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Aquatic Ecosystem Classification version 1: A review and direction forward

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Introduction

The Aquatic Ecosystem Classification (AEC) is a science-based tool for classifying Ontario's flowing waters—rivers and streams—into reaches and larger stream segments based on their physical attributes (e.g., water flow, water temperature) and the characteristics of the associated watershed (e.g., drainage area, geology). The Ministry of Natural Resources and Forestry (MNRF) is responsible for sustainably managing and deriving economic benefit from Ontario's fisheries and water resources contained in the countless rivers and streams across the province. An aquatic classification system provides a standard base for resource management decision making, helping to simplify the complexity of these aquatic systems, increase consistency in their evaluation, and facilitate landscape scale planning and policy development.

Here we provide an overview of the development of the Aquatic Ecosystem Classification version 1 (AECV1) and document issues and problem areas discovered during consultation with stakeholders and end users. We also provide direction for version 2 of the AEC. Over 30 meetings were held with and presentations provided to organizations including MNRF, conservation authorities, Department of Fisheries and Oceans Canada, universities, and non-government organizations. Given overwhelming positive response to the initial version of the AEC and the need for/widespread use of this product in MNRF and other agencies, we provide recommendations for developing an updated second version.

Overview of version 1 of the classification system

A 2013 technical report outlined the theoretical basis for building an aquatic ecosystem classification for Ontario's rivers and streams (Melles et al. 2013a). This followed a 2011 client needs survey to determine how an AEC would be useful to/used in MNRF (Melles et al. 2011). These reports, as well as a review of classification systems world-wide (Melles et al. 2012, 2013b), were used as a guide to design and build a

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spatial data framework to classify all rivers and streams in the province into ecologically homogenous units at several hierarchically nested spatial scales.

During the development of the AEC, we leveraged the intellect of many individuals in Ontario and internationally including helpful meetings and discussions. In August 2012, we met with experts—Drs. Paul Seelbach, Li Wang, Kevin Wehrly, and Catherine Riseng at the University of Michigan, Ann Arbor—to learn about the classification approach used in Michigan and along the U.S. side of the Great Lakes. In 2017, Paul Seelbach, science lead of the U.S. Geological Survey (Coastal Ecosystems Branch), came to Peterborough to share Michigan's experience with aquatic classification and their water withdrawal assessment process. We also consulted with members of the Nature Conservancy of Canada's Freshwater Classification Team for the North Atlantic Landscape Conservation Cooperative (New Brunswick, Nova Scotia, Prince Edward Island, and the Eastern portion of Quebec). This input was used to fine-tune the classification.

The AEC serves as a landscape scale resource management tool to group Ontario's streams into aquatic classes and provides a provincially consistent spatial framework for monitoring and reporting of Ontario's river and steam ecosystems and fisheries. This means that everyone is using the same map with the same unique reach and segment identifications, which improves collaboration through ease of data sharing.

The classification can be used to improve fisheries management, landscape planning, and overall decision making by:

- informing inventory and monitoring efforts
- helping to identify species at risk and invasive species habitat
- supporting aquatic class park development
- guiding site selection for broad- and fine-scale monitoring and field inventory projects
- improving statistical design and analysis to detect change
- allowing extrapolation from data rich to data poor regions so that inferences can be made at unsampled sites, removing the need to sample everywhere

The AEC and its underlying data provide us with the ability to model the distribution/abundance of many species such as those that are at risk, invasive, or highly valued (e.g., brook trout, *Salvelinus fontinalis*). Using modelling approaches, we can generate expectations for fisheries indicators such as presence/absence, abundance, or biomass of coldwater fishes. These expectations can then be compared to sites sampled in the field (i.e., expected vs. observed), providing a quantitative assessment of the health of populations. The AEC can also be used to predict the locations of habitat for rare aquatic species (e.g., redside dace, *Clinostomus elongatus*), which could help with reintroduction/restoration efforts.

