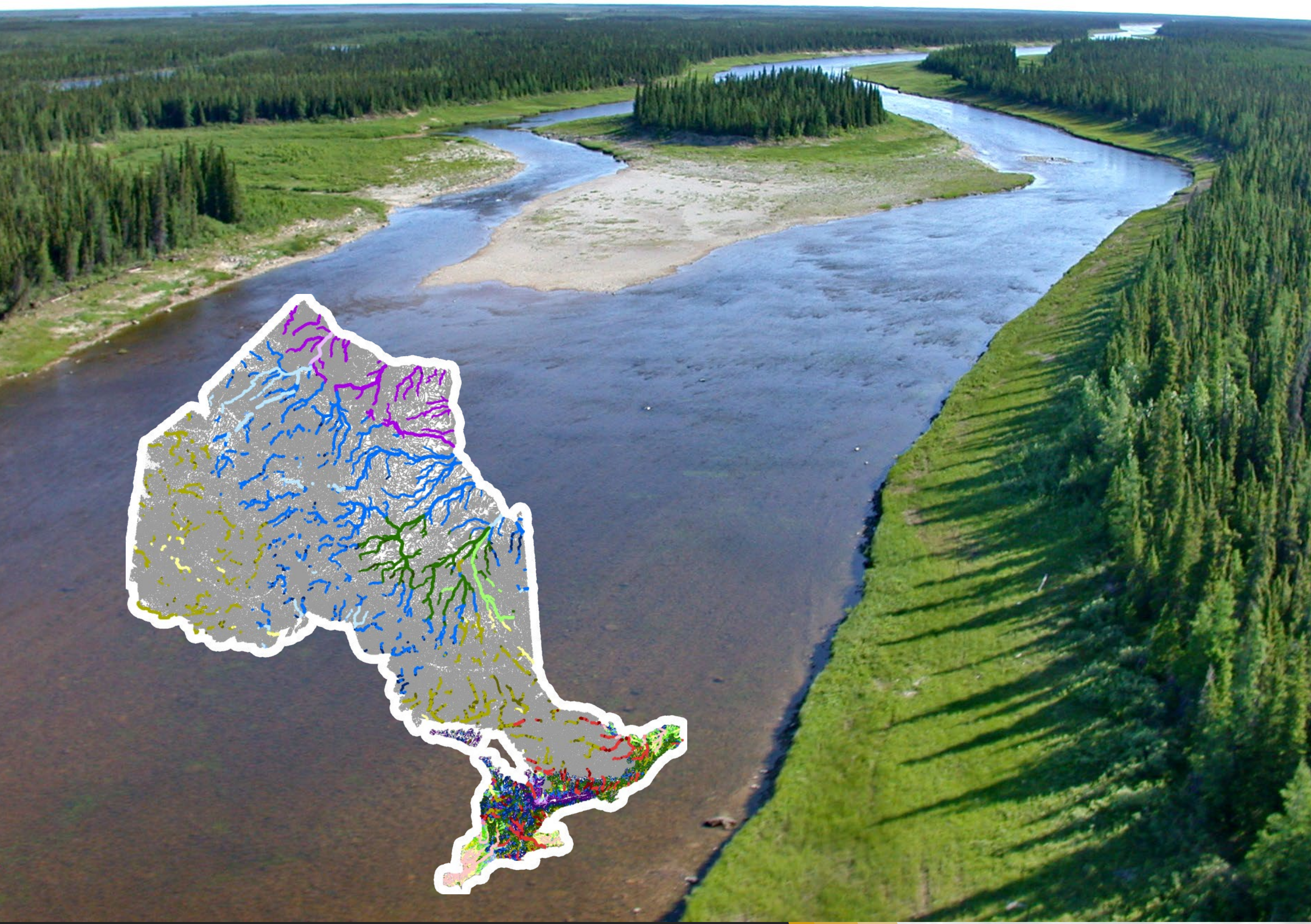


Aquatic ecosystem classification for Ontario's rivers and streams, version 2

Technical Report TR-47
Science and Research Branch
Ministry of Northern Development, Mines, Natural Resources and Forestry

Ontario

Science and Research Technical Report TR-47

Aquatic ecosystem classification for Ontario’s rivers and streams, version 2

N. Jones and B. Schmidt

Aquatic Research and Monitoring Section, Peterborough, ON

2022

Science and Research Branch

Ministry of Northern Development, Mines, Natural Resources and Forestry

Copies of this publication are available from info.mnrfscience@ontario.ca.

Cette publication hautement spécialisée, Aquatic Ecosystem Classification for Ontario’s Rivers and Streams, Version 2, n’est disponible qu’en anglais conformément au Règlement 671/92, selon lequel il n’est pas obligatoire de la traduire en vertu de la Loi sur les services en français. Pour obtenir des renseignements en français, veuillez communiquer avec le ministère du Développement du Nord, des Mines, des Richesses naturelles et des Forêts au info.mnrfscience@ontario.ca.

Cover photo: Map of Ontario showing the aquatic ecosystem classification superimposed on river image.

Some of the information in this document may not be compatible with assistive technologies. If you need any of the information in an alternate format, please contact info.mnrfscience@ontario.ca.

Cite this report as:

Jones, N.E. and B.J. Schmidt. 2022. Aquatic ecosystem classification for Ontario’s rivers and streams, version 2. Ontario Ministry of Northern Development, Mines, Natural Resources and Forestry, Science and Research Branch, Peterborough, ON. Science and Research Technical Report TR-47. 30 p. + appendices.

Data Availability: Spatial data including Google Earth and geodatabase files associated with this report are available via GeoHub.

Abstract

The aquatic ecosystem classification (AEC) is a science-based tool used to group and classify Ontario's rivers and streams based on their physical attributes, such as water temperature, and watershed characteristics, such as upstream drainage area. The first version of the AEC has been refined based on input gathered via numerous stakeholder meetings. Both versions of the AEC share the same underlying spatial source data (i.e., Ontario Integrated Hydrology). Refinements in version 2 include replacing the base flow index with modelled average July water temperature for all streams of the Mixedwood Plains Ecozone and the large streams (>700 km^2) of the Ontario Shield and Hudson Bay Lowlands ecozones. We also refined turbidity and slope estimates, and improved lake influence estimates using more sophisticated analysis methods. The Ministry of Northern Development, Mines, Natural Resources and Forestry (NDMNRF) is responsible for sustainably managing and deriving economic benefit from the fisheries and water resources in the estimated 500,000 km of Ontario's rivers and streams. The AEC reduces the complexity of these vast aquatic networks by using consistent and quantitative methods to build a standardized data foundation that helps NDMNRF staff with landscape-scale planning and policy development.

Résumé

Classification des écosystèmes aquatiques pour les cours d'eau de l'Ontario, version 2

La classification des écosystèmes aquatiques (CEA) est un outil scientifique utilisé pour regrouper et classer les rivières et les ruisseaux de l'Ontario en fonction de leurs attributs physiques, comme la température de l'eau, et de caractéristiques de leurs bassins versants, comme l'aire de drainage en amont. La première version de la CEA a été affinée en fonction des commentaires recueillis lors de nombreuses réunions avec les parties prenantes. Les deux versions de la CEA reposent sur les mêmes données de source spatiale sous-jacentes (c.-à-d. les Données hydrologiques intégrées de l'Ontario). Les améliorations apportées à la version 2 comprennent le remplacement de l'indice de débit de base par la température moyenne modélisée de l'eau en juillet pour tous les cours d'eau de l'écozone des plaines à forêts mixtes et les grands cours d'eau (>700 km^2) des écozones du bouclier ontarien et des basses terres de la baie d'Hudson. Nous avons également précisé les estimations de la turbidité et de la pente, et amélioré celles de l'influence des lacs en utilisant des méthodes d'analyse plus complexes. Le ministère du Développement du Nord, des Mines, des Richesses naturelles et des Forêts (MDNRF) est chargé de gérer de façon durable les ressources halieutiques et hydriques des estimé 500 000 km de rivières et de cours d'eau de l'Ontario, et d'en tirer des avantages économiques. La CEA réduit la complexité de ces vastes réseaux aquatiques en utilisant des méthodes cohérentes et quantitatives pour établir une base de données normalisée qui aide le personnel ministériel à planifier et à élaborer des politiques à l'échelle du paysage.

Acknowledgements

Many people have contributed to the development of the classification system including the AEC Technical Committee; staff from the Provincial Geomatics Services Centre, conservation authorities across Ontario, and the federal Department of Fisheries and Oceans; and especially Stephanie Melles, Isaac Sutton, Mike Parna, Sarah Parna, Kimisha Ghunowa, Paul Seelbach, Lizhu Wang, and Dan McKenney. Funding for the AEC came from the then Ontario Ministry of Natural Resources and Forestry's Far North Branch, the Canada-Ontario Agreement on Great Lakes Water Quality and Ecosystem Health, and Fish and Wildlife.

Contents

Preface

The aquatic ecosystem classification (AEC) is an ongoing project that will continue to be updated and supplemented with additional variables and information that can be used to better understand and manage Ontario's aquatic resources. The AEC reduces the complexity of these vast aquatic networks using consistent and quantitative methods to build a standardized data foundation. Based on numerous stakeholder meetings, version one of the AEC was refined. The first and the second version of the AEC share the same underlying spatial source data (i.e., Ontario Integrated Hydrology from 2014). Refinements in version two include replacing the base flow index with modelled average July water temperature for all streams of the Mixedwood Plains Ecozone and the large streams (>700 km^2) of the Ontario Shield and Hudson Bay Lowlands ecozones. We also refined turbidity and slope estimates, and improved lake influence estimates using more sophisticated analytical methods. Provided here is an update of documentation provided for version 1 that includes all information needed to understand the components and use of the AEC, some of which duplicates information provided by Melles et al. (2013).

Getting involved

During our many regional and local presentations about the AEC we have gained much insight and learning from participant feedback. We encourage AEC users to continue to provide us with valuable information about where the classification works well and where it does not. We would like to hear from you if you think a change in class designation is warranted and why. For example, if a stream is classified as warm water in the AEC but you are certain it is a coldwater stream from experience and have evidence, we would consider adjusting the AEC classification manually to reflect that knowledge. To submit comments, suggestions, or concerns about the AEC class assignments, please email the form included in the GeoHub zipped data packages (also provided in Appendix 4 of this report) to AEC@ontario.ca.

Introduction

The aquatic ecosystem classification (AEC) is a science-based tool that groups and classifies Ontario's rivers and streams based on their physical attributes, such as water temperature, and watershed characteristics, such as upstream drainage area. The main goals of the AEC are to provide a universal and consistent spatial framework for Ontario's flowing waters, capture the ecological nature of streams and rivers, validate the classification by working with stakeholders during development and testing, and simplify the enormous complexity of streams across Ontario for understanding and management.

Ontario has an area of about 1 million square kilometres and much of it is remote and difficult to access. Before development of the AEC, we did not have a full inventory of the character of Ontario's streams and rivers. We did not know what kinds of rivers we had and how they were distributed in the province. Such information is vital for managing our rivers and their inhabitants as a natural resource, including monitoring them, reporting on their health, and assessing the effectiveness of our management actions. The Ministry of Northern Development, Mines, Natural Resources and Forestry (NDMNRF) is responsible for sustainably managing and deriving economic benefit from the fisheries and water resources in the estimated 500,000 km[1] of Ontario's rivers and streams. The AEC reduces the complexity of these vast aquatic networks using consistent and quantitative methods to build a standardized data foundation.

Before the computer age, aquatic classification schemes often relied on a combination of hand drawn watershed maps and terrestrial land classifications (Omernik 1987, Hawkins et al. 2000). In their synthesis, Hawkins et al. (2000) noted that landscape classifications accounted for more biotic variation than would be expected by chance but that the amount of variation related to landscape features was minimal. They suggested that landscape classifications have a role in initial stratification, but a tiered classification based on both reach- and larger-scale landscape features is needed to accurately predict the composition of freshwater fauna. Modern geographic information systems (GIS) have allowed for increasingly powerful and sophisticated analyses of stream networks, changing the ways we can perceive streams and their inhabitants. Contemporary and historical classifications are predicated on the idea that the valley rules the stream (Hynes 1975). The ecological characteristics of streams, particularly abiotic, are strongly influenced by the characteristics of their catchments (i.e., the areas of land they drain). Landscape characteristics such as physiography, topography, climate, geology, and land cover will determine thermal and flow regimes, nutrients in the water, and sediment dynamics. We are now able to inventory our river systems from small headwaters to kilometre wide lowland rivers using their landscape characteristics. We can also identify similarities and differences in the characteristics of our streams across large areas.

---

[1] The cumulative length of Ontario's streams is an estimate of the true length of streams on the ground and is likely an underestimation. It was arrived at using the spatial base data developed for the aquatic ecosystem classification (AEC). The AEC network lines were trimmed in the headwaters, as described in more detail in this report, and simplified using a common ArcGIS function.

In 2013, the ministry's river and stream ecology team published a technical report outlining the theoretical basis for building an aquatic ecosystem classification for Ontario's rivers and streams (Melles et al. 2013). We also conducted a client needs survey to determine the usefulness of an AEC and how it would be applied in the ministry (Melles et al. 2011). This survey and a literature review of classification systems world-wide (Melles et al. 2012, 2014) were used as a guide to design and build a new spatial data framework to classify all rivers and streams in the province into ecologically homogenous units at several hierarchically nested spatial scales. The AEC serves as a landscape-scale resource management tool to group Ontario's streams into aquatic classes that will support efforts such as:

- informing resource inventory and monitoring efforts (e.g., fisheries)
- helping identify habitat of highly valued species, species at risk, and invasive species
- supporting aquatic class park development and land use planning

The AEC is a hypothesis that aims to capture major ecological differences among streams in Ontario. Based on feedback gathered over many meetings with stakeholders from across the province, the AEC classifies most streams correctly. The few incorrectly classified streams need to be scrutinized by those familiar with them, as some are rare or unique in character (e.g., karst systems, groundwater springs) or have base data issues (e.g., inaccurate geologic mapping). The AEC was built using a small set of landscape variables that strongly influence stream character. Many other variables could have been added, perhaps slightly improving class predictive power but at a cost of reduced interpretability. No right or wrong level of detail, spatial resolution, or number of stream classes exists: these factors are not scientifically defined but rather reflect the questions of interest and geographic scale. In general, a high degree of complexity at small local scales becomes problematic at regional scales. This dichotomy is why we used a hierarchical approach for classifying streams at different spatial scales. Like all hypotheses, ours will change and improve as we gain additional knowledge.

