Aquatic Ecosystem Classification for Ontario's Rivers and Streams: Version 1

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Introduction

Streams and rivers are complex systems for which there has been a scientific emphasis on a hierarchy of nested environmental filters and abiotic controls at multiple scales. In these systems upstream areas are connected to areas downstream in a directionally nested framework essentially making all reaches the product of the cumulative structure and character of areas upstream. Rivers are also laterally connected to the surrounding landscape and riparian areas which have an intimate influence on the nature and health of the rivers. The advent of computers and geographic information systems have allowed for more powerful and sophisticated analyses of stream networks forever changing the ways we can perceive streams and their inhabitants. We now have the ability to make inventories and assessments about the state of our rivers systems from small headwaters to kilometre wide lowland channels, and all this across very large areas. We can find similarities and differences in the characteristics of the many streams we have across large areas. Ontario has an area of 1 million square kilometres and much of it is remote and difficult to access. Prior to the AEC we did not have a full inventory of Ontario's streams and rivers. We did not know what we had and where it was 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 the effectiveness that our management actions have on them.

In 2013, the Aquatic Research and Monitoring Section (ARMS) River and Stream Ecology team published a technical report that outlined the theoretical basis for building an Aquatic Ecosystem Classification (AEC) for Ontario's rivers and streams (Melles et al. 2013). This followed a 2011 client needs survey to determine how an AEC would be useful to or used in the Ministry of Natural Resources and Forestry (Melles et al. 2011). These reports, as well as a review of classification systems world-wide (Melles et al. 2012, Melles et al. 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 will serve as a landscape scale resource management tool to group Ontario's streams into aquatic classes to inform inventory and monitoring efforts, help identify species at risk and invasive species habitat, and support aquatic class park development and land use planning.

The AEC is a hypothesis and an attempt to capture major ecological differences among streams in Ontario. Based on many meetings with stakeholders from across the province including virtually canoeing the rivers with them, the AEC classifies about 90% of streams correctly. The remaining 10% need to be vetted through those familiar with streams as some are rare (e.g., karst systems) and/or have base data issues. The AEC is built with a small set of variables that profoundly influence streams. Many other variables could have been added and perhaps improved the model by ~5% but at a cost of increased complexity. There is no right or wrong level of detail or spatial resolution. This is not scientifically defined but reflects the question of interest and geographic scale. In general, a high degree of complexity and small local scales becomes problematic at regional scales. Simple can be harder to accomplish than complex because it requires clear thinking. Like all hypotheses, ours will change and improve with additional knowledge. This document represents version 1 of the classification system. Subsequent versions will incorporate corrections, new variables, and validation, but the basic approach will remain the same.

Building the spatial data framework

To put the theory described in the AEC's initial technical proposal into practice, a new Geographic Information System (GIS) data processing and management framework was needed. The AEC was built using a bottom-up approach, with the province divided into fundamental spatial units called reaches, which were grouped into increasingly larger ecological units. The final product is a multi-scale hierarchical classification system. Steps in the process are listed here and described in more detail below:

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*, summarizing a variety of landscape characteristics (e.g., geology, landcover, climate) at various spatial scales (e.g., channel, reach contributing area, upstream contributing area)
4. Grouping reaches into ecologically homogenous stream *segments* using a set of stream size and landscape similarity rules.

5. Grouping segments into classes with ecologically relevant landscape characteristics (e.g., groundwater contributions to the stream, potential for inorganic turbidity and channel bed slope).
6. Grouping segments into broad geo-climatic regions.

Simplifying the stream network

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 outer branches of the full stream network by applying a uniform upstream catchment area threshold of 1 km^2. Network simplification serves these three purposes:

- Standardize 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., $km \cdot km^{-2}$).

- Reduce uncertainty of stream intermittency: Classifying whether a stream is perennial or intermittent is not the goal of the classification and is a complicated process outside the scope of the AEC. We made an attempt to remove many intermittent streams by using the 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 intermittent. Some perennial streams have smaller drainages particularly those associated with spring upwellings.

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

While the excluded very small streams may be the focus of some resource management scenarios, the classification’s intended use is at the provincial scale and the base data used to create it (i.e., 30 m Digital Elevation Model) is less accurate at smaller scales. Given a need and sufficient base data to warrant the effort, the AEC framework could be extended to accommodate such fine scales in some areas of the province.

Generating the fundamental spatial framework

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 that are portions of stream between two stream confluences (i.e., interconfluence links). To understand streams in Ontario it is crucial that an AEC include lakes (Jones 2010). We achieved this by combining the basic 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 basic 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 in place of the basic interconfluence link layer.

Arc Hydro proceeds with several geoprocessing steps that include delineating reach contributing areas, assigning unique identifiers to each reach and adding network awareness by finding reach downstream neighbour identifiers. The ‘next-down’ neighbour information makes it possible to perform network analyses and the unique identifiers allow us to join the resulting spatial data with landscape characteristics tables gathered during the next step. Forty-seven Arc Hydro geodatabases were generated to cover the province using watershed-based divisions called *work units*. Over 710,000 reaches were generated. A portion of the Hayes River on the Ontario-Manitoba border was not processed because OIH data was not available in that area.

Stream reach inventory

Using the Arc Hydro geodatabases we gathered a large inventory of landscape and network attributes using four scales of collection for each of the 710,000 reaches in Ontario (Figure 1 and 2). 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 over one thousand fields across several dozen data categories. From this we determined that Ontario has approximately 410,000 stream reaches and ~300,000 virtual connector reaches in lakes.