Systematic approaches for assessing terrestrial representation for protected area planning are well-established, but examples of comparable methods for aquatic ecosystems are few. Consequently, freshwater ecosystems are often included incidentally in terrestrial protected areas. Some protected areas in Northern Ontario are defined by a thin buffer around a river but the primary purpose of these parks (e.g., Black Sturgeon River, Missinaibi) is to provide high quality recreational and educational experiences. National and international commitments are in place to conserve at least 17% of terrestrial and inland waters in protected areas by 2020. The gap in protection for freshwater biodiversity in Ontario and the urgency for action are recognized. The AEC can be used as a basis for assessing uniqueness, representation, and ecological integrity of streams and rivers for use in an aquatic biodiversity protection framework. The AEC can also be used by land use planners who need to understand the capacity and sensitivity of a landscape, e.g., the Far North of Ontario.

The AEC had four main guiding principles:

1. provide a universal and consistent spatial framework for Ontario's flowing waters
2. capture the ecological nature of streams and rivers
3. reduce complexity for improved understanding, resource planning, and management
4. enable the effective design of monitoring programs

Ontario has an area of approximately 1 million square kilometres, much of it remote with limited access. Before the classification system was developed, a full inventory of landscape attributes for Ontario's streams and rivers did not exist, nor did we have an ecological classification of their types or how those types were distributed. We simply did not know what we have and where it is in the province. Yet, such information is vital for managing our rivers and their inhabitants as a natural resource.

In brief, the process for building AECV1 was as follows. A new Geographic Information System (GIS) data processing and management framework was developed. The AEC was built using a bottom-up approach, with the province's rivers and streams 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 by Jones and Schmidt (2017).

1. The stream network was simplified and standardized by applying a uniform upstream catchment area threshold of 1 km^2. Intermittent streams are often shown in small streams in southern Ontario whereas in Northern Ontario small streams are often not mapped. Excluding small, likely intermittent, streams reduces the complexity of the final network, increasing data processing and display speeds.

2. The spatial framework, including a set of Arc Hydro geodatabases from the stream-lake network for the full extent of the province, was developed based on the fundamental interconfluence stream reach (hereafter referred to as stream reaches).

3. An inventory of stream reaches was generated, 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. Adjacently connected reaches were grouped into ecologically homogenous stream segments using a set of stream size and landscape similarity rules (e.g., groundwater contributions to the stream, potential for inorganic turbidity and channel bed slope).
5. Segments were grouped into classes with ecologically relevant landscape characteristics without considering network flow adjacency.
6. Segments were grouped into broad geo-climatic regions.

For AECV1 we created a characterized inventory of all stream reaches (≈410,000) in Ontario via remotely sensed data (e.g., geology) and then reduced this complexity by grouping and classifying. The reaches were grouped into 335,000 stream segments, and these segments were classified into 16 stream classes (Figure 1). The variables driving the classification are hydrological and thermal regimes (i.e., base flow index), perennial turbidity, and channel slope. Geo-climatic productivity regions further inform the context for the classes. These regions are the product of combing information on growing degree-days and terrestrial ecozones, which relate to the conductivity of water. Lakes were incorporated into the AEC spatial framework to predict their influence downstream of their outlets. The AECV1 is a hypothesis and an attempt to capture major ecological differences among streams in Ontario. Like all hypotheses, it will change and improve with additional knowledge.

Products and tools

To create AECV1 we developed several data products and automation tools. We enhanced the Ontario Hydrographic Network (OHN) by explicitly integrating waterbodies into the stream network, creating a new base data product for the province. Ontario has many lakes that influence river ecology and cannot be ignored when trying to understand river and stream ecology. We integrated lakes into the network hydrography, meaning they are now explicitly spliced and connected into the stream networks. Aside from properly representing hydrologic connectivity between still and flowing aquatic systems, this coupling enables many leading-edge scientific research opportunities such as complex lake-network interaction analyses. From this integrated stream-lake network, we determined that Ontario has about 410,000 stream reaches and 300,000 virtual connector reaches in lakes.