Potential uses of the classification

The aquatic ecosystem classification can be used in many ways to support policy and management decisions. Some relevant applications of the AEC are summarized here.

Provincial resource monitoring

- Guide site selection to ensure efficient use of time and money for coarse- and fine-scale monitoring and field inventories.
- Improve statistical sampling design resulting in greater power to detect change (e.g., stratification).
- Provide a provincially consistent spatial framework for monitoring and reporting.
- Allow extrapolation from data rich to data poor areas.

Conservation status

- Provide biologists with an understanding of the nature/ecology of streams across the province without needing to visit the stream.
- Contribute to the development of models predicting the distribution/abundance of invasive, at risk, or highly valued species (e.g., brook trout; Thorn et al. 2016, Jones et al. 2020).
- Provide quantitative assessment of the health of populations (e.g., expected vs. observed brook occupancy or trout biomass).
- Understand how human disturbances influence fish abundance and biodiversity (e.g., Jones et al. 2019).
- Predict locations of rare aquatic species (e.g., redside dace) to support reintroduction and restoration efforts.

Policy and guideline improvement

- Make guidelines more context dependent with criteria specific to stream types. For example, evaluation criteria for indicators such as fish abundance can be tailored for specific classes of stream.

Parks and land use planning

- Determine representation and uniqueness of aquatic features on the landscape.
- Help assess the ecological integrity of streams across Ontario.
- Develop aquatic class parks.
- Understand ecological sensitivity and capacity of the landscape.

Special considerations

When using the classification, consider the following:

- The AEC is a general habitat template model, not a species-specific model (for species-specific models see Jones et al. 2020).
- The classification does not include the influence of human development (e.g., urbanization, agriculture; see Jones et al. 2019). Unlike geology and stream size, human development changes quickly and would require frequent changes to the classification.
- The intended scale of use does not include identification of sub-reach habitat heterogeneity (e.g., pools, riffles). We recognize that heterogeneity exists at a scale below the AEC reach level, but provincial-scale base data resolution does not support work at such a fine spatial scale.

- The intended scale of use does not include very small, often intermittent, streams. We recognize the importance of such features for some applications, but they are smaller than can reasonably be represented using provincial-scale base data (i.e., 30 m digital elevation model).
- Some elements of the classification, like stream temperature, include a level of uncertainty.
- Stream classes are based on similarities and differences in their abiotic characteristics. Although the classification divides reaches into discrete classes abiotic variables remain continuous. Depending on the position along the continuum, a stream reach may show strong affinity to a class, whereas others may be close to the boundary of an adjacent class. For example, a stream with an average July temperature of 12 ˚C is clearly in the coldwater class, but a reach with an average July temperature of 17 ˚C is near the cold to cool class threshold (18.5 ˚C) so has a lower affinity for the cold class.
- Small streams are more susceptible to underlying base data errors (e.g., geologic misclassification or spatial inaccuracies).
- Temperature predictions may change abruptly as drainage area increases above 700 km^2 because small streams (<700 km^2) were modelled separately from larger (≥700 km^2) ones.

Aquatic ecosystem classification: Transition from version 1 to version 2

Between 2013 and 2017, we conducted more than 30 meetings to provide organizations an understanding of the initial version of the classification (AECv1), including the then Ministry of Natural Resources and Forestry (MNRF), conservation authorities (CA), Department of Fisheries and Oceans Canada (DFO), universities, and non-government organizations. Given the positive reception of the AECv1 and the demonstrated need for this product in the ministry and other agencies, we recommended the development of an updated second version (Jones and Schmidt 2019). Participants of our stakeholder meetings identified that the AECv1 correctly classified most streams in southern Ontario. The remaining reaches need to be vetted through those most familiar with streams, as some are rare (e.g., karst streams), have base data issues (e.g., missing waterbodies), or are special cases/conditions in Ontario (e.g., deeply incised valleys with connections to the deep aquifers).

One issue with AECv1 was the interpretation of groundwater inputs as base flow index (BFI; Neff et al. 2005), particularly in Northern Ontario. In the AEC, BFI is a measure of potential cold groundwater contribution to stream flow and is commonly interpreted as a surrogate for stream temperature. This assumption worked well in southern Ontario where the correspondence between water temperature and BFI is generally good. This high correspondence is because most streams in southern Ontario are relatively small (<100 km^2) and are strongly influenced by local catchment BFI characteristics rather than air temperature. However, this approach did not work as well in Northern Ontario, particularly for larger rivers (>700 km^2 catchment area). These rivers can have high BFI (i.e., large amounts of groundwater influx) in headwater areas, which carries through to relatively high BFI in large rivers far downstream. On the AEC map they appeared as large cold streams but in fact are much warmer. This result is not surprising given that when stream size increases, the influence of BFI on its thermal character diminishes and air temperature and solar heating increasingly become the dominant drivers of water temperature. This effect can be attributed to the increase of river surface area open for convective heating combined with the reduced ability of riparian vegetation to provide shade, allowing more of the rivers' surface to be exposed to solar radiation (Caissie 2006). The first version of the AEC (AECv1) and the new version (AECv2) share the same underlying spatial source data (i.e., Ontario Integrated Hydrology). Major changes from AECv1 to AECv2 include replacing BFI with modelled average July water temperature for all streams of the Mixedwood Plains Ecozone and the large streams (>700 km^2) of the Ontario Shield and Hudson Bay Lowlands ecozones. Small streams of these northern ecozones will be included once an ongoing field temperature collection campaign allows for more accurate modelling. Other refinements include the following (with rationale and more details provided in Jones and Schmidt 2019):

- refining the geology-based turbidity classification because too many streams were incorrectly classified as being turbid; some quaternary geology types containing clay were removed (types 4, 6, 8, 15, and 21) because they did not produce low flow turbidity leaving only types 24, 26, and 29 (as defined in Barnett 1992)
- applying a more dynamic turbidity assignment process based on per cent upstream catchment area instead of a single static threshold
- correcting channel slope class codes across the Haldimand Clay Plain of Niagara Peninsula and the St. Clair Clay Plains west of London as their extremely low topographic relief and digital elevation model (DEM) conditioning methods result in DEM base data issues
- using a more intuitive method for creating stream classes and segments (Jones and Schmidt 2019)
- improving lake influence estimates using more sophisticated analysis methods (in progress PhD thesis, M. Allerton)

Primary components of the aquatic ecosystem classification

The primary abiotic components that define AEC habitat are average July water temperature, perennial turbidity, and channel slope (i.e., flow velocity potential).

Stream temperature

Thermal regime is of central importance in sustaining the ecological integrity of aquatic ecosystems. Water temperature has been described as the master (controlling) variable for fishes (Brett 1971, Hannah and Garner 2015) and as an ecological resource that defines habitat availability (Magnuson et al. 1979). Water temperature influences the distribution and abundance of species, water quality, nutrients, ice dynamics, as well as the metabolic activity, growth, timing of migration, and spawning events of fishes (Caissie 2006; Prowse 2001a,b). In turn, a good understanding of the thermal regime of streams and rivers is needed for effective fisheries management and environmental impact assessments (Jones and Schmidt 2019).

Water temperatures vary spatially within a stream (longitudinally, laterally, and by depth) and temporally (year to year, seasonally, and daily). Fish can inhabit streams that can rise several degrees above their preferred temperature; how much excess heat they can tolerate depends on the duration of the exposure, food resources, and their ability to find cooler patches of water (e.g., groundwater seeps). Although fish have temperature preferences and their general distribution is largely related to average summer stream temperature, they can inhabit a wide range of temperatures through behavioural adaptations and thermal tolerances (Reynolds 1979, Biro 1998). Both the spatial-temporal variability in temperature and the tolerances and behavioural adaptations of fishes make it difficult to develop a single classification for stream temperature. Although periods of high temperatures during the summer months may cause fish to seek cooler water, for the remainder of the year temperature is not a limiting factor and fish may move freely within the stream network or into neighbouring lakes. In winter, fishes may make similar movements into overwintering habitats to find warmer water. Considering this thermal seasonality, with the peak of summer generally being most limiting, basing the AEC thermal classes on average July water temperatures (i.e., the time when the peak of stream thermograph occurs across Ontario) seems logical.

Given the complex nature of stream temperature, a common misconception is that coldwater fishes (e.g., brook trout) will only be observed in coldwater streams. In fact, some coolwater streams support the highest biomass and production of trout (Lyons et al. 2009). Warm water fishes (e.g., catfish and bass) are often found amongst coldwater fishes during the summer months. Likewise, warm water streams may provide important habitats for cool- and coldwater species during non-summer months. Refer to Jones and Schmidt (2019) for more information on understanding stream water temperature and thermal classification. The role of lakes in influencing stream temperature is discussed in more detail below.

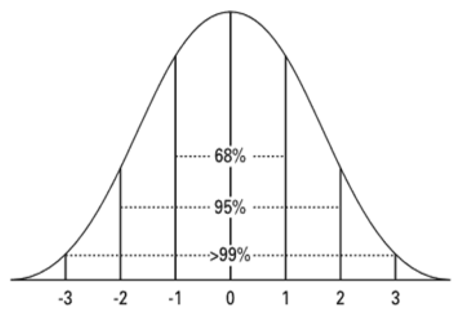
Most predictive models provide a temperature value that is based on average summer temperatures of a single year or 30-year climatic averages, providing little understanding of inter-annual variability. Point-in-time temperature sampling using the Stoneman and Jones (1996) or Chu et al. (2009) methods is also vulnerable to annual variation in air temperatures. A more robust approach entails using multiple years of data to create probabilities for given temperatures (e.g., with 10 years of stream temperature data only 2 years (20%) had temperatures above 19 °C). For the AECv2, we made 30 predictions of mean July temperature based on 30 individual years of July air temperature data, providing 30 predicted stream temperatures per reach that could be used to determine probabilities for different temperature thresholds (Figure 1; see Jones et al. 2021 for details). We acknowledge that a landscape-scale temperature model will not capture the target processes perfectly because all models have some degree of uncertainty.

We developed an approach that establishes each reach's affinity to the three primary thermal classes of cold, cool, and warm using the class membership probability of the average and standard deviation of 30 years of normally distributed data. If a reach's class probability did not exceed the minimum primary class membership probability threshold of 0.8 it was assigned one of two transitional classes of cold-cool or cool-warm (Figure 1). This five-class naming system is consistent with the five classes of Chu et al. (2009), however, the two methods differ in how the classes are determined. Our method explicitly incorporates uncertainty of inter-annual variability into the class membership assignment because it determines a reach's membership probability using the z-score based on 30 individual Julys of data. A primary thermal class is assigned only if the probability of membership is greater than 0.8 in the three primary temperature classes (i.e., cold, cool, warm). The grey bands on Figure 1 define the transitional temperature classes of cold-cool and cool-warm, where the probability of membership in both cold and cool, or cool and warm are below 0.8 (e.g., a cold-cool stream might have a cold probability of 0.6 and cool probability of 0.4).

In southern Ontario, cold class streams are generally small headwater streams that are very cold even during the hottest year while warm class streams are either large rivers or smaller streams draining the clay plains of southwestern Ontario. The latter are warm even during the coolest summers. Cool class streams can be streams of all sizes, often with heterogenous baseflow conditions in their upstream catchment areas. Cool streams never get very cold or very warm, even during the coldest or warmest summers. Most years streams in the cold-cool class are cool, but they become cold during the coolest summers. Likewise, cool-warm class streams are cool most years but can become warm during the hottest summers (Figure 2).

Lake influence on stream temperature

Throughout much of Ontario, lakes and rivers are connected in an alternating series of lentic (still water) and lotic (running water) reaches. Previous research has shown that rapid and predictable changes occur downstream of lakes (Jones 2010) and these changes override any temperature influence of the upstream drainage area. Water flowing into streams at lake outlets will often be warmer and carry large amounts of dissolved organic carbon, phytoplankton, and zooplankton also known as seston, which is a source of forage for species downstream. In addition, the storage potential of lakes in stream networks dampens responses to rainstorm events. These changes in the abiotic and biotic conditions fundamentally alter the ecology of the outlet stream, however, the changes are context dependent. The lake influence on small streams attenuates quickly (<1 km), whereas for large streams it may take several kilometres to attenuate (Jones 2010).



$$Z = \frac{X_i - \mu}{\sigma} \qquad Z = \frac{18.5 - 17}{0.8}$$

$$Z = 1.875$$

$$P = 0.97$$

Five classes

Temperature °C	<18.5	18.5–21.5	>21.5	
Class	Cold	Cool	Warm	
15.0	1.00	0.00	0.00	
15.5	1.00	0.00	0.00	
16.0	1.00	0.00	0.00	
16.5	0.99	0.01	0.00	
17.0	0.97	0.03	0.00	
17.5	0.89	0.11	0.00	
18.0	0.73	0.27	0.00	Cold-cool
18.5	0.50	0.50	0.00	Cold-cool
19.0	0.27	0.73	0.00	Cold-cool
19.5	0.11	0.89	0.01	
20.0	0.03	0.94	0.03	
20.5	0.01	0.89	0.11	
21.0	0.00	0.73	0.27	Cool-warm
21.5	0.00	0.50	0.50	Cool-warm
22.0	0.00	0.27	0.73	Cool-warm
22.5	0.00	0.11	0.89	
23.0	0.00	0.03	0.97	
23.5	0.00	0.01	0.99	
24.0	0.00	0.00	1.00	
24.5	0.00	0.00	1.00	
25.0	0.00	0.00	1.00	

Figure 1. Five class system for assigning stream reaches for Ontario streams. The method uses 30 predictions of July average temperature to create a frequency distribution from which a probability can be obtained for a threshold temperature value. As an example, a stream with an average July temperature of 17 °C and a standard deviation of 0.8 would have a high probability (P=0.97) of belonging to the coldwater class (<18.5 °C). A stream with an average July temperature of 20 °C and a standard deviation of 0.8 would also have a high probability (p=0.94) of belonging to the coolwater class. In contrast, a stream with an average July temperature of 21.5 °C and a standard deviation of 0.8 would have a low probability for both the cool and warm classes, placing it into the transitional cool-warm class. This measure of uncertainty is useful in making decisions about thermal class and the strength of the determination.