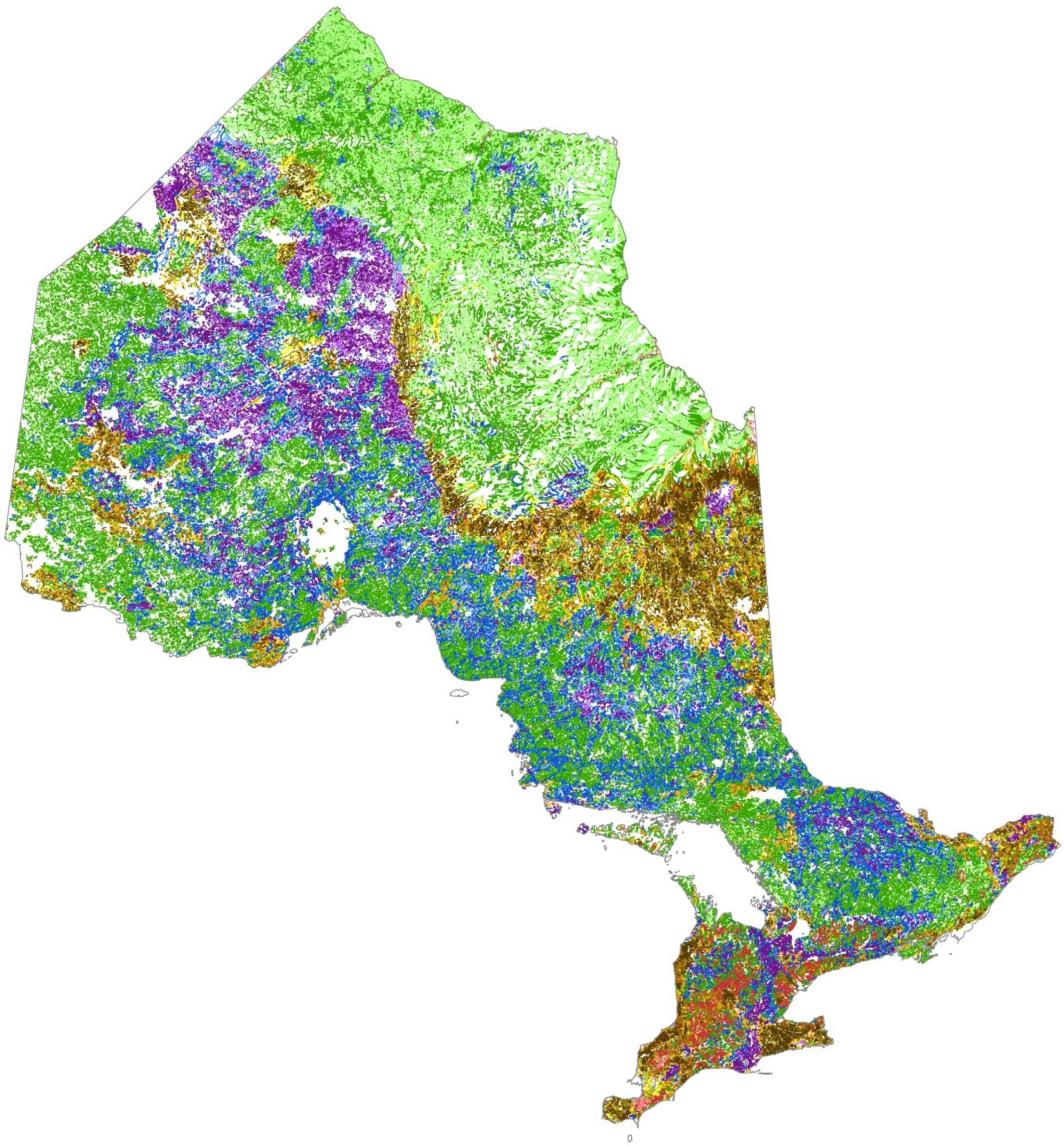


Figure 1. An overview of the aquatic ecosystem classification showing individual colour-coded streams. At this scale of representation individual stream are not evident but regional patterns in stream types are clear.

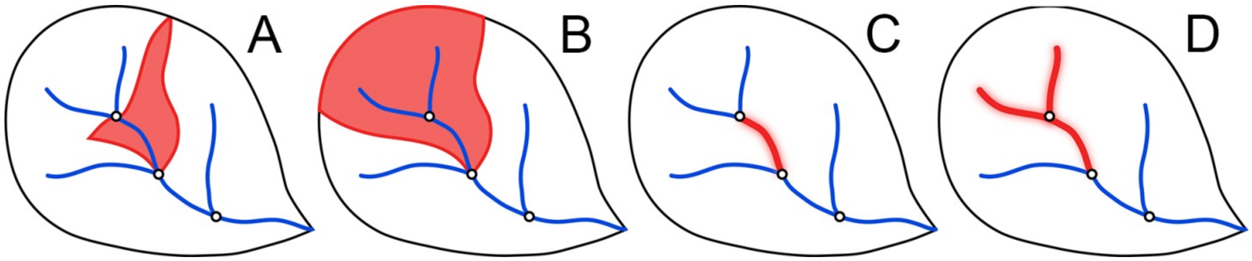


Figure 2. The four scales of variables summary applied to group stream reaches: a) reach contributing area, b) upstream catchment, c) reach channel (30 m raster), and d) upstream channel for the catchment (30 m raster).

Grouping the reaches into segments

The complexity of stream reaches 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 in Matlab that clusters stream reaches and virtual segments in lakes into stream segments. Stream segments are assumed to be more homogenous, have similar habitat characteristics, and support similar ecological communities that respond to stressors in the same way (Hynes 1975). Without this aggregation tool there would be more breaks or changes in class type in the stream networks. RAFT is based on the Valley Affinity Search Technique (VAST) software developed by researchers at the University of Michigan (Brenden et al. 2008).

With their permission we used the VAST VBA source code as a foundation for our MATLAB code. We adapted and extended the algorithms contained in VAST for classifying rivers across the large geographic area of Ontario with more complex segmentation rules, while also increasing processing stability and speed. The grouping process reduced data complexity, with the 410,000 reaches across the province joining to form about 335,000 segments (not including virtual reaches in lakes).

