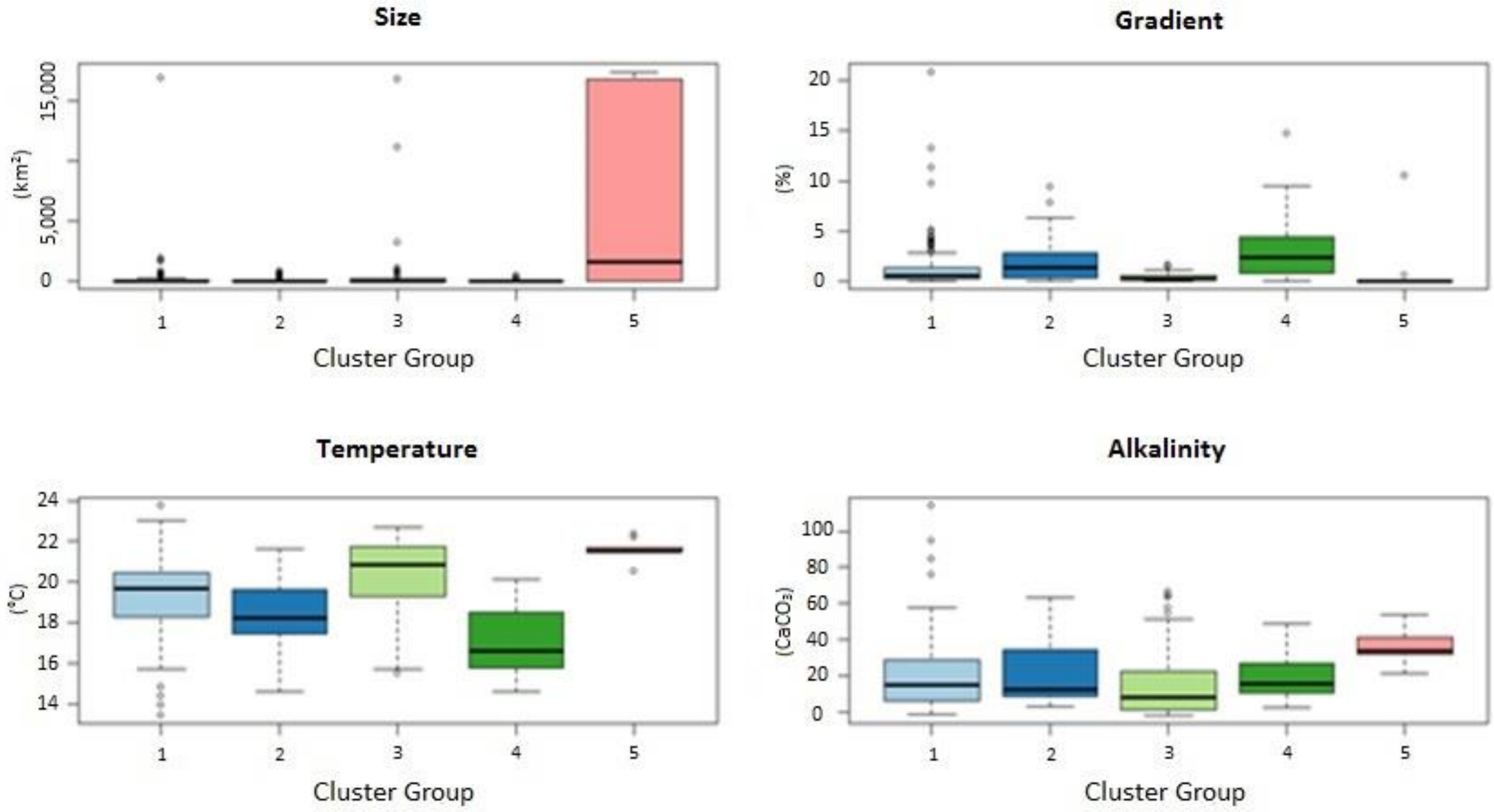


Figure E2. Boxplots of environmental variables versus five cluster groups

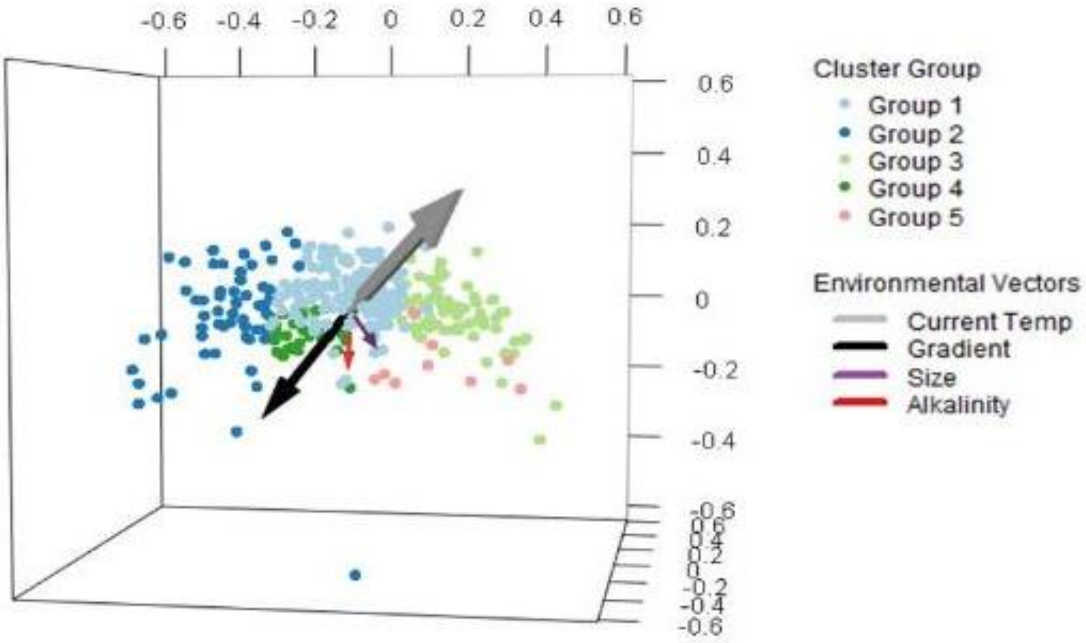


Figure E3. 3-D plot of NMDS ordination of catchments based on species data (The catchments are shown by cluster group and are overlaid with