For the AEC we determined the lake effect index (LEI) attenuation with a focus on water temperature, where initial lake influence is a function of upstream drainage area and lake surface area. Streams start with this initial LEI at the outlet and decay towards a minimum value of zero some distance downstream. The LEI below a tributary confluence was assigned the area weighted average of the main channel and tributary values. We recognize that the temperature of large streams (>2000 km^2) is less influenced by lakes because, like lakes, their water temperature is primarily a function of air temperature. As a result, water temperatures for lakes and large rivers are similar. Such rivers were assigned a LEI of zero. For the AEC, the LEI values were further simplified into a binary index of influenced (LEI≥0.1) and not influenced (<0.1). We included this index as a secondary attribute of the AEC as an implicit class modifier.

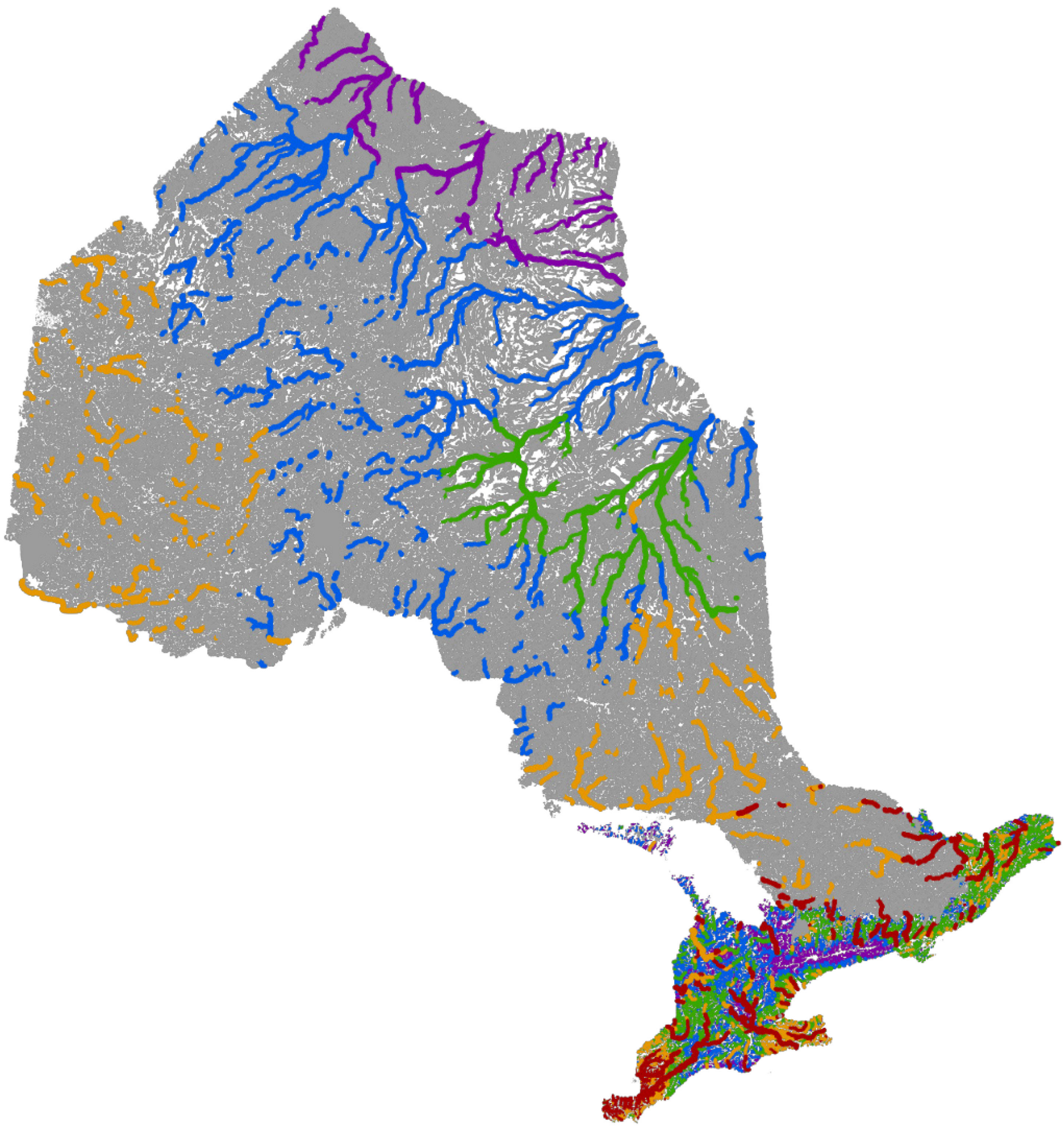


Figure 2. The five water temperature classes based on the statistical distribution of 30 years of annually modelled stream temperatures for each stream reach. The three core thermal classes are cold (purple), cool (green), and warm (red) with two transitional classes of cold-cool (blue) and cool-warm (orange). Predictions for large streams (>700 km^2) span all of Ontario. Predictions for small streams (<700 km^2) are available for the Mixedwood Plains Ecozone (southern Ontario). Small streams in the north are coloured grey and do not yet have predictions but hope to provide soon.

Turbidity

The clarity or cloudiness of a stream relates to its productivity (e.g., autotrophic vs. heterotrophic energy sources) and invertebrate and fish community characteristics (e.g., sauger/mooneye/catfishes vs. trout/charr). In turbid streams light penetration is limited and sources of energy are primarily allochthonous (i.e., imported from external sources) organic matter. Even relatively small turbid tributaries can influence the ecology of larger mainstem rivers. In the context of the AEC, such streams are cloudy for most of the year, even during summer low flow periods. They are typically associated with very fine glaciolacustrine deposits (i.e., clay). Perennial turbidity in streams is largely a function of clay geology types underlying the river channel, not necessarily the whole upstream catchment area, because surface run-off is not a factor during low flows. See Jones and Schmidt (2019) for a detailed rationale for changes to turbidity.

In some instances, the quaternary geologic regions are not homogenous (i.e., gradients of varying clay content occur in a single polygon). This heterogeneity within geology regions complicates modelling because it creates two different turbidity levels from the same geology type. For example, St. Joseph Till which extends along the coast from Sarnia to Southampton is composed of silt to silty clay matrix, with clay content that increases southward. Streams at the north end of St. Joseph Till tend to be clearer than the turbid streams near Sarnia. Tavistock Till occurs predominantly in three large polygons near Chatham-Kent, London, and Shelburne. This geology type is composed of sandy silt to silt matrix and silty clay matrix in the south and has moderate to high carbonate content in the north, with clast content decreasing from moderate to poor northward. Streams south of Chatham-Kent are turbid, whereas those in the north are clearer despite their association with the Tavistock Till. We addressed these issues by developing a new quaternary geologic turbidity spatial base layer that better represents whether geologic regions will produce low-flow turbidity. We then applied multiple upstream catchment area thresholds. For a reach to be classified as turbid, the combined proportion of these clay geology types underlying the channel upstream must exceed the upstream catchment area (UCA)-dependent thresholds of Table 1.

Table 1. Drainage areas and their associated values for clay geology types in the stream channel (30 m digital elevation model) used in the aquatic ecosystem classification in Ontario.

Reach upstream catchment area (km^2)	Proportion (%) of upstream channel with underlying clay geology needed for low flow turbidity
<500	≥10
500–5,000	≥8
5,000–50,000	≥6
>50,000	≥4

In southern Ontario, turbid streams are located primarily in the Haldimand Clay Plain of Niagara Peninsula, the St. Clair Clay Plains west of London, and the Ottawa Valley and Winchester Clay Plains in eastern Ontario. Quaternary geology (1:1,000,000) was used to assess and model turbidity in southern Ontario. Although the southern Ontario geology layer, referred to as MRD128 (1:50,000), is more detailed, the geology under stream channels is largely two geology types called modern alluvial deposits (class 19) that contain clay, silt, sand, gravel, and may contain organic remains and older alluvial deposits (class 12) containing clay, silt, sand, gravel, and sometimes organic remains. The ambiguous nature of the material textures means the data is not useful for assessing turbidity. For example, rivers in the glaciolacustrine Haldimand Clay Plain produce high turbidity in the Niagara Peninsula and are underlain by a mixture of old and modern alluvial deposits. Much clearer rivers in the Norfolk Sand Plain also have a mixture of old and modern alluvial deposits. The strong difference in water clarity in concert with no differences in channel geology makes numerical modelling difficult because turbidity levels differ for the same geology type (Figure 3).

We recognize the gradient of turbidity levels across Ontario that reflects the types of geology and per cent coverage in each drainage. Many rivers are seasonally turbid (spring and fall) and some temporarily become turbid in response to summer rainstorm events. Many rivers are in agriculture areas that may artificially increase turbidity levels directly through soil erosion and indirectly through nutrient additions that promote primary production of phytoplankton. These rivers are often a khaki green colour during low flow conditions in summer. Bioturbation from the activities of fish (e.g., carp) and mammals (e.g., muskrats, cattle) can persistently increase turbidity levels in many streams.

Stream channel slope

Stream channel slope is a determinant of flow velocity potential (i.e., current), which affects organisms in running waters. Current strength defines sediment size and food delivery, and is a direct physical force acting on organisms. Channel slope was computed as rise over run along the length of a reach based on a 30 m DEM (i.e., Ontario Integrated Hydrology). Channel slope was categorized as slow moving (≤0.1%) or fast moving (>0.1%; Figure 4; Knighton 1998). This threshold is meant to differentiate between streams whose beds are dominated by sands and finer sediments and those composed of larger sediments such as gravel and coarser substrates (Hjulström 1935). The categorization is a generalization that averages intra-reach differences of fast riffles and slow pools, which are assumed to occur along most reaches because of finer scale geomorphological processes operating at a scale below that of the AEC. We acknowledge that an average reach slope will misrepresent sudden elevation changes within a reach (e.g., waterfalls). For example, the channel slope of the Niagara River not including the drop at Niagara Falls is just 0.011, but including the falls is 0.204 (~20x greater). Like the classes of temperature and turbidity, slope class boundaries are imposed onto a continuum. As such, channel slopes close to the fast/slow threshold of 0.1% have less affinity to their slope class. These streams are intermediary (0.05–0.15%) and should be implicitly interpreted as transitional.

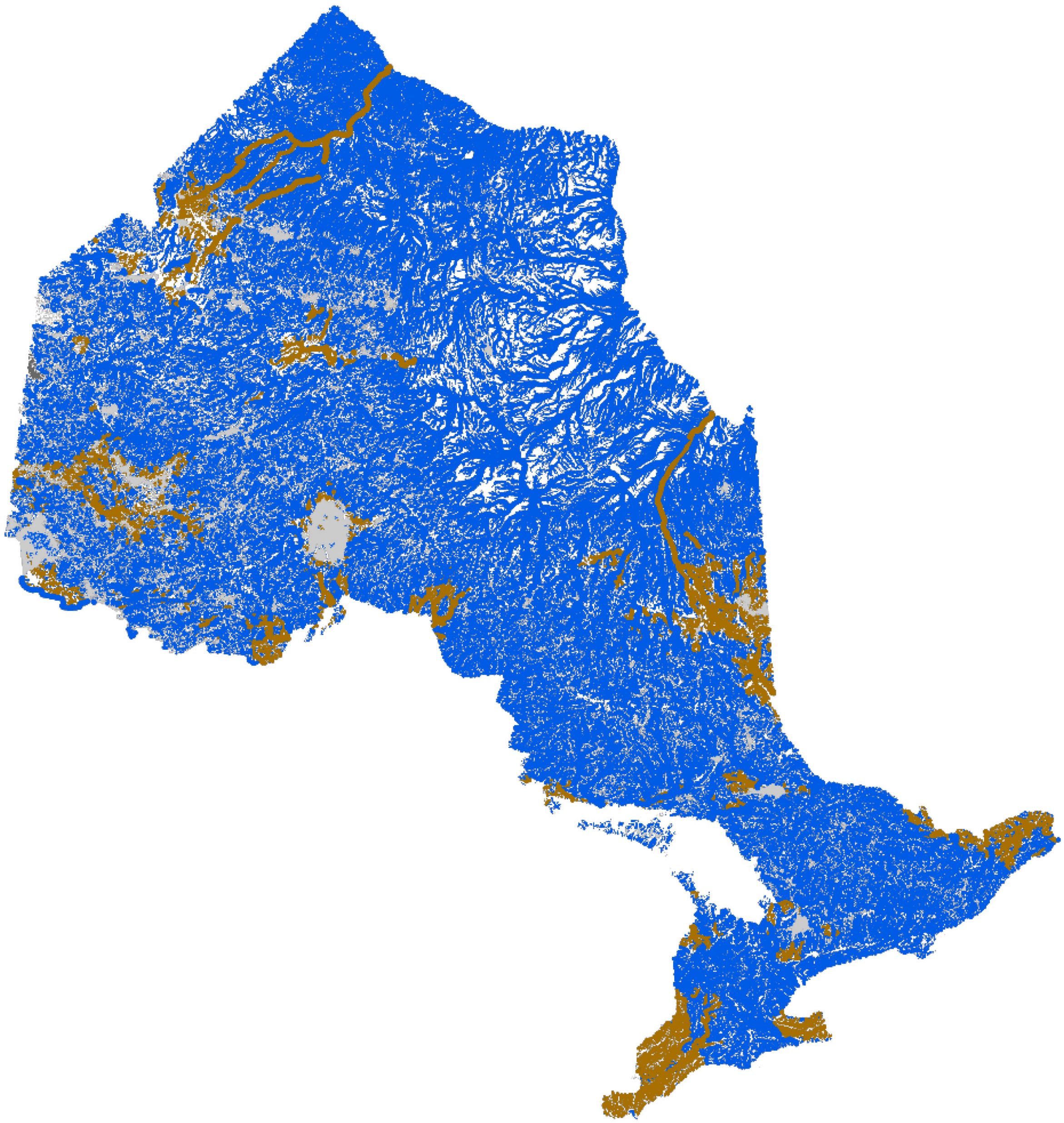


Figure 3. Perennial turbidity of streams for the province of Ontario. Streams shown in blue are typically clear during the low flow summer period, whereas those in brown are turbid for much of the year, even during low flow.