RAFT algorithm overview

The probability of a significant change in the ecology downstream from a tributary is high when two streams of similar size and with similar landscape characteristics merge. Small tributaries with similar landscape characteristics have a low probability of causing changes. As the landscape similarity of the two drainages decreases, the probability of change downstream from the confluence increases. This recognizes that a small tributary might influence downstream characteristics on the main stem if it is very different in character (i.e., draining a very different landscape). For example, a relatively small, warm, and turbid tributary flowing into a cold clear trout stream may change the main stem more than a similarly sized tributary that is also cold and clear. These relationships set up simple expectations about the relative importance of confluences in stream networks and provide a physical basis for the likelihood of change downstream of tributaries and network heterogeneity of habitats (Jones and Schmidt 2017).

Based on stream size and similarity in characteristics, reaches are grouped into segments using two stages of processing of the tabular input data:

1. Dividing the networks into neighbourhoods based on confluence symmetry ratio, which is the ratio of tributary to main channel upstream catchment areas

2. Joining reaches within neighbourhoods if they are network neighbours and landscape characteristics are similar

Defining network neighbourhoods using upstream catchment areas

Abrupt changes in the volume of flow, temperature, and sediment along the length of a stream are addressed by calculating the ratio of the tributary upstream catchment area (UCA) to the mainstem UCA. This is called the confluence symmetry ratio, where 1.0 indicates that both reaches have exactly the same UCA. As tributary size decreases CSR approaches zero. Four rules are applied using the CSR values, as shown diagrammatically in Figure 3:

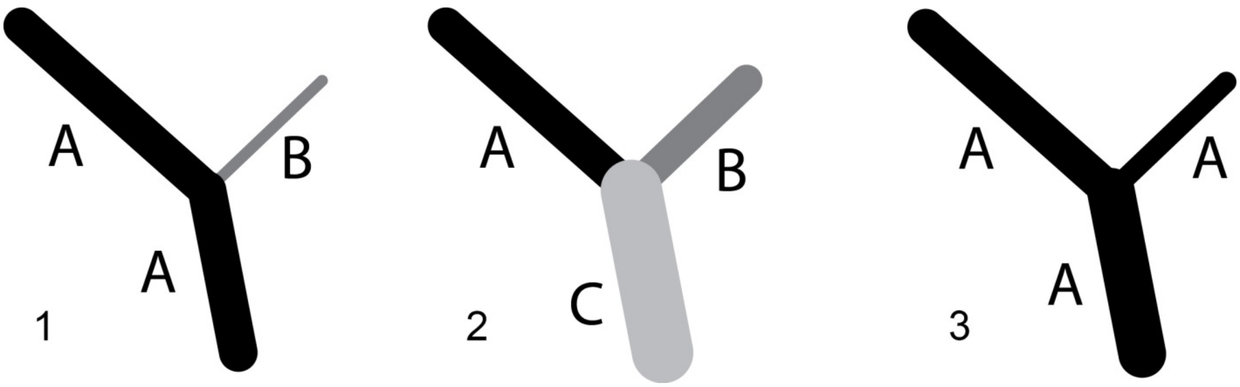


Figure 3. Diagrammatic representation of the first three rules applied to group stream reaches using the confluence symmetry ratio. See points 1, 2, and 3 below for rationale.

1. If the CSR is below a lower threshold (e.g., we used 0.25), a tributary is considered too small to significantly affect the main channel (Figure 3 left). In this case, 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).

2. 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 3 middle). 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).

3. Stream reaches between confluence symmetry ratios of 0.25 to 0.5 are allowed to join because they have similar sizes, and thus, potentially similar ecological characteristics (Figure 3 right).

4. Every stream network has many more headwater streams than larger higher order streams and this relationship is approximated by a geometric progression according to the law of stream numbers (Horton 1945). For instance, wadeable streams (<200

km²) account for 90% of stream segments in Ontario. The mainstems of rivers have large drainage areas and large flow volumes. Few tributaries are large enough relative to the mainstem to break the neighbourhood based on the upper CSR thresholds (all CSR<0.25). However, many small tributaries may join the mainstem causing its flow volume to steadily increase. The larger the mainstem grows, the less likely it is that a tributary will break the neighbourhood and as a result long portions of river are likely to be grouped into a neighbourhood. This can be inappropriate if the UCAs of its reaches are very different (e.g., start of neighborhood 1,500 km² and end of neighborhood 3,000 km²). The many individually small accumulating tributaries have increased the flow volume of the river without producing an abrupt change in the ecology. This is problematic because at the upstream end of the neighbourhood the stream might have a bankfull width of 30 m whereas at the downstream end it might be 100 m. These reaches should not be considered ecologically homogeneous and consequently such neighbourhoods need to be divided further.

To remedy this problem of artificially uniform segments, RAFT is coded to identify the segments that are too long given differences in their upstream and downstream catchment areas. This applies only to streams with a UCA larger than 50 km². To find the largest tributary to create a break, RAFT is coded to determine the minimum and maximum reach UCAs inside each neighbourhood and calculate a ratio of the two UCAs called the Neighbourhood Upstream Catchment Area Ratio (e.g., NUCAR = 3,000 km²/1,500 km² = 2.0). The problem neighbourhoods are defined as having a NUCAR >1.25. RAFT then divides the neighbourhood into sub-neighbourhoods and identifies reaches whose UCAs fall between the lower and upper bound of the NUCAR window (NUCAR values1.25 to 1.75). The upper threshold allows for some flexibility to find the best (largest) tributary for the break. This approach prevents neighbourhoods from being divided at very small tributary confluences that push the NUCAR above the lower threshold. The process repeats until all neighbourhoods have a NUCAR below the lower threshold value.