The reach scale attribute data was calculated for each reach in the province using ArcGIS Zonal Statistics toolboxes. We developed a custom MATLAB-based application called Network Catchment Attribute Tool (NCAT). The tool automates the process of calculating upstream catchment attribute summaries for each reach (e.g., per cent forest cover upstream) as well as assigning other network metrics such as stream order (Horton 1945, Strahler 1952) and confluence symmetry ratio. The final attribute count for each reach was over one thousand fields across several data categories (e.g., landcover, geology, climate) and collection scales (e.g., reach contributing area, total upstream contributing area).

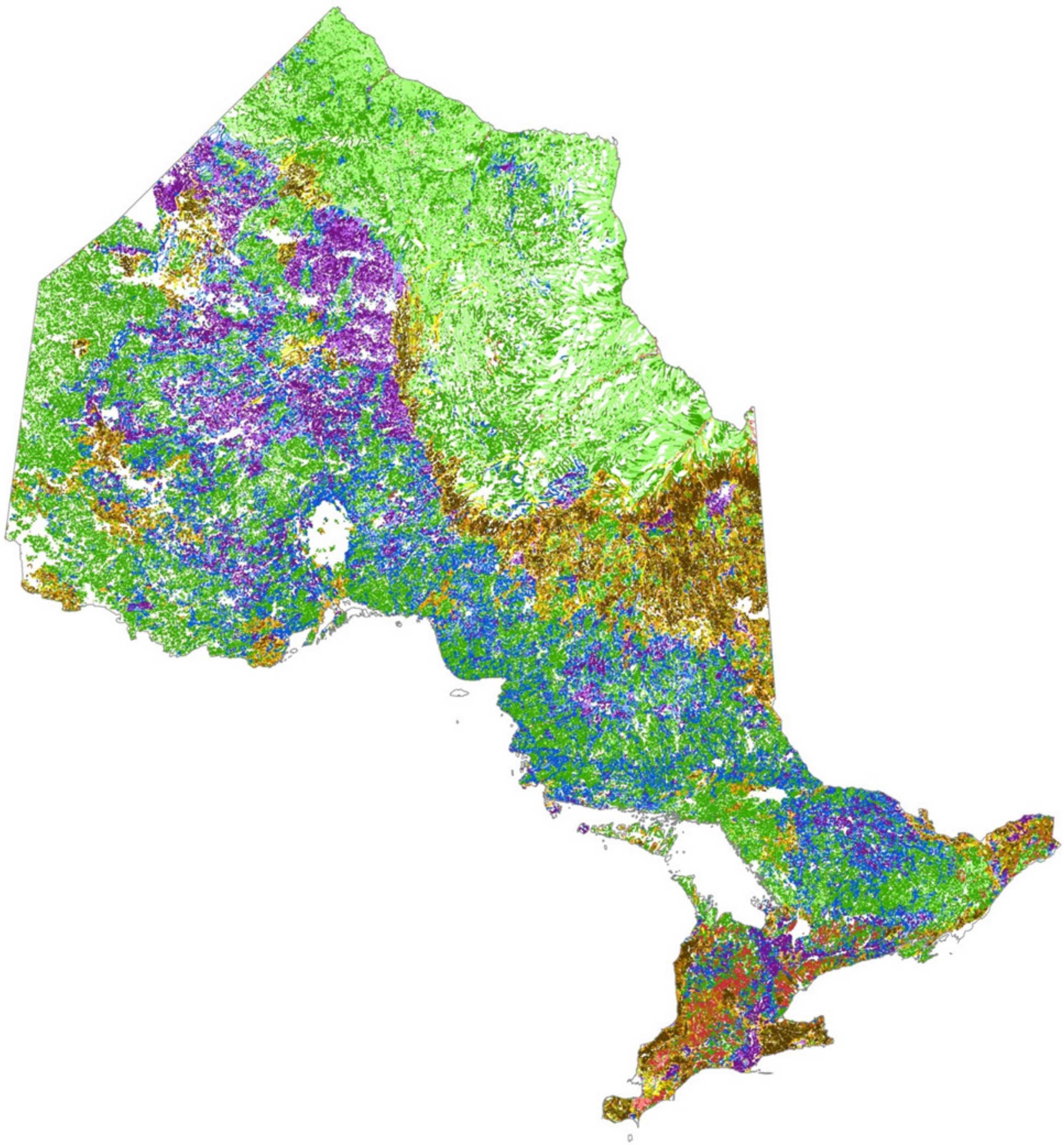

Figure 1. An overview of the aquatic ecosystem classification version 1 showing colour-coded streams. At this scale, individual streams are not evident but regional patterns in stream types are clear.

The complexity of the stream reach inventory database was immense and needed to be reduced to improve ecological meaning and understanding. To reduce complexity, we developed a custom application called the Reach Affinity Tool (RAFT), a network-based tool that is programmed using Matlab. The tool is used to cluster stream reaches into ecologically homogenous stream segments based on reach adjacency, stream size, and landscape character similarity. It can also be used to cluster all virtual reaches in a lake into one lake segment. This clustering tool also smooths out subtle variation in stream attributes while maintaining substantial breaks in stream character along the network. Without this smoothing, breaks in class types along the stream networks would be more common. RAFT has its roots in the Valley Affinity Search Technique (VAST) software developed by researchers at the University of Michigan (Brenden et al. 2008), with many enhancements incorporated to make it suitable for use in an Ontario context.

Consultation with end users: Identifying issues and limitations