Figure 4. Stream channel slopes of Ontario reaches categorized as slow (green lines) and fast (blue lines) moving.

Fundamental spatial framework

The AEC partitions the province's stream network into fundamental spatial units called reaches. These reaches were grouped into increasingly larger ecological units. The final product is a multi-scale hierarchical classification system. The process used in version two of the AEC is the same as that used in version one and includes the following steps:

1. simplifying and standardizing the stream network
2. developing the *spatial framework* including a set of Arc Hydro geodatabases from the stream-lake network for the full extent of the province, including the fundamental reach units
3. generating an inventory of stream *reaches*, which summarize a variety of landscape characteristics (e.g., geology, landcover, climate) at various spatial scales (e.g., channel, reach contributing area, upstream contributing area)

Simplifying the base data

Two provincial data sets form the foundation of the classification: the Ontario Integrated Hydrology (OIH) raster data set, which has a cell size of 30 m, and the Ontario Hydro Network (OHN) vector data set. We combined information from these two data sets to prune the headwaters of the full stream network by applying a uniform upstream catchment area threshold of 1 km^2. Network simplification serves three purposes:

- Standardizes stream network density: The OHN data is captured at various scales throughout the province (i.e., 1:10,000 in the south, 1:20,000 in the near north, and 1:50,000 in the far north) resulting in different stream densities (i.e., $km \cdot km^{-2}$) and stream orders (Hansen 2001). Across the province, the mapping of streams and their location are inconsistent. In Northern Ontario, many small perennial streams are missing or in the wrong location. In southern Ontario, issues are similar and include mapping relatively more temporary (intermittent and ephemeral) streams that might have flows for only a few weeks each year. Many of these streams are in active farm fields. The variable nature of temporary streams in relation to flows and temperature requires a different classification approach not possible with our current base data. We recognize that temporary streams are abundant, understudied, vulnerable, and are significant in the ecological integrity of stream networks (McDonough et al. 2011).

- Reduces uncertainty of stream intermittency: Classifying whether a stream is perennial or temporary is not the goal of the classification and is a complicated process that is beyond the scope of the AEC. We attempted to remove many temporary streams by applying a minimum size threshold. Stream lines mapped at small scales (e.g., 1:10,000) with an upstream catchment area of less than 1 km^2 are often temporary. We recognize that some perennial streams will have smaller catchment areas, particularly those associated with spring upwellings.

- Reduces network complexity: Excluding small, likely intermittent and ephemeral, streams reduces the complexity of the final network, increasing data processing and display speeds.

While the very small streams that were excluded may be the focus of some resource management efforts, the base data available (i.e., 30 m DEM) does not support such fine scale analyses (Buttle et al. 2012). Given a pressing need and accurate high-resolution base data, the AEC framework could be extended to accommodate finer scales in some areas of the province.

Building the stream-lake network

We used Arc Hydro to establish and delineate the structure of the GIS framework. Using our simplified stream network, Arc Hydro initially defines units called links or, in the context of the AEC, reaches, which are portions of stream between stream confluences (i.e., interconfluence reaches). To understand streams in Ontario, an AEC must include lakes (Jones 2010). We fulfilled this need by combining the basic Arc Hydro interconfluence link raster with attributes of the OHN data. The OHN vector data includes information that differentiates line features representing actual streams from virtual connectors, whose purpose it is to provide uninterrupted network flow through waterbodies. We intersected the link raster with rasterized OHN virtual connectors to create an alternate link raster that includes waterbody inlet/outlet breaks. We substituted this lake-interconfluence link raster for the interconfluence link layer (Figure 5).

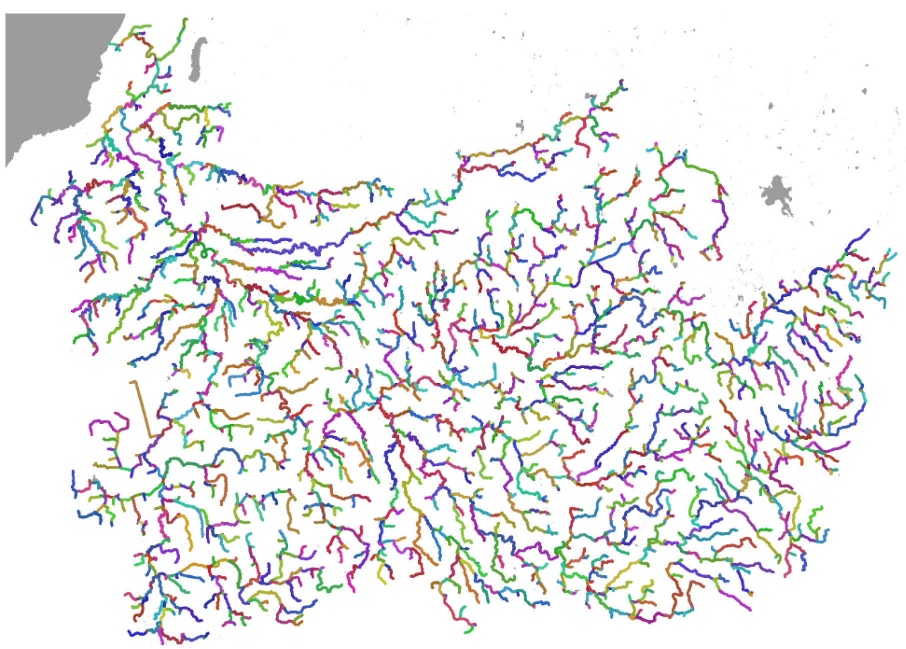


Figure 5. The 2957 reaches of the Saugeen River drainage in southern Ontario. Different colours represent individual stream reaches.

Arc Hydro proceeds with several geoprocessing steps that include delineating reach contributing areas, assigning unique identifiers to each reach, and creating crucial network components (e.g., to-from node fields). The network components make it possible to perform network analyses while the unique identifiers allow joining the spatial data with the landscape attribute tables gathered during the next step. Forty-seven Arc Hydro geodatabases were generated to cover the province using watershed-based divisions called work units (see Appendix 1). Portion of the Hayes, Manigotagan, and Poplar rivers on the Ontario-Manitoba border were not processed fully because OIH data for that area was not available when data was processed.

Gathering the stream reach inventory database

Using the Arc Hydro geodatabases, we gathered a large inventory of landscape and network attributes using four scales of collection (Figure 6) for each of the 710,000 reaches in Ontario. The reach scale attribute data was calculated using ArcGIS Zonal Statistics toolboxes. To automate the process of calculating upstream catchment attributes from individual reaches and assigning network metrics such as Strahler and Shreve order (Horton 1945, Strahler 1952) to the reaches, we developed a custom MATLAB-based application called Network Catchment Attribute Tool (NCAT). The final attribute count for each reach was more than 1000 fields across several dozen data categories. From this analysis, we determined that Ontario has about 410,000 stream reaches (total length of ~475,000 km) and ~300,000 virtual connector reaches in lakes.

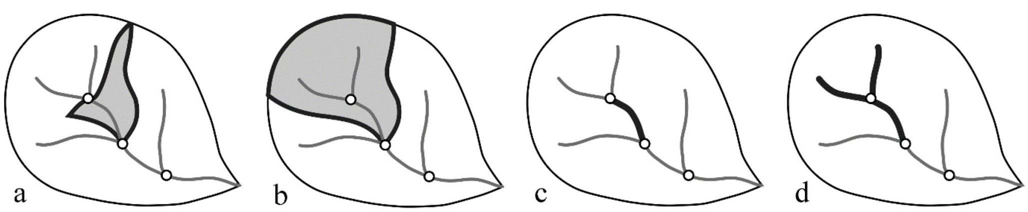


Figure 6. The four scales of landscape variable inventory collection illustrated by the grey polygons and thick black lines are: a) reach contributing area, b) upstream catchment, c) reach channel (30 m raster), and d) upstream channel for the catchment (30 m raster).

Hierarchical ecological units

The complexity of the Ontario stream network is immense and needs to be reduced to be understood effectively. We developed a custom application called the Reach Affinity Tool (RAFT). It is a network-aware program that clusters stream reaches into larger segments (Schmidt and Jones 2020). Segments are assumed to be have similar habitat templates and therefore support similar ecological communities. RAFT is based on the Valley Affinity Search Technique (VAST) software developed by researchers at the University of Michigan (Brenden et al. 2008). The following steps were used to group the reaches:

1. grouping adjacent *reaches* (i.e., spatially connected, upstream downstream reaches) into larger stream *neighbourhoods* using a set of stream size similarity rules
2. assigning a *class* for each reach by concatenating its five stream temperature subclasses, two turbidity subclasses, and two channel slope subclasses, resulting in twenty class combination.
3. creating *segments* by combining the *neighbourhood* identifiers with the 20 *class* codes to create the unique *segment* identifiers
4. grouping *reaches* into broad geo-climatic *productivity regions* to provide broad-scale context for the *reaches*

Stream neighbourhoods

Abrupt changes in the volume of flow, temperature, and sediment at tributary confluences along the length of a stream are addressed by calculating the ratio of the tributary upstream catchment area (UCA) to the mainstem UCA. This ratio is called the confluence symmetry ratio (CSR) for which a value of 1 indicates that both reaches have the same area. As tributary size decreases, CSR approaches zero. Four rules are applied to determine stream neighbourhoods using the CSR values (Figure 7). For a practical example of neighbourhoods in a landscape context see Figure 8.

1. Stream reaches between the lower and upper CSR (e.g., 0.25–0.50) are joined into a neighbourhood because they have similar sizes and thus potentially similar ecological characteristics (Figure 7i).
2. If the CSR is below a lower threshold (e.g., <0.25), a tributary is considered too small to significantly affect the main channel (Figure 7ii). In this scenario, the main channel neighbourhood remains uninterrupted while the tributary becomes part of another neighbourhood. The rationale is that a small tributary should not become part of the main stem neighbourhood because they likely have different channel morphology (e.g., riparian shading, bankfull width).
3. Conversely, when the CSR at a confluence exceeds the upper threshold (e.g., >0.5), a new neighbourhood is initiated beginning with the reach directly downstream of the confluence (Figure 7iii). The reasoning is that the combined volume of water in the downstream channel increases enough to change channel morphology (e.g., channel width, shading, temperature, riparian influence).

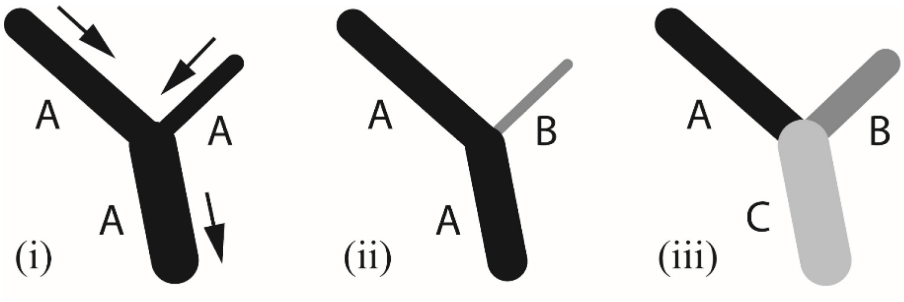


Figure 7. Schematic representation of the rules applied while grouping stream reaches into neighbourhoods using the confluence symmetry ratio (CSR). Arrows indicate stream flow direction. In scenario (i), the tributary is neither too small nor too large (e.g., CSR=0.3) compared to the main stem, allowing all three reaches to be assigned to the same neighbourhood A. In scenario (ii), the tributary is too small (e.g., CSR=0.1) to cause a split in neighbourhood A and the tributary is assigned to a new neighbourhood B. The tributary in scenario (iii) is large enough (e.g., CSR=0.9) to cause a split in neighbourhood A, initiating a new neighbourhood C with the tributary being assigned to a new neighbourhood B.