5. The final step uses upstream catchment area to determine the downstream influence of lakes (i.e., lake outlet streams). Lakes and rivers are intimately connected in an alternating series of lentic and lotic reaches in many regions in Ontario. Rapid and predictable changes in the ecological characteristics of streams occur at the interface with lakes (Jones 2010). In many cases, water leaving the lake will be warmer and carry large amounts of seston (e.g., dissolved organic carbon, phytoplankton, zooplankton). Flows will be more constant (less flashy) and less influenced by rainstorms. The stream water at the lake outlet might be clearer as particulate matter precipitates in the lake. The combination of changes in the abiotic and biotic conditions fundamentally changes the ecology of the outlet stream however, changes are context dependent. For the AEC we estimate a "zone of influence" downstream from every lake as an attenuation function based on the UCA at the downstream end of the reaches. We are aware that the proportion of groundwater contribution (i.e., baseflow index, BFI) and riparian cover may also play a role in determining the rate of attenuations but it is currently not included in the function. Lake Influence (LI) calculations are performed using a MATLAB application separate from RAFT, where each reach is assigned an average LI value ranging from zero to one, and where one is the maximum influence a lake a can exert at the

lake outlet. This maximum value attenuates to zero a distance downstream from the outlet. LI can also increase or decrease at confluences depending on the terminal LI of the tributaries.

The following process is applied to every reach on the network. The initial LI at the beginning of a reach is set to one at lake outlets or calculated as the combined LI contributions of joining tributaries using an area weighted average. The terminal reach LI is calculated by multiplying the reach length by an attenuation rate, which is the rate of change of LI per kilometre of reach length (Lake Influence Rate of Change, $LIROC = 1.66 \cdot CA^{-0.6}$), then subtracting the product of the multiplication from the initial LI. The final LI value assigned to a reach is the average of the initial LI and terminal LI. If the LI attenuates to zero along the reach, the proportion of reach length at zero is used to weight the final LI value. First order streams without headwater lakes are simply assigned a final LI of zero.

The form of the attenuation function means that LI in small streams quickly decays to zero (<1 km), whereas, for large streams it may take several kilometres. The final cumulative output table of the LI application is joined to the RAFT input table where it is used to determine whether a segment is considered lake influenced or not. However, LI is not used in the landscape character similarity assessment (i.e., Euclidean distance) discussed below.

Grouping reaches into segments within neighbourhoods

RAFT's second stage operates within the neighbourhoods and groups the reaches into stream segments based on their landscape and channel similarities (e.g., geology, channel slope). Within a neighbourhood, segments cannot expand beyond neighbourhood boundaries. Each neighbourhood can have multiple stream segments. To begin, reaches in a neighbourhood are sorted by Shreve order ensuring that processing goes from the downstream to the upstream end.

Next the attributes of first reach are compared with the attributes of its largest adjacent upstream reach (i.e., the main channel) using a Euclidean Distance (ED) measure. The algorithm processes the mainstem of the neighbourhood first and then moves on to tributaries from largest to smallest. Smaller adjacent reaches at confluences are set aside for processing later. The ED for the two reaches is compared to an affinity threshold (AT; e.g., 0.15). Lower values of AF create small segments with more homogeneity; higher values create larger segments with more heterogeneity. A value of 0.15 provided a good balance of complexity. When ED is below the AT, adjacent reaches are considered to be similar and part of the same segment.

The new segment is considered to be open and RAFT proceeds to calculate the distance between the reaches of the open segment and the next adjacent upstream target reach. Comparison can be done several ways: 1) the complete linkage (CLINK) method, which uses the largest ED between the target reach and the reaches of the open segment, 2) the single linkage method, which uses the smallest ED between the target reach and the reaches of the open segment, and 3) the Unweighted Pair Group Method with Arithmetic Mean (UPGMA) method, which uses the average of the EDs of the open segment to calculate ED to the target reach. Details about differences amongst these methods can be found in Romesburg (1989). If required, the ED calculation can also include attribute weighting although for the AEC we used equal weights. This grouping process continues until a reach is found whose ED to the open segment is at or above the specified affinity threshold. RAFT then goes back to any tributary branches it set aside earlier, starting with the furthest downstream branches, calculating their affinity to the open growing segment. If these tributary reaches pass the similarity test then they are added to the segment. This process continues until no adjacent reaches can join the open segment.

Before a segment is considered closed it is treated to a within segment double-check, where the affinity of each reach to every other reach in the open segment is checked once more. This ensures that all reaches in the segment remain under the AT because reaches added earlier in the process might exceed the AT when compared to reaches added later. If a reach is found with an affinity above the AT then it is assigned its own segment and the remainder of the reaches are returned for clustering. If no such reaches are found then the segment is closed and a new segment is opened. The algorithm runs until all reaches in a neighbourhood have been assigned to a segment.

The last phase of this algorithm is a check for stability amongst segments. It may be the case where a reach has a higher affinity to an adjacent segment than to the segment to which it is currently assigned due to processing order. An affinity check is performed at the interface of segments (i.e., segment boundaries, not neighbourhoods). Reaches with higher affinity to an adjacent segment are reassigned to that segment. This process is iterative until no reaches can be found to reassign, indicating that stability has been achieved.

Input data

RAFT input is composed of tabular data describing each reach in a river network as a row in a table. The data is drawn from the reach inventory from which we chose three ecologically relevant landscape characteristics: hydrological and thermal regimes, turbidity, and channel slope.

1) Hydrologic and thermal regimes: Baseflow index (BFI, Neff et al. 2005) is an attempt to quantify the amount of groundwater contributing to stream flow and is 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 including coarse and fine textured sediments, till, shallow bedrock, and organic deposits (Piggott and Sharpe 2007).

2) Turbidity: The clarity or cloudiness of the water relates to the productivity of the stream (e.g., autotrophic vs heterotrophic metabolism) 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 organic matter. Even relatively small turbid tributaries can influence the ecology of large mainstem rivers. The proportion of clay geology in a watershed influences the turbidity and suspended inorganic particulate of a stream. It does not influence how stained the water is from organic matter (e.g., tannins). For a segment to be classified as turbid, the area-weighted average value for the upstream channel

must be ≥10% of one or a combination of the clay geology types. Clay geology was defined as surficial quaternary geology types 4, 6, 8, 15, 21, 24, 26, and 29.