vectors for the most significantly correlated ancillary variables. Temperature has the strongest correlation with the ordination, followed by gradient**).**

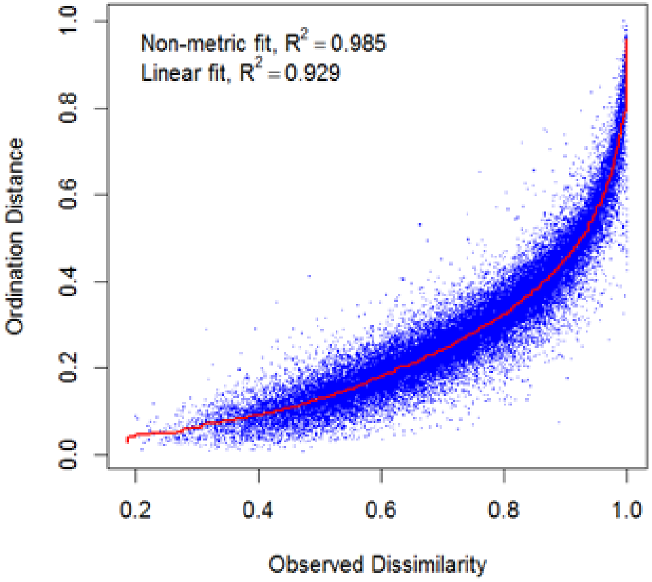


Figure E4. Shepard plot of ordination distances versus original Bray Curtis dissimilarities for 3-D plots