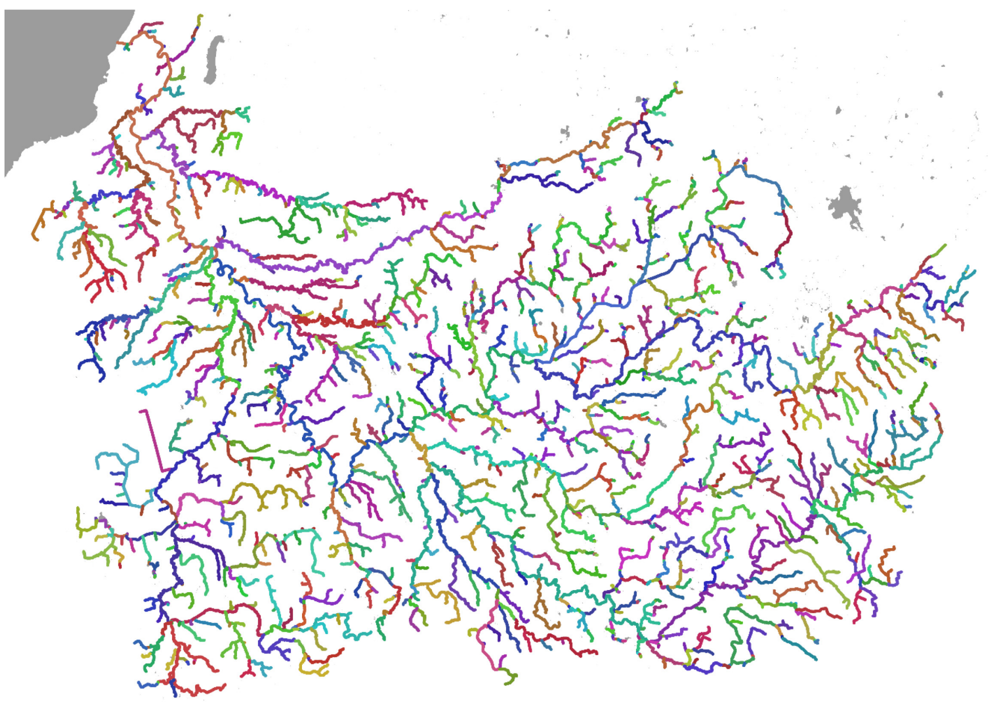


Figure 8. The 1818 neighbourhoods of the Saugeen River drainage in southern Ontario. Different colours represent individual neighbourhoods.

Subsequently, a fourth rule is applied that prevents large main stem river neighbourhoods from becoming too large. The mainstems of rivers of higher Strahler order have large drainage areas and few tributaries are large enough relative to these mainstem rivers to split the neighbourhood based on the upper CSR threshold (Figure 7iii). However, many small tributaries may join the mainstem causing its flow volume to gradually increase without causing any abrupt changes in stream character (Figure 7ii). The larger the mainstem catchment grows, the less likely it is that a tributary will be large enough to cause a split, so large portions of the river are likely to be grouped into a single neighbourhood. This result is problematic because the stream reaches at the upstream end of such a neighbourhood might have a bankfull width of 25 m (i.e., UCA=1000 km^2) whereas at the reaches at the downstream end might be 50 m wide (i.e., UCA=2000 km^2) and therefore the reaches of this neighbourhood should not be considered ecologically homogeneous. Consequently, neighbourhoods with such an unacceptably wide range of reach UCAs need to be divided (refer to Schmidt and Jones (2020) for details).

Stream classes

The AEC classes are composed of the three abiotic subclasses as described above: average July water temperature (cold, cold-cool, cool, cool-warm, or warm), perennial turbidity (clear or turbid), and channel slope (fast or slow). The reach class membership does not factor in the spatial context of reaches (e.g., network position or size), which is captured by their size neighbourhood membership. The AEC classes are defined by the 20 combinations of the three subclasses (Table 2; figures 9 and 10).

Table 2. The cartographic symbology of the 20 aquatic ecosystem classification classes and their counts and measures for Ontario's Mixedwood Plains Ecozone (MWP).

Map colour code	Class code	30-year average July temperature	Turbidity	Channel slope	Reach count	Stream length (km)	% Length of MWP
	CDCF	Cold	Clear	Fast	8212	9,775	17.0
	CDCS			Slow	663	286	0.5
	CDTF		Turbid	Fast	557	802	1.4
	CDTS			Slow	48	45	0.1
	CCCF	Cold-cool transitional	Clear	Fast	9415	13,655	23.8
	CCCS			Slow	1695	1,481	2.6
	CCTF		Turbid	Fast	1147	1,984	3.5
	CCTS			Slow	224	317	0.6
	CLCF	Cool	Clear	Fast	6294	9,763	17.0
	CLCS			Slow	2513	2,944	5.1
	CLTF		Turbid	Fast	2327	4,134	7.2
	CLTS			Slow	1127	1,740	3.0
	CWCF	Cool-warm transitional	Clear	Fast	823	1,315	2.3
	CWCS			Slow	852	1,091	1.9
	CWTF		Turbid	Fast	473	821	1.4
	CWTS			Slow	1546	3,029	5.3
	WMCF	Warm	Clear	Fast	290	546	1.0
	WMCS			Slow	548	792	1.4
	WMTF		Turbid	Fast	91	154	0.3
	WMTS			Slow	1367	2,658	4.6

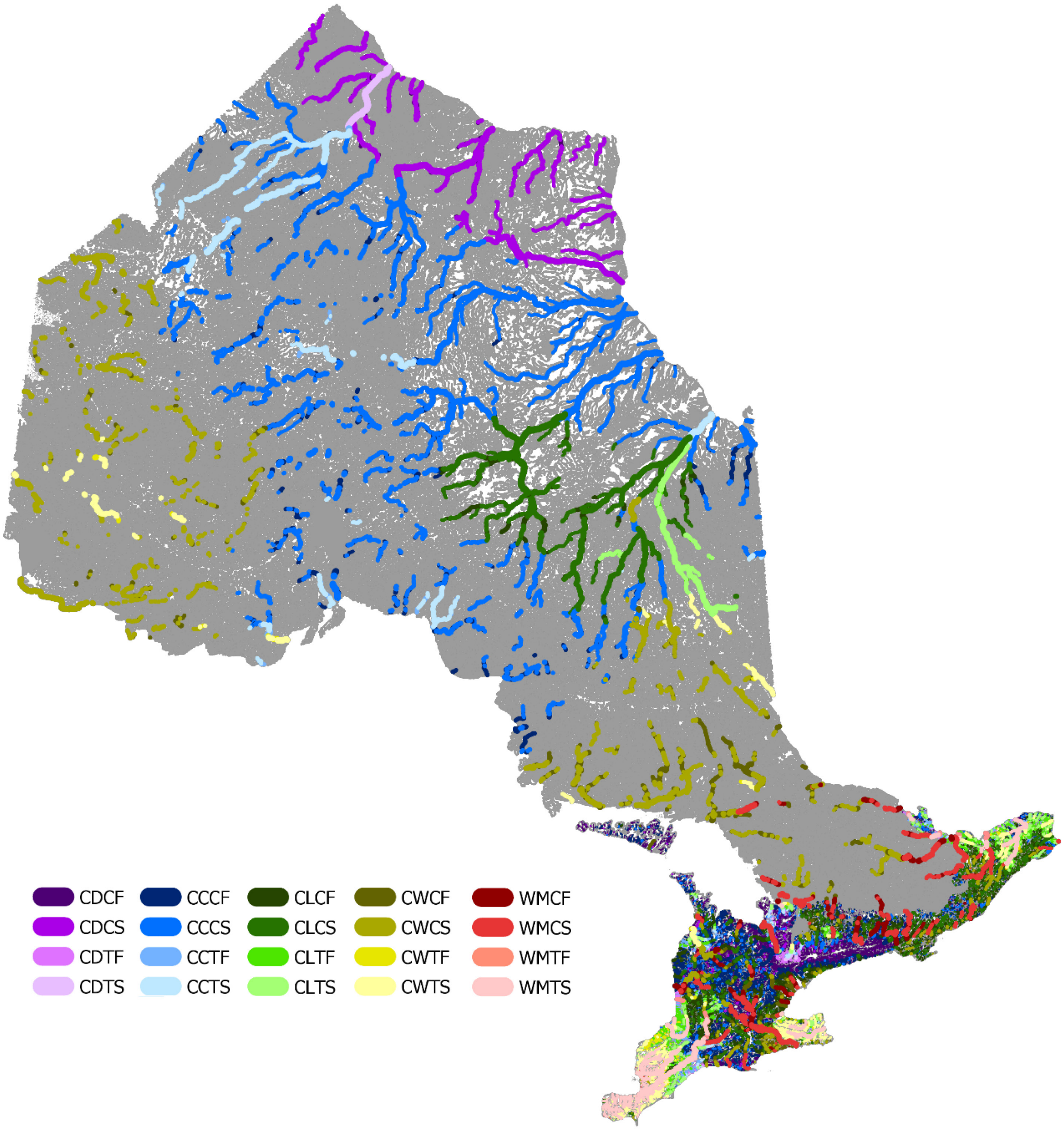


Figure 9. The distribution of 20 aquatic ecosystem classification classes across Ontario (see Table 2 for detailed descriptions). Grey lines denote small rivers with drainage areas below 700 km^2 in the Ontario Shield and Hudson Bay Lowlands ecozones for which temperatures are not yet modelled and therefore have not been assigned classes; stream temperature predictions are in development for these ecozones.

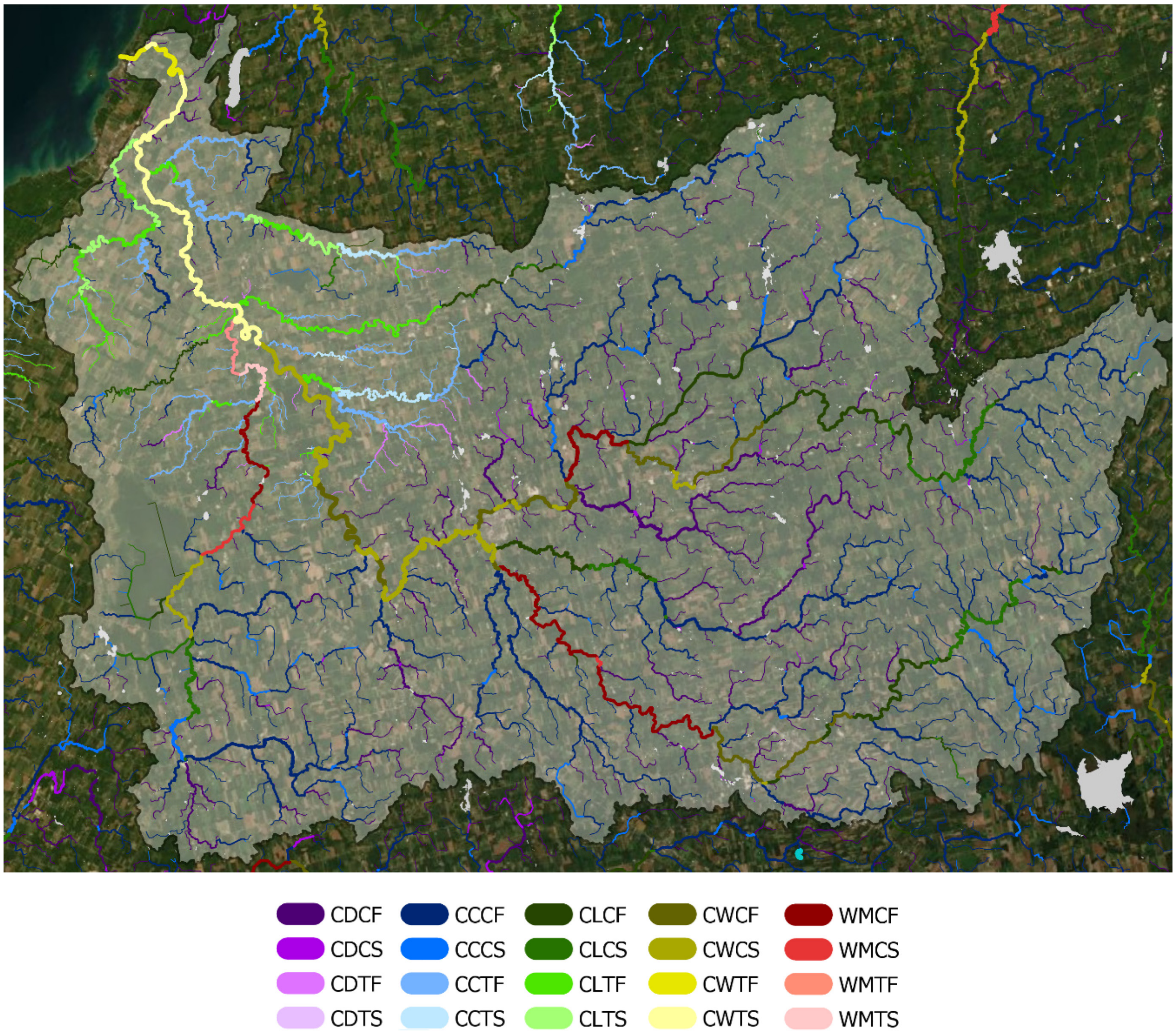


Figure 10. The 20 aquatic ecosystem classification classes in the context of the Saugeen River drainage in southern Ontario. Line width illustrates Strahler stream order. Classes are defined in Table 2.

Stream segments

The segments are created by spatially overlaying the neighbourhoods with the reach classes. The result is ecological units that are similar in size and character (temperature, turbidity, and slope). The reaches in a segment do not have to be spatially contiguous; however, they cannot expand beyond neighbourhood boundaries. A neighbourhood can contain multiple segments (Figure 11).