3) Channel slope: Water velocity represents an important factor affecting organisms in running waters. Current defines sediment sizes, food delivery, and is a direct physical force on organisms. Water velocity was inferred from channel slope measured as maximum-minimum rise over run for the reach based on a 30 m digital elevation model (DEM). Given inaccuracy inherent in a 30 m DEM, channel slope was categorized as slow (≤0.1%) and fast (>0.1) moving rivers. The slow to fast threshold was meant to differentiate between streams dominated by sands and finer sediments and those composed of larger sediments. This categorization does not include differences in riffles (fast) and pools (slow) assumed to occur in all streams as a result of finer scale processes. The calculation of slope will misrepresent waterfalls or other sudden elevation changes. For the AEC, we used each reach's maximum and minimum elevations and channel length (i.e., rise over run).

Landscape attributes were range scaled (Legendre and Legendre 2012). BFI and per cent clay geology were both scaled to a range from zero to one hundred. Channel slope was also scaled to this range for slopes from 0% to 1%. All slopes above 1% were simply assigned a value of 100 (approximately 10% of all reach slope values).

In version 2 of the AEC we plan to build models to predict stream temperature and turbidity. We also hope to include aspects of stream geomorphology other than channel slope but a 30 m DEM does not allow fine scale analyses particularly for small streams. The output of these derived layers will then be used to attribute reaches and reprocess them using RAFT. New versions of the AEC will incorporate significant improvements, many of which were described in the initial technical proposal.

Grouping the segments into classes

The next step groups stream segments into classes using a multi-tiered binning approach, which greatly reduces the complexity of the classification. The binning considers only the attributes of the segments, not their spatial context (e.g., network position or connectivity, geographic location). The first binning tier is based on turbidity and split all streams in Ontario as either turbid (≥10% clay geology) or clear (<10%). The next tier assigns BFI to five bins: very high (≥0.65), high (≥0.51 and <0.65), moderate (≥0.35 and <0.51), low (≥0.2 and <0.35), and very low (<0.2). The third binning tier uses channel slope with each segment assigned as either fast (≥0.1%) or slow <0.1%). The three tiers combine into 20 distinct classes. An alphanumeric code denotes class membership. For example, the code VHCF denotes a segment with very high base flow, clear and fast flowing. Membership in four of the binning combinations was low and these were subsequently moved into adjacent classes resulting in 16 classes.

Grouping the segments into regions and zones

Regions and zones constitute the highest levels of the classification hierarchy in the AEC, and unlike segments, results from a top-down approach based on expectations of aquatic productivity. Productivity is an important aspect of flowing waters with respect to harvest and ecosystem resiliency.

In lakes, productivity is affected by three principal influences; morphometric, edaphic, 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 otherwise 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 (GDD) 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.

There are 5 growing degree-day$^{>5^{\circ}C}$ *regions* in Ontario (<700, 700-1100, 1100-1500, 1500-1900, >1900; Canadian Forestry Service 2006). In addition there are three ecozones of the terrestrial classification system (Hudson Bay Lowlands, Boreal Shield, and Mixedwood Plains). Water conductivities in the Mixedwood Plains average 540 μS whereas in the Boreal Shield and Hudson Bay Lowlands conductivities average 150 μS (Ryder 1964). The combination of growing degree-days regions and ecozones creates 10 aquatic zones that delineate large areas of potential differences in productivity (Figure 4).