From 2013 to 2018, we travelled the province talking about the AEC (e.g., at regional fisheries workshops) and meeting with groups of aquatic resource professionals to review digital AEC maps (KMZ files in Google Earth) and to describe how the AEC was made, how it should/should not be used, and to “virtually canoe the river” with participants. Each meeting lasted 3 to 4 hours and typically included participants from a variety of agencies. We held meetings with staff of MNRF in Guelph, Midhurst, Owen Sound, Sault Ste. Marie, Timmins, and Thunder Bay; staff of conservation authorities (Halton Region, Credit Valley, Central Lake Ontario, Grand River, Toronto Region, Upper Thames, Mississippi Valley, Nottawasaga Valley); members of Ontario Federation of Anglers and Hunters in Peterborough, and staff of Department of Fisheries and Oceans in Sault Ste. Marie. These meetings were valuable and informative. They proved to be great opportunities to learn about what we got right and wrong in the AECV1, how users might interact with the classification media (e.g., digital maps), and how they anticipate using the classification.

Meeting participants identified that the AECV1 classifies about 90% of streams in Ontario correctly. The remaining 10% need to be vetted through those familiar with streams, as some are rare, have base data issues (e.g., missing waterbodies), or are extraordinarily special cases/conditions in Ontario. The AECV1 has several known limitations related to base data issues and base flow index, particularly in Northern Ontario. Several of these limitations are outlined below.

Karst stream segments: Some streams are found in karst networks and all or part of their flow can disappear underground for several hundred metres. These are not captured in the classification. Several of these streams occur along the Niagara Escarpment.

Deeply incised valleys: Some headwater areas (e.g., Bowmanville Creek near Enniskillen, Willow Creek near Midhurst) have deeply incised valleys that have cut down into geology types that differ from the mapped surficial geology. The surficial geology for the headwaters of Bowmanville Creek are largely Halton Till, which is predominantly silt to silty clay matrix that does not convey much groundwater to the stream. The stream, however, cuts down into the underlying geology layers of the Oak Ridges moraine, which consist predominately of gravel and sand, including esker, kame, and end moraine deposits, all of which can contribute a lot of groundwater. As a result, the base flow index value, which is an interpretation of how much groundwater is provided by the surficial geology types, is incorrect.