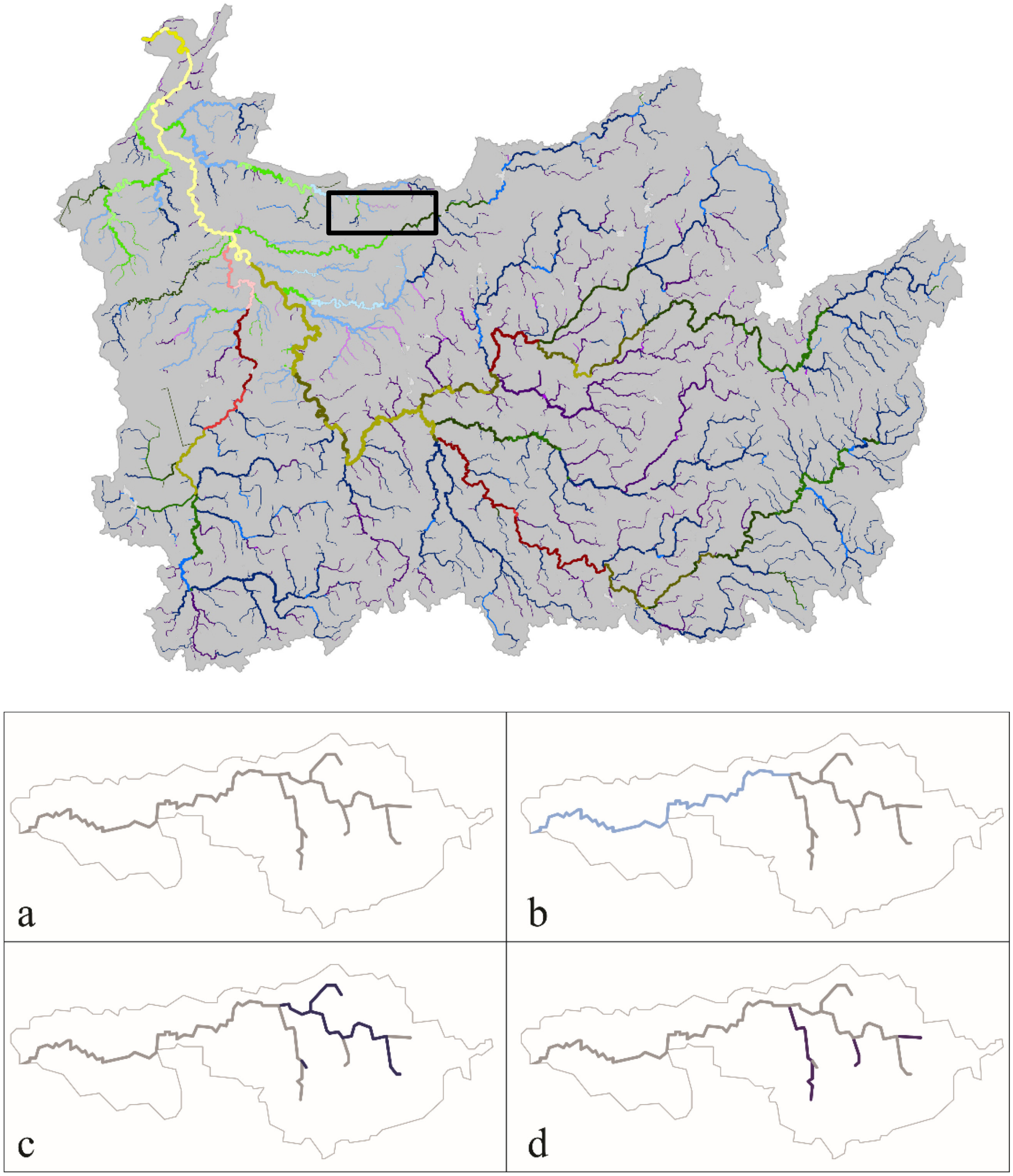


Figure 11. The Saugeen River watershed in southern Ontario has 2080 segments. The black rectangle on the large map captures the extent of a single neighbourhood's stream lines and watershed boundary shown enlarged in (a), which has the unique identifier N13.301. The three classes in that neighbourhood are CCTF (b), CCCF (c), and CDCF (d). Note that the coloured class reaches shown in (c) and (d) are not spatially contiguous or directly flow-connected. The combination of the unique neighbourhood identifier and the class code results in a unique segment code, e.g., S13.301.CDCF for the segment shown in (d). This approach results in each segment being composed of reaches with similar upstream catchment areas, temperature regimes, perennial turbidity, and channel slopes.

Productivity regions

Regions and zones constitute the highest levels of the classification hierarchy in the AEC and, unlike segments, are developed using a top-down approach based on expectations of aquatic productivity. Productivity is an important aspect of flowing waters with respect to harvest and ecosystem resilience. In lakes, productivity has three principal influences: morphometric (shape/dimension), edaphic (soil/geology), and climatic factors (Ryder 1965). It is difficult to generalize about the morphometry of streams and rivers across Ontario; however, the potential of the fluvial environment to produce biota can be approximated by combining growing degree days and conductivity, broadly akin to the morphoedaphic index (MEI) developed by Ryder. The relationship between MEI and productivity likely holds true for flowing waters as well, wherein channel length, drainage basin area, or total floodplain area are more relevant measures than river depth (Welcome et al. 1989). Growing degree days of air temperature was used to approximate regional differences in the potential growth and development of ectotherms during the growing season (Shuter et al. 1980, Neuheimer and Taggart 2007). Riparian shading related to stream size and turbidity can alter expectations because high levels of turbidity reduce photosynthesis, potentially affecting productivity.

Five growing degree day (>5 °C) bands occur in Ontario (<700, 700–1000, 1000–1500, 1500–1900, >1900) as do three ecozones of the terrestrial classification system: Hudson Bay Lowlands, Ontario Shield, and Mixedwood Plains. Water conductivities in the Mixedwood Plains average 540 µS, whereas in the Boreal Shield and Hudson Bay Lowlands they average 150 µS. Growing degree day bands and a reach's predominant upstream ecozone combine to create nine unique productivity regions across Ontario. These regions delineate large areas of potential differences in aquatic ecosystem productivity (Figure 12).

Stream size

Stream size and rules defining stream neighbourhoods and segments were discussed above. Here stream size is used to further stratify streams over broader spatial scales, independent of stream class. Stream size determines many stream characteristics, with predictable changes as streams grow from headwater to large rivers. Vannote et al.'s (1980) highly influential River Continuum Concept described downstream changes that include depth, channel width, velocity, discharge, temperature, and entropy gain. Overlain on these abiotic gradients are corresponding changes in biological characteristics in riparian influence, algae, benthic invertebrates, and fishes. The AEC provides Strahler order, where numbers are used to represent stream order: small streams (1–3), mid size streams (4–6), and lower reach large rivers (>6). The AEC also provides stream size based on drainage area divided into three categories that address constraints on field sampling methods: wadeable streams (<200 km^2), non-wadeable streams (>2,000 km^2), and intermediate streams (≥200 to <2,000 km^2) (Figure 13). For wadeable streams, more than 95% of the stream is wadeable and many sampling methods can be used. For non-wadeable streams, 95% is boatable and methods designed for slow moving rivers and lakes may apply. The intermediate streams are difficult to travel, navigate, and sample and require a mixture of approaches. Notable exceptions to these rules include that streams running through clay geology and organics tend to have U-shaped channels that can be unwadeable, even in relatively small streams. Backwater conditions near the estuaries of the Great Lakes may be accessible by boat.

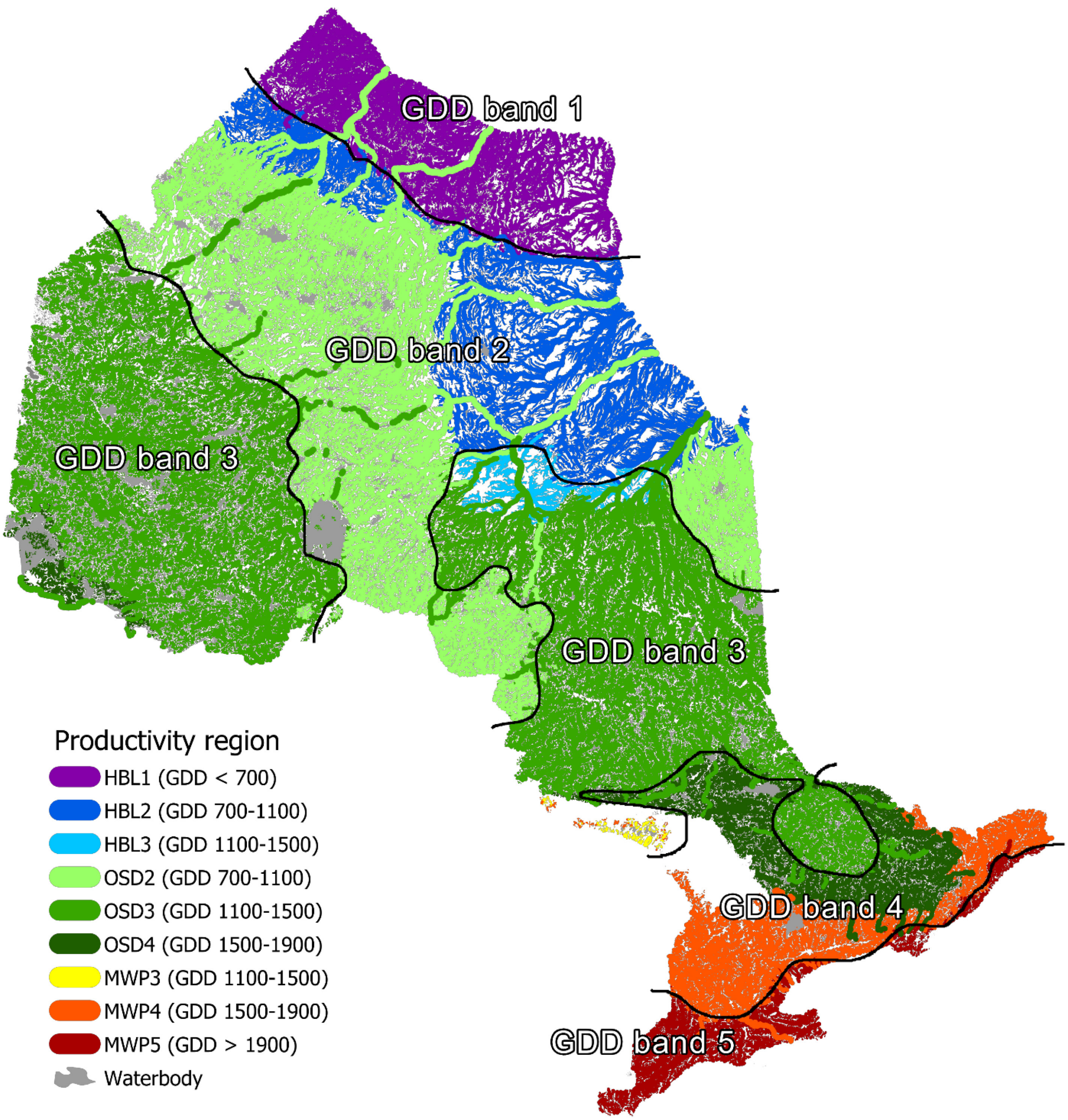


Figure 12. The combinations of bands of air growing degree days (GDD) above 5 ˚C and ecozones create nine unique productivity regions that delineate large areas of potential differences in productivity across Ontario (HBL = Hudson Bay Lowlands; OSD = Ontario Shield; MWP = Mixedwood Plains). The regions overlap some because the upstream influence of a region carries downstream for a distance, especially on large mainstem rivers.

Figure 13. Based on drainage area, three categories of stream size in Ontario are wadable streams (<200 km², light blue), non-wadeable streams (>2,000 km², dark blue), and intermediate streams (≥200 to <2,000 km², medium blue).

Summary

The aquatic ecosystem classification is a science-based tool that groups and classifies Ontario's rivers and streams. The main goals of the AEC project include providing a universal and consistent spatial framework for Ontario's flowing waters, capturing the ecological nature of streams and rivers, validating the classification by working with stakeholders during development and testing, and simplifying the enormous complexity of streams across Ontario for understanding and to support management. The AEC is an ongoing project that will continue to be supplemented with additional variables and information that can be used to better understand and manage Ontario's aquatic resources. Version two of the classification addresses issues discovered during the application of version one. The AEC is complete in the Mixedwood Plains Ecozone and for large streams (>700 km^2) in the Ontario Shield and Hudson Bay Lowlands. We intend to complete water temperature predictions for small streams (<700 km^2) in Northern Ontario, estimate growing degree days of stream water, classify flow regimes, and continue to improve our understanding of the influence of lakes on streams. The current version of the AEC uses OHN and OIH data from 2014. Major updates to the AEC spatial data will be considered when significant revisions to hydrography and digital elevation data are available. Light detection and ranging (lidar) technologies may improve our understanding of stream network geometry, including our ability to classify small (<1 km^2) temporary streams. In the meantime, users of the AEC can provide valuable information about where the classification works well and where it does not. A classification error reporting form is provided in Appendix 4 for users to submit possible errors. Spatial data including Google Earth and geodatabase files associated with this project are available via GeoHub (https://geohub.lio.gov.on.ca/).

References

Barnett, P.J. 1992. Quaternary geology of Ontario. Pp. 1011–1088 *in* Thurston, P.C., H.R. Williams, R.H. Sutcliffe and G.M. Stott (eds.). Geology of Ontario. Ontario Geological Survey, Sudbury, ON. Special Volume 4.

Biro, P.A. 1998. Staying cool: Behavioral thermoregulation during summer by young-of-year brook trout in a lake. Transactions of the American Fisheries Society 127: 212–222.

Brenden, T.O., L. Wang, P.W. Seelbach, R.D. Clark, J.M. Wiley and B.L. Sparks-Jackson. 2008. A spatially constrained clustering program for river valley segment delineation from GIS digital river networks. Environmental Modelling and Software 23: 638–649.

Brett, J.R. 1971. Energetic responses of salmon to temperature. A study of some thermal relations in the physiology and freshwater ecology of sockeye salmon (*Oncorhynchus nerka*). American Zoology 11: 99–113.