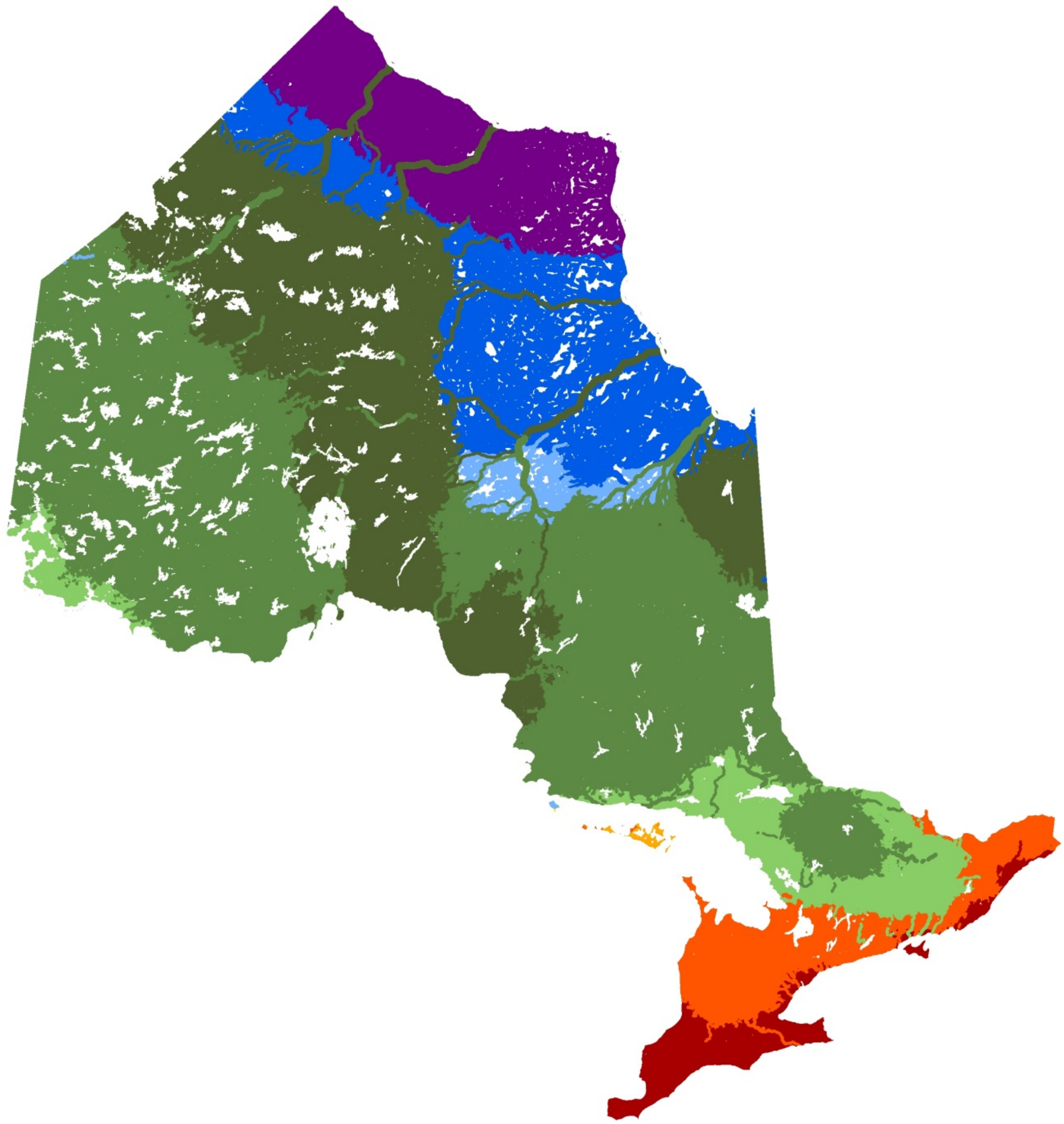


Figure 4. The combination of growing degree-days and ecozones creates 10 AEC zones that delineate large areas of potential differences in productivity.

Network structure: stream size and lakes

Network structure is composed of two very important modifiers of stream character: Strahler order and lake influence. Strahler order provides an indication of the size of the stream (e.g., 1st order streams are small headwaters and 7th order streams are large lowland rivers). As streams grow in size there are progressive shifts in structural and functional attributes of aquatic communities (Vannote et al. 1980). For example, many headwater streams are influenced strongly by riparian vegetation which reduces autotrophic production by shading and contributes large amounts of allochthonous detritus. As stream size increases, the reduced importance of terrestrial organic input coincides with enhanced significance of autochthonous primary production and organic transport from upstream. From headwaters to mouth, the physical variables within a river network will show a gradient of physical conditions if the landscape which it drains is 100% homogenous in character (Hynes 1975). For example, a 1st order headwater stream might have a high baseflow index and have a lot of cold groundwater feeding it, but far downstream as it becomes a 6th order stream we should not expect it to be cold even if it still has a high BFI: it might be cool or warm because of a more open and generally slower channel being warmed by the sun.

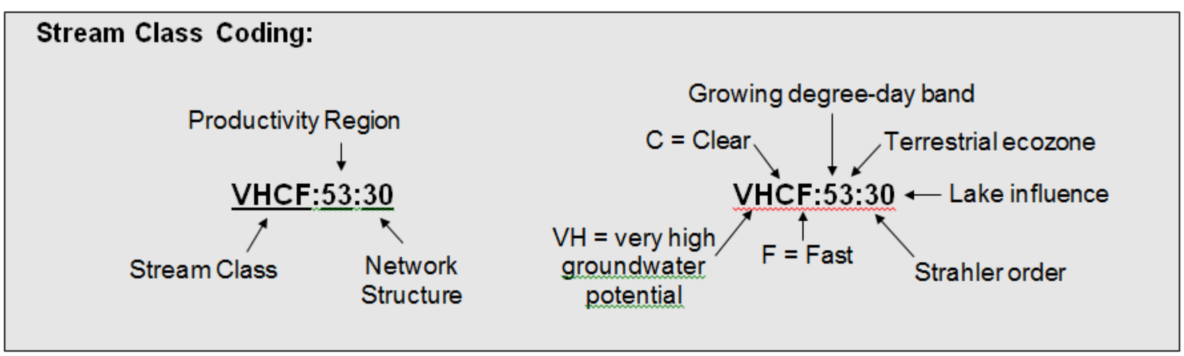
Throughout much of Ontario lakes and rivers are connected in an alternating series of lentic and lotic reaches. Some lakes appear as widenings of rivers. In many cases, the distinction between a lake and a river is unclear. Previous research has shown that there are often rapid and predictable changes that occur downstream of lakes (Jones 2010). For many lake outlet streams, water leaving the lake will be warmer and carry large amounts of dissolved organic carbon, phytoplankton, zooplankton, flows attenuate slowly and less influenced by rainstorms than streams without lakes, and the stream water at the lake outlet might be clearer as particulate matter precipitates in the lake. The suite of changes in the abiotic and biotic conditions fundamentally changes the ecology of the outlet stream, however, changes are context dependent. For the AEC we estimate a “zone of influence” downstream from every lake as a continuous attenuation function based on the size of the stream (width). For small streams the lake influence attenuates quickly (< 1 km), whereas, for large streams it may take several kilometers. We are conducting further research to develop a more complex model to quantify this effect.

There is also an upstream influence of lakes from estuaries, particularly around the Great Lakes, that can dramatically alter stream characteristics (e.g., backwater segments, slower and deeper water estuaries). These network modifiers inform us about the ecological nature of the stream, but the fundamental class of stream does not change.

Stream classes legend with variables and bins shown in the table and alpha-numeric key shown in the text box

Symbol	Class Code	Baseflow Index	Channel Slope	Segments (% of Total)
Clear streams*				
	VHCF	≥ 0.65 (Very High)	≥ 0.1% (Fast)	29,224 (8.7%)
	VHCS		< 0.1% (Slow)	11,057 (3.3%)
	HCF	≥ 0.51 AND < 0.65 (High)	≥ 0.1% (Fast)	45,757 (13.7%)
	HCS		< 0.1% (Slow)	16,799 (5.0%)
	MCF	≥ 0.35 AND < 0.51 (Moderate)	≥ 0.1% (Fast)	115,355 (34.4%)
	MCS		< 0.1% (Slow)	66,818 (19.9%)
	LCF	< 0.35 (Low)	≥ 0.1% (Fast)	4,554 (1.4%)
	LCS		< 0.1% (Slow)	1,147 (0.3%)
Turbid streams*				
	HTF	≥ 0.51 (High)	≥ 0.1% (Fast)	2,017 (0.6%)
	MTF	≥ 0.35 AND < 0.51 (Moderate)		8,210 (2.5%)
	LTF	≥ 0.20 AND < 0.35 (Low)		10,701 (3.2%)
	VLTF	< 0.2 (Very Low)		12,576 (3.8%)
	HTS	≥ 0.51 (High)	< 0.1% (Slow)	570 (0.2%)
	MTS	≥ 0.35 AND < 0.51 (Moderate)		2,998 (0.9%)
	LTS	≥ 0.20 AND < 0.35 (Low)		3,706 (1.1%)
	VLTS	< 0.2 (Very Low)		3,530 (1.1%)

*during low flow conditions



Field sampling considerations

Stream size, water conductivity, turbidity, and channel slope strongly influence the way we sample streams in the field. We split stream size into three categories based on drainage area: wadeable streams (<200 km²), non-wadeable streams (>2,000 km²) and intermediate streams (≥200 to <2,000 km²) (Figure 5). For wadeable streams, greater than 95% of the stream is wadeable and many existing sampling methods can be used.

For non-wadeable streams, 95% is boatable and methods designed for rivers and lakes apply. The intermediate streams are difficult to travel, navigate, and sample and require a mixture of approaches. 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. Water conductivity strongly influences our ability to effectively employ electrofishing techniques. Turbidity limits our ability to see fish and to wade/boat safely. Channel slope determines the speed at which water flows and influences methods and safety. All of these factors collectively influence our ability to measure physical, chemical, and biological variables, and each plays a role in the detection and catchability of different species.

Figure 5. Three categories of stream size based on drainage area are: wadeable streams (<200 km², light blue), non-wadeable streams (>2,000 km², dark blue) and intermediate streams (≥200 to <2,000 km², medium blue).

Considerations for using the draft classification

1. It is a general habitat template model not a species specific model.
2. It is the habitat template as it would be without the influence of human development (e.g., urbanization, agriculture).
3. Its 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 reach but the provincial scale base data resolution does not support work at such a fine spatial scale.
4. Its intended scale of use does not include very small 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).
5. Its segments and classes represent portions of the stream network with an increased likelihood of sharing a similar ecological habitat template but like all models it includes an element of uncertainty.
6. The landscape data on which the classes are based is on a continuum but we needed to aggregate the segments into discrete classes for cartographic purposes. Each segment has an affinity to its class (e.g., distance to class centroid), an idea that we plan to include in future versions.

Uses of the aquatic ecosystem classification

The classification and the inventory data can be used in many ways to support policy and management decisions. A few of the more important applications are outlined here.

Provincial monitoring

- Guide site selection to ensure efficient use of time and money for large and small scale monitoring and field inventory.
- Improve statistical sampling design resulting in greater power to detect change.
- Provide a provincially consistent spatial framework for monitoring and reporting.
- Allow extrapolation from data rich to data poor regions.

Conservation status

- Contribute to the development of models predicting the distribution/abundance of many species, e.g., at risk, invasive, or highly valued (e.g., brook trout; Thorn et al. 2016).
- Provide quantitative assessment of the health of populations (e.g., expected vs observed brook trout biomass).
- Understand how human disturbances influence fish abundance and biodiversity.
- Predict locations of rare aquatic species (e.g., redside dace) to support reintroduction/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 providing more power to detect change than when all streams lumped together.

Parks and land use planning

- Determine representation and uniqueness of aquatic features on the landscape.
- Develop aquatic class parks.
- Know ecological sensitivity and capacity of the landscape, e.g., Far North.

References

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 (5): 638–649.

Horton, R.E. 1945. Erosional development of streams and their drainage basins: hydro-physical 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 fur Theoretischeund Angewandte Limnologie 19: 1–15.

Jones N.E. and B.J. Schmidt. 2017. Tributary effects in rivers: Interactions of spatial scale, network structure, and landscape characteristics. Canadian Journal of Fisheries and Aquatic Sciences 74: 503–510.

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.

Legendre P. and L. Legendre. 2012. Numerical Ecology (Third Edition). Elsevier Press, Amsterdam, NL. 990 p.

Melles, S., Jones, N.E., Schmidt, B. 2011. Aquatic Ecosystem Classification (AEC): Client Needs Survey Response. Aquatic Research Series 2011-04. Ontario Ministry of Natural Resources. 19 pp + 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. DOI:10.1111/j.1365-2427.2011. 02716.x

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.

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

Neff, B.P., Day, S.M., Piggott, A.R. and Fuller, L.M. 2005. Base flow in the Great Lakes Basin. U.S. Geological Survey, Washington, D.C. 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(2): 375–385.

Piggott, A.R. and D.R. Sharpe. 2007. Geological interpretations of baseflow for southern Ontario. Pp. 394-401 in Proceedings of the 60th Canadian Geotechnical and 8th Joint IAH-CNC and CGS Groundwater Specialty Conferences, Ottawa, ON.

Romesburg, H.C. 1989. Cluster Analysis for Researchers. Lulu Press, Morrisville, NC. 334 p.

Ryder, R.A. 1964. Chemical characteristics of Ontario lakes as related to glacial history. Transactions of the American Fisheries Society 93: 260–268.

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.

Shuter, B. J., J. A. Maglean, 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.