Buttle, J.M., S. Boon, D.L. Peters, C. Spence, H.J. Meerveld and P.H. Whitfield. 2012. An overview of temporary stream hydrology in Canada. Canadian Water Resources Journal 34: 279–310.

Caissie, D. 2006. The thermal regime of rivers: A review. Freshwater Biology 51: 1389–1406.

Chu, C., N.E. Jones, A.R. Piggott and J.M. Buttle. 2009. Evaluation of a simple method to classify the thermal characteristics of streams using a nomogram of daily maximum air and water temperatures. North American Journal of Fisheries Management 29: 1605–1619.

Hannah, D.M. and G. Garner. 2015. River water temperature in the United Kingdom: Changes over the 20th century and possible changes over the 21st century. Progress in Physical Geography 39: 68–92.

Hansen, W.F. 2001. Identifying stream types and management implications. Forest Ecology and Management 143: 39–46.

Hawkins, C.P., R.H. Norris, J. Gerritsen, R.M. Hughes, S.K. Jackson, R.K. Johnson and R.J. Stevenson. 2000. Evaluation of the use of landscape classifications for the prediction of freshwater biota: Synthesis and recommendations. Journal of the North American Benthological Society 19: 541–556.

Hjulström, F. 1935. Studies of the morphological activity of rivers as illustrated by the River Fyris. Bulletin. Geological Institute Upsalsa 25: 221–527.

Horton, R.E. 1945. Erosional development of streams and their drainage basins - hydrophysical approach to quantitative morphology. Geological Society of America Bulletin 56: 275–370.

Hynes, H.B.N. 1975. The stream and its valley. Verhandlungen der Internationalen Vereinigung fuer Theoretische und Angewandte Limnologie 19: 1–15.

Jones, N.E. 2010. Incorporating lakes within the river discontinuum: Longitudinal changes in ecological characteristics in stream-lake networks. Canadian Journal of Fisheries and Aquatic Sciences 67: 1350–1362.

Jones, N.E. and B. Schmidt. 2019. Thermal habitat: Understanding stream temperature and thermal classifications. Ontario Ministry of Natural Resources and Forestry, Science and Research Branch, Peterborough, ON. Science and Research Information Report IR-18. 13 p.

Jones, N.E. and B.J. Schmidt. 2019. Aquatic Ecosystem Classification version 1: A review and direction forward. Ontario Ministry of Natural Resources and Forestry, Science and Research Branch, Peterborough, ON. Science and Research Technical Note TN-05. 12 p.

Jones, N., B. Schmidt and K. Ghunowa. 2019. Landscape-based identification of human disturbance gradients and ecological integrity for Ontario's streams and rivers. Ontario Ministry of Natural Resources and Forestry, Science and Research Branch, Peterborough, ON. Science and Research Technical Report TR-33. 32 p.

Jones, N.E., I.A. Sutton, B.J. Schmidt and K. Ghunowa. 2020. Occupancy of brook trout and brown trout in streams of the Mixedwood Plains Ecozone. Ontario Ministry of Natural Resources and Forestry, Science and Research Branch, Peterborough, ON. Science and Research Technical Report TR-34. 18 p. + appendices.

Jones, N.E., B.J. Schmidt, I.A. Sutton and K. Ghunowa. 2021. Thermal habitat of flowing waters in Ontario: Prediction and classification. Ontario Ministry of Natural Resources and Forestry, Science and Research Branch, Peterborough, ON. Science and Research Technical Report TR-43. 23 p.

Knighton, D.A. 1998. Fluvial Forms and Processes: A New Perspective. Arnold, London, UK.

Lyons, J., T. Zorn, J. Stewart, P. Seelbach, K. Wehrly and L. Wang. 2009. Defining and characterizing coolwater streams and their fish assemblages in Michigan and Wisconsin, USA. North American Journal of Fisheries Management 29: 1130–1151.

Magnuson, J.J., L.B. Crowder and P.A. Medvick. 1979. Temperature as an ecological resource. American Zoologist 19: 331–343

McDonough, O.T., J.D. Hosen and M.A. Palmer. 2011. Temporary streams: The hydrology, geography, and ecology of nonperennially flowing waters. Pp. 259–289 *in* Elliot, H.S. and L.E. Martin (eds.). River Ecosystems: Dynamics, Management and Conservation. Nova Science Publishers, Hauppauge, NY.

Melles, S.J., N.E. Jones and B. Schmidt. 2011. Aquatic Ecosystem Classification (AEC): Client needs survey response. Ontario Ministry of Natural Resources, Peterborough, ON. Aquatic Research Series 2011-04. 19 p. + appendices.

Melles, S.J., N.E. Jones and B.J. Schmidt. 2012. Review of theoretical developments in stream ecology and influence on ecosystem classification of flowing waters. Freshwater Biology 57: 415–434.

Melles, S.J., N.E. Jones and B.J. Schmidt. 2013. Aquatic ecosystem classification for Ontario: A technical proposal. Ontario Ministry of Natural Resources, Aquatic Research and Development Section, Peterborough, ON. Aquatic Research Series 2013-05.

Melles, S.J., N.E. Jones and B.J. Schmidt. 2014. Evaluation of current approaches to stream classification and a heuristic guide to developing classifications of integrated aquatic networks. Environmental Management 53: 549–566.

Neff, B.P., S.M. Day, A.R. Piggott and L.M. Fuller. 2005. Base flow in the Great Lakes Basin. U.S. Geological Survey, Washington, DC. Scientific Investigations Report 2005-5217.

Neuheimer, A.B. and C.T. Taggart. 2007. The growing degree-day and fish size-at-age: The overlooked metric. Canadian Journal of Fisheries and Aquatic Sciences 64: 375–385.

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

Prowse, T.D. 2001a. River-ice ecology. I: Hydrologic geomorphic, and water quality aspects. Journal of Cold Regions Engineering 2001: 1–16.

Prowse, T.D. 2001b. River ice. II: Biological aspects. Journal of Cold Regions Engineering 2001: 17–31.

Reynolds, W.W. 1979. Thermoregulation behaviour of brown trout, *Salmo trutta*. Hydrobiologia 62: 79–80.

Ryder, R.A. 1965. A method for estimating the potential fish production of north-temperate lakes. Transactions of the American Fisheries Society 94: 214–218.

Schmidt, B.J. and N. E. Jones. 2020. A clustering program for delineating ecologically homogenous segments within a stream network using catchment area and valley landscape similarity rules. Environmental Modelling and Software 132: 104776.

Shuter, B.J., J.A. MacLean, F.E.J. Fry and H.A. Regier. 1980. Stochastic simulation of temperature effects on first-year survival of smallmouth bass. Transactions of the American Fisheries Society 109: 1–34

Stoneman, C.L. and M.L. Jones. 1996. A simple method to classify stream thermal stability with single observations of daily maximum water and air temperatures. North American Journal of Fisheries Management 16: 728–737.

Strahler, A.N. 1957. Quantitative analysis of watershed geomorphology. Transactions, American Geophysical Union 38: 913–920.

Thorn, M.W., C. Chu and N.E. Jones. 2016. Influence of environmental variables on the occurrence of brook trout (*Salvelinus fontinalis*) within streams of the Lake Simcoe watershed. Ontario Ministry of Natural Resources and Forestry, Science and Research Branch, Peterborough, ON. Science and Research Technical Report TR-09. 58 p.

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell and C.E. Cushing. 1980. River continuum concept. Canadian Journal of Fisheries and Aquatic Sciences 37: 130–137.

Welcomme, R.L., R.A. Ryder and J.A. Sedell. 1989. Dynamics of fish assemblages in river systems: A synthesis. Canadian Special Publication of Fisheries and Aquatic Sciences 106: 569–577.

Appendix 1. Aquatic ecosystem classification work units for analysis and data distribution

To make the data more manageable for analysis and distribution, the province of Ontario is divided into 47 smaller portions, called work units (Figure A1.1).

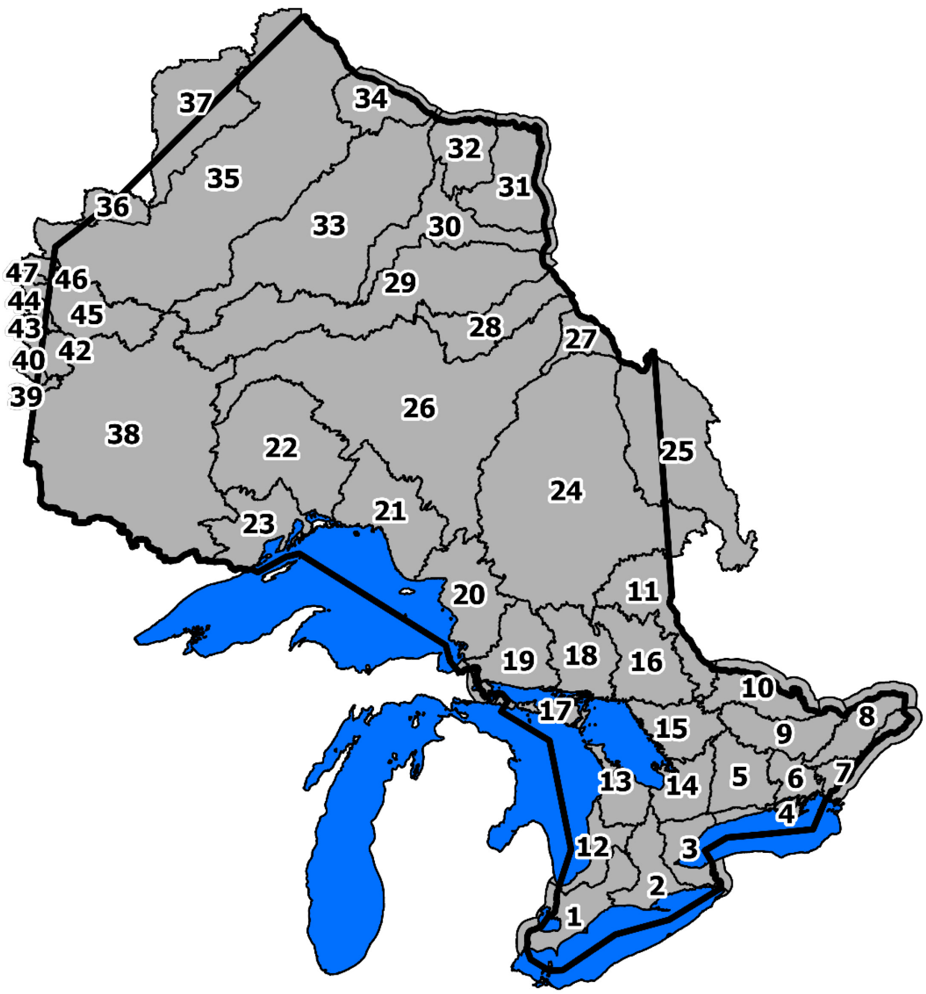


Figure A1.1. Location of work units used to make the aquatic ecosystem classification data more manageable (work units are named in table below).

WUID	Name	WUID	Name
1	Lake Erie - West	25	Harricanaw River
2	Lake Erie - East	26	Albany River
3	Lake Ontario - West	27	Kinosheo River
4	Lake Ontario - Central	28	Kapiskau River
5	Lake Ontario - Kawarthas	29	Attawapiskat River

WUID	Name	WUID	Name
6	Lake Ontario - East	30	Ekwan River
7	St. Lawrence River	31	Opinnagau River
8	Ottawa River - Lower	32	Sutton River
9	Ottawa River - Central South	33	Winisk River
10	Ottawa River - Central North	34	Shagamu River
11	Ottawa River - Upper	35	Severn River
12	Lake Huron - South	36	Hayes River A
13	Lake Huron - Bruce Peninsula	37	Hayes River B
14	Georgian Bay - South - Lake Simcoe	38	English River
15	Georgian Bay - Central	39	Bird River
16	Georgian Bay - North - Lake Nipissing	40	Manigotagan River - A
17	Lake Huron - Manitoulin Island	41	Manigotagan River - B
18	Lake Huron - North	42	Bloodvein River - A
19	Lake Huron - North West	43	Bloodvein River - B
20	Lake Superior - East	44	Pigeon River
21	Lake Superior - North East	45	Upper Berens River
22	Lake Superior - Lake Nipigon	46	Poplar River - A
23	Lake Superior - North West	47	Poplar River - B
24	Moose River		

Appendix 2. Working with streams smaller than 1 km^2

The fundamental spatial framework of the aquatic ecosystem classification (AEC) includes a rule that excludes streams that have an upstream catchment area of less than 1 km^2. This rule was applied to provide a consistent drainage density across the entire province and to minimize the inclusion of intermittent streams in the AEC. However, some sampling sites may be located on streams with drainage areas below this threshold and therefore do not have a stream reach that can be directly associated with them. This can occur in instances of streams that have a strong spring or ground water upwelling source but very small drainage areas. A few recommendations for how to use the AEC in such cases are illustrated in Figure A2.1.