Strahler, A.N. 1952. Hypsometric (area-altitude) analysis of erosional topology, Geological Society of America Bulletin 63: 1117–1142.

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 Lake Simcoe watershed. 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. Cummings, J.R. Sedell, and C.E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences 37: 130–137.

Welcome, R.L., R.A. Ryder and J.A. Sedell. 1989. Dynamics of fish assemblages in river systems - a synthesis. *In*: Dodge, D.P. (ed.) Proceedings of the international Large River Symposium. Canadian Special Publication of Fisheries and Aquatic Science 106: 569–577.

Glossary

Affinity threshold: A Euclidean based threshold that helps determine if characteristics of two reaches or group of reaches are similar or different.

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

Aquatic ecosystem classification (AEC): Describes types of flowing waters in Ontario. Future efforts will include lakes.

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

Baseflow index: BFI is an attempt to quantify the amount of groundwater contributing to stream flow and is 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 including coarse and fine textured sediments, till, shallow bedrock and organic deposits.

Binning: Grouping continuous values into to reduce their numbers for statistical purposes. Histograms are an example of data binning used in order to observe underlying distributions. They typically occur in one-dimensional space and in equal intervals for ease of visualization however some may use ecologically meaning break points.

Bottom-up approach: Small elements (interconfluence reaches) are linked together to form larger subsystems (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 to channel length.

Confluence symmetry ratios (CSR): Tributary size relative to the mainstem river.

Digital elevation model (DEM): A model or 3D representation of a terrain's surface created from terrain elevation data.

Ectotherm: An animal that is dependent 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.

Euclidean distance (ED): the Euclidean distance or Euclidean metric is the "ordinary" straight-line distance between two points in Euclidean space. With this distance, Euclidean space becomes a metric space.

Fundamental spatial units: For the AEC, this is the interconfluence reach.

Geodatabase: An alternate way to store GIS information in one large file, which can contain multiple point, polygon, and/or polyline layers.

Growing degree-day>5°C: A measure of the accumulated thermal units above 5°C for each day of the growing season. Growing-degree days are a reliable predictor of 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): Section of stream between two inflowing tributary streams of any size.

Intermittent stream: Flows only during certain times of the year (seasonal).

Lake influence: is calculated by multiplying the reach length by an attenuation rate, which is the rate of change of LI per kilometre of reach length (Lake Influence Rate of Change. For the AEC we estimate a "zone of influence" downstream from every lake as an attenuation function based on the UCA at the downstream end of the reaches.

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, Nw, and the corresponding order, w (Horton 1945).

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

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

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, RAFT finds the largest tributary to create a break. 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 = 3,000km^2 / 1,500 km^2 = 2.0).

Netwo**rk Catchment Attribute Tool (NCAT):** A custom MATLAB-based application to automate the process of calculating the upstream catchment attributes from individual reaches as well as assigning network metrics such as Strahler and Shreve order to the reaches.

Network neighbourhood: A group of adjacent stream reaches defined by drainage area size rules in which reaches may be joined together to form stream segments.

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

Ontario Hydro Network (OHN): Identifies hydrographic poly features in Ontario.

Ontario Integrated Hydrology (OIH): A collection of related elevation and mapped water features used to generate watersheds and support provincial-scale hydrology applications.

Open and closed segments: An open segment is still available to be joined to other reaches; a closed segment is not available for further joining.

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

Productivity zones: The combination of growing degree-days and ecozones creates 10 AEC zones that delineate large areas of potential differences in productivity.

Reach Affinity Tool (RAFT): A network-aware program in Matlab that clusters stream reaches and virtual segments in lakes into stream segments.

Reach contributing area: 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, and created by 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)

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

Stream segment: A segment is a collection of adjacent interconfluence 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 is 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 classifying into progressively smaller 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 murkier it seems and the higher the turbidity.

Upstream contributing area: Total area draining to a point on the downstream end of a stream reach.

Virtual connector reaches: Stream reaches that run through lake polygons.

Wadeable streams (<200 km2): Greater than 95% is wadeable and diverse sampling methods can be applied.

Water conductivity: A measure of water's capability to pass electrical flow, which is directly related to the concentration of ions in the water. Also correlated with total dissolved solids and the amount of nutrients in freshwater.

Work units: Areas of the province within which data are processed; constrained by processing power of computers.

Résumé

Classification des écosystèmes aquatiques des rivières et cours d'eau de l'Ontario : version 1

La province de l'Ontario ne dispose actuellement d'aucun inventaire ou système de classification des cours d'eau. Un manque de connaissance des types de cours d'eau qui circulent sur notre territoire et de leur emplacement inhibe notre capacité à bien surveiller leur état, à produire des rapports de la situation et à mesurer l'efficacité de nos actions et de nos politiques de gestion. La Classification des écosystèmes aquatiques (CEA) crée un inventaire de tous les tronçons de cours d'eau (~410 000) en Ontario grâce à des données de télédétection (p. ex. géologie), puis réduit cet ensemble complexe à l'aide de regroupements et de classification. Les tronçons sont groupés en 335 000 segments de cours d'eau, eux-mêmes classés en 16 catégories (figure 1). Les variables à l'origine de la classification sont les régimes hydrologiques et thermiques (c.-à-d. l'indice de débit de base), la turbidité et l'inclinaison du canal d'écoulement. Ces catégories sont par la suite subdivisées en régions de productivité formées d'une association de degrés-jours de croissance et d'écozones terrestres. Des lacs sont incorporés à la CAE, mais seulement pour prévoir l'étendue de l'incidence en aval, dans les exutoires. La CAE est une hypothèse et une tentative de saisie des grandes différences écologiques entre les divers cours d'eau en Ontario. Comme toutes les hypothèses, la CAE changera et se perfectionnera avec le concours de nouvelles connaissances. Ce document technique est la première version du système de classification. Les versions subséquentes comporteront des corrections, de nouvelles variables et une validation, mais la démarche de base demeurera la même.

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