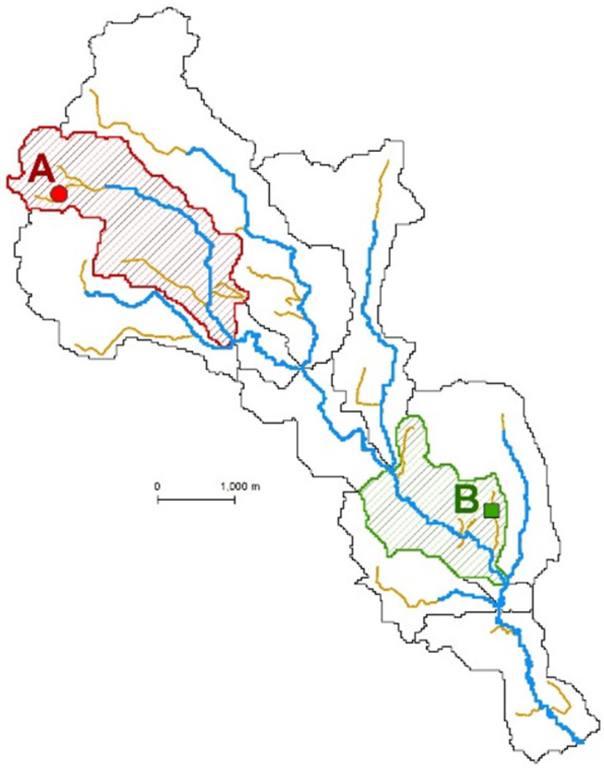


Figure A2.1. An example of two sites that are on streams with upstream catchment areas (UCA) of less than 1 km^2. The blue lines represent the aquatic ecosystem classification reaches (UCA>1 km^2) and the orange lines represent the OHN mapped water courses. Site A (red circle) can be associated with the reach contributing area (or reach line) indicated by the red hatching. Site B (green square) cannot be associated with the reach contributing area (or reach line) indicated by green hatching.

In the case where the site is within the reach contributing area (RCA) of a first Strahler order stream, the unique reach identifier (i.e., ProvReachID) of that first order stream can be used to link the site to the AEC spatial framework. Any reach contributing area or reach channel (RCA/RCh) attributes and upstream catchment area or channel (UCA/UCh) attributes can be assumed to correspond closely with the site (Site A). If a site is within the RCA of a reach with a Strahler stream order greater than 1, the unique reach identifier (i.e., ProvReachID) cannot be used because the landscape contributing to this site is not represented well by any of the AEC's attribute collection scales (Site B).

Appendix 3. Using KML cartography

Data access: Spatial data including Google Earth and geodatabase files associated with this report are available via GeoHub (https://geohub.lio.gov.on.ca/).

Google Earth is a convenient, powerful, and free-of-charge software that allows users to load their own spatial data overlays in the KML (keyhole markup language) data format. The aquatic ecosystem classification (AEC) KML files can be downloaded from GeoHub by work unit (see Appendix 1 for descriptions). On the maps, clicking on the AEC streamlines reveals a pop-up table containing core AEC attributes such as the provincial AEC ReachID (aka ProvReachID) and AEC class (Figure A3.1). The same data can be downloaded as a file geodatabase for use in a GIS environment.

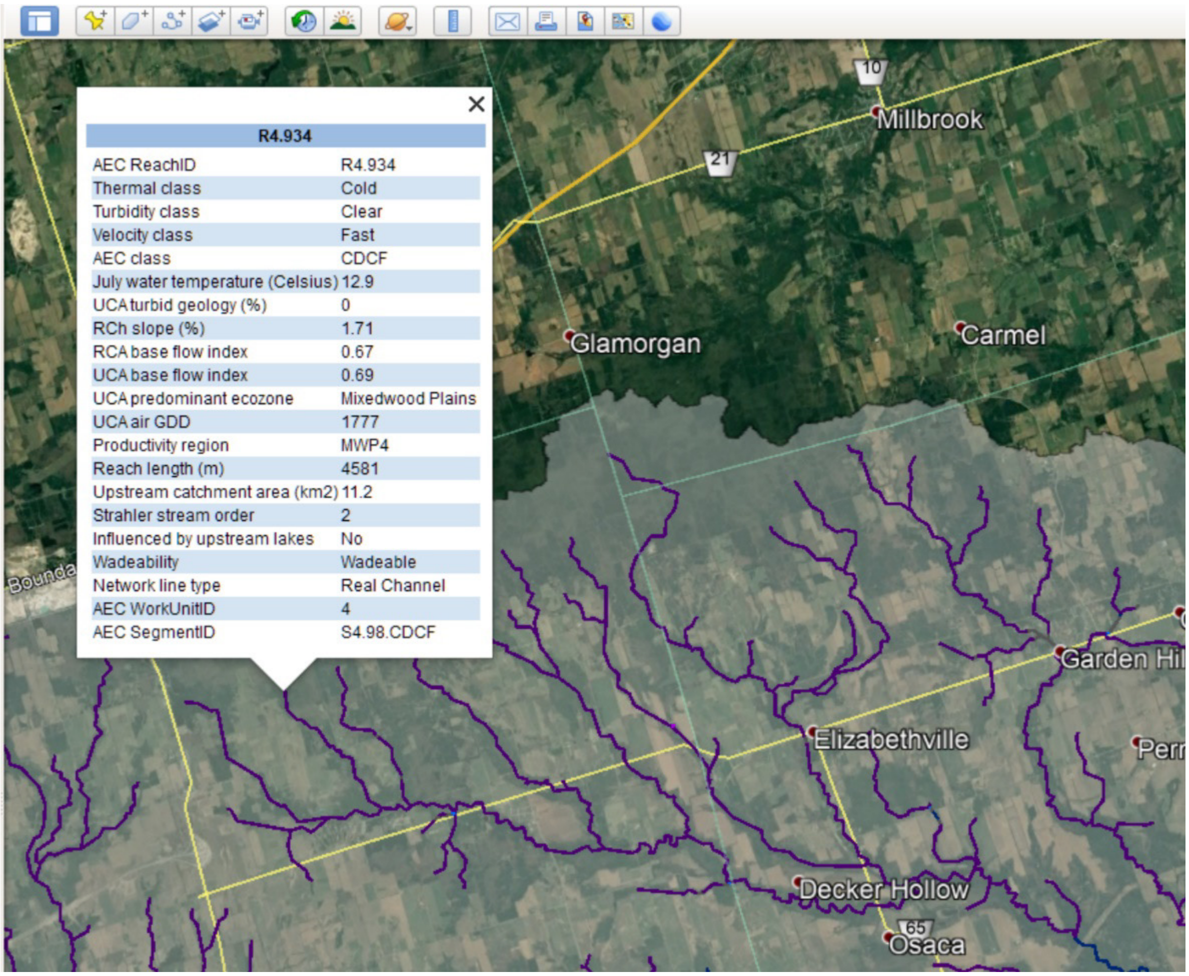


Figure A3.1. Example screen shot from version 2 of the aquatic ecosystem classification shown in Google Earth. Clicking on any part of the stream network, will result in a pop-up table that provides detailed information about the reach, in this case a cold, clear, and fast reach called R4.934.

Appendix 4. Classification error reporting form

Users of the aquatic ecosystem classification (AEC) can provide valuable information about where the classification works well and where evidence fundamentally disagrees with it. We would like to hear from you so we can adjust class designations if warranted. Please use the table below to submit possible errors for evaluation and consideration. Additional rows can be added if required.

Please email the completed form to aec@ontario.ca.

Name	
Position	
Organization	
Primary use of the AEC	

AEC reach ID *(ProvReachID)*	Current AEC class	Suggested class	Reason for change
R7.1234	CLCF	CDCF	Measured average July water temperature was below 16 ˚C between 2015 and 2020
Mariposa Brook: R5.11983 to R5.11941	CWTS	CWCS	Main creek channel is not turbid during summer
Nowhere Creek: all reaches upstream of R33.1234	CDCF	CDTF	Entire upstream watershed is turbid all year

Glossary

Glossary of terms as used/defined in this report. Compiled and adapted from various sources.

Allochthonous: Organic matter entering a stream, lake, or ocean but derived from an adjacent terrestrial ecosystem.

Aquatic ecosystem classification (AEC): A consistent system of rules that describes types of flowing waters across Ontario.

Autochthonous: Organic matter produced in an ecosystem is known as autochthonous material (diatoms, algae, macrophytes).

Baseflow index (BFI): An attempt to quantify the amount of groundwater contributing to stream flow and very important in defining the hydrology and thermal characteristics of streams which are fundamental to their ecology. BFI values represent the ratio of groundwater to total stream flow for five classes of quaternary geology: coarse and fine textured sediments, till, shallow bedrock, and organic deposits.

Binning: Grouping continuous values into discrete bins to reduce data complexity for statistical purposes. Histograms are examples of a data binning method used to observe underlying distributions. They typically occur in one-dimensional space and in equal intervals for ease of visualization, however some may use ecologically meaningful break points.

Bottom-up approach: Small elements (e.g., interconfluence reaches) are linked together to form larger subsystems (e.g., neighbourhoods, segments), which in turn are linked, sometimes through many levels, until a complete top-level system is formed.

Channel slope: Ratio of channel elevation change (from upstream to downstream end of a reach) to reach channel length.

Confluence symmetry ratios (CSR): A relative ratio of tributary upstream catchment area (UCA) over the mainstem river UCA.

Digital elevation model (DEM): A model or three-dimensional representation of a terrain's surface created from terrain elevation data.

Ectotherm: An animal that depends on external sources of body heat.

Edaphic: Characteristic of the geology and soil of a region including drainage, texture, or chemical properties such as soil pH.

Fundamental spatial units: For the AEC, refers to the interconfluence reach (between tributary junctions), including breaks at waterbody inlets and outlets.

Geodatabase: A proprietary (ESRI Inc.) way to store GIS information in one large file, which can contain multiple point, polygon, polyline layers, and tables.

Growing degree day >5 °C: A measure of the accumulated thermal units above a threshold temperature (5 °C) for each day of the growing season. Growing degree days are a reliable predictor of organism growth and development.

Habitat template: Results from the long-term pattern of physicochemical variability in conjunction with the complexity and stability of the flow, thermal, and sediment regimes, and theoretically influences which combinations of behavioural, physiological, and life history characteristics constitute appropriate *ecological strategies* for persistence in that habitat.

Interconfluence reach (stream reach): A section of stream between inflowing tributary streams of any size.

Intermittent stream: A stream that flows only during certain times of the year (seasonal) while drying up other times.

Lake influence: The influence a lake exerts on the temperature, flow, sediment, and nutrient regimes of reaches downstream of the outlet. For AECv2, lake influence refers to the influence on temperature regime.

Law of stream numbers: The Horton law of stream numbers states that a geometric relationship exists between the number of streams of a given order (Horton 1945).

Lentic: Of, relating to, or living in still fresh waters such as lakes, ponds, or swamps.

Lotic: Of, relating to, or living in actively moving fresh water.

Neighbourhood: A grouping of reaches based on upstream catchment area rules such as confluence symmetry ratio (CSR).

Neighbourhood upstream catchment area ratio (NUCAR): A ratio calculated to determine when a stream segment is getting too large, i.e., the upstream and downstream drainage areas differ too much. In such segment, the reach affinity tool (RAFT) finds the largest tributary to create a break. It uses minimum and maximum reach UCAs inside each neighbourhood and calculates a ratio of the two UCAs called the Neighbourhood Upstream Catchment Area Ratio (e.g., NUCAR = 3,000 km^2/1,500 km^2 = 2.0).

Network Catchment Attribute Tool (NCAT): A custom MATLAB-based software application that automates the process of calculating the upstream catchment attributes from individual reach contributing area (RCA) attributes and assigning network metrics such as Strahler and Shreve order to the reaches.

Network neighbourhood: see Neighbourhood

Non-wadeable streams (>2,000 km2): About 95% of such a stream is boatable and methods designed for large rivers and lakes will apply.

Ontario Hydro Network (OHN): The official province-wide data set that identifies hydrographic features in Ontario (e.g., stream lines, waterbody polygons).

Ontario Integrated Hydrology (OIH): A collection of data created using a digital elevation model (DEM) and its derivatives (e.g., flow direction) and mapped water features. It is used to generate watershed boundaries at various scales and supports provincial-scale hydrology applications.

Perennial stream: A stream or river that has continuous flow in parts of its stream bed all year during years of normal rainfall.

Productivity regions: The combination of growing degree day bands and predominant upstream ecozones creates 10 AEC regions that delineate large areas of potential differences in stream productivity.

Reach: see interconfluence reach

Reach Affinity Tool (RAFT): A network-aware computer program that is used to clustes (i.e., group) stream reaches into stream segments.

Reach contributing area (RCA): The lateral area of land contributing surface and subsurface flow of water, nutrients, and organic and inorganic materials to a stream reach independent of catchment size and upstream contributions. RCA is defined by the local topography.

Strahler order: Provides an indication of the size of the stream (e.g., first order streams are small headwaters and seventh order streams are large lowland rivers); see Strahler (1957).

Stream class: A type of stream characterized by a unique set of factors (e.g., a warm, turbid, and slow river).

Stream segment: A segment is a grouping of adjacent reaches that have similar characteristics and are considered relatively homogenous in hydrologic, limnologic, geomorphic, and biotic characteristics. River segments are considered useful in stream classifications because their sizes are considered appropriate for many types of fishery and water resource management decisions.

Stream-lake network: A series of stream reaches and interconnecting lakes in a network.

Top-down approach: Starting at large spatial extents (e.g., regional) and dividing them into progressively smaller spatial units.

Turbidity: A measure of the degree to which water loses its transparency due to the presence of suspended particulates; the more total suspended solids in the water, the cloudier it appears and the higher the turbidity.

Upstream contributing area (UCA): Total area of land draining to a point at the downstream end of a stream reach.

Virtual connector reaches: Stream reaches that run through waterbody polygons that artificially provide network connectivity routing through the waterbodies to maintain network ‘flow’ downstream.

Wadeable streams (<200 km^2): More than 95% of the stream can be waded. A diverse and well established set of sampling methods are available.

Water conductivity: A measure of water's capability to pass electrical current, which is directly related to the concentration of chemical ions in the water (e.g., Ca^{++}, HCO_3^-). It also correlates with total dissolved solids (TDS) and the amount of nutrients in freshwater.

Work units: Areas of the province for which stream network data are processed and distributed to the end user.

(0k P.R. 22 02 09)
ISBN 978-1-4868-5842-2 (pdf)