Mismatches in flow contribution area: Some headwater streams associated with spring upwellings are not mapped because in AECV1 streams must have a 1 km^2 catchment area cut off. These unmapped streams result from high volume springs that might be 1 to 3 m wide at their source (Figure 2). Such streams are most common where the geology consists of highly permeable sands and gravel deposits (e.g., Oak Ridges Moraine).

Figure 2. Illustration of a stream that is not included in the AECV1: Albemarie Brook north of Wiarton is fed by three spring upwellings in the headwaters but the AEC 1 km^2 threshold does not include the stream near the road at the bottom of the picture (green line is the AEC stream reach); this stream reach is also not shown on the Ontario Hydrologic Network

Base data realities: The AECV1 is only as good as the data used in its development. In many instances spatial mapping and attribute information for local geology is incorrect, and both issues can influence turbidity production and groundwater potential. This is perhaps not surprising because the Quaternary geology layer is at the 1:1,000,000 scale and covers the entire province. Locations of transitions between geology types (polygon borders) are a rough approximation. This scale mismatch becomes more noticeable when using the data to assign groundwater potential for small headwater streams due to the scale mismatch, but certainty in stream types increases as upstream catchment area increases.

Some streams are incorrectly routed (networked) based on flow direction and upstream catchment area. We have found several instances in the Ontario Hydrographic Network (OHN). One example is Bannerman Creek, which has been the main outlet from Onapping Lake since a dam was installed on the Onapping River outlet, which is not reflected in the network flow. Another area is the upper Credit River involving Roger's Creek, Shaw Creek, and Silver Creek, where the GIS network flow direction does not match the actual flow.

The fundamental spatial framework of the AEC includes a rule that excludes stream lines that have an upstream catchment area of less than 1 km^2. This rule was applied to provide a consistent drainage density and to reduce the likelihood of intermittent streams being included in the AEC.

Some areas of the province show every rivulet in clay-dominated agricultural areas whereas on the Canadian Shield many streams were missed during the photogrammetric mapping process. Sites of some field sampling initiatives may be on streams that are below this threshold (i.e., catchments smaller than 1 km^2) and therefore do not have an AEC stream reach that can be associated with them. This can occur in instances of streams that have a spring (Figure 2). For most of these reaches not mapped in the AECV1, associated sites can be assumed to have the same characteristics as the AEC class immediately downstream. Comprehensive guidance for how to deal with theses reaches will be provided in version 2 of the AEC.

Turbid streams: In turbid streams, sunlight cannot penetrate the water to produce attached algae and aquatic macrophytes. In turn, energy sources for the stream are mainly from leaves and dissolved organic carbon imported from the landscape. Turbid streams often harbour different invertebrate and fishes (e.g., sauger (*Sander canadensis*), mooneye, catfishes vs. trout, char) than are found in clear water streams because they employ different foraging strategies.

The turbidity layer in the AECV1 was meant to represent streams that are perennially turbid, even during low flows. This means that the streams are turbid for >90% of the year and are typically associated with fine glacial lake deposits (e.g., silt and clay).

Turbidity in streams is largely a function of clay geology underlying the river channel, and not necessarily the upstream catchment valley areas. For instance, a large lobe of clay in the headwaters of a drainage may not produce turbidity downstream because it is not connected to the stream channel during low flow conditions. A prime example of this is the perennially turbid Pic River near Marathon, where the upstream catchment has relatively little clay geology but the geology underlying channel is largely clay for many kilometres upstream from Lake Superior.

Some Quaternary geology type polygons in southern Ontario are not homogeneous. 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 are generally clearer than those near Sarnia. Tavistock Till is predominantly found in three large polygons near Chatham-Kent, London, and Shelburne. This geology type is composed of sandy silt to silt matrix, with silty clay matrix in south, and in the north moderate to high carbonate content, with clast content decreasing from moderate to poor northward. Streams south of Chatham-Kent are turbid whereas to the north the streams are clearer but still in the Tavistock Till. This heterogeneity within geology polygons makes modelling difficult because the same geology type has two turbidity levels. As a result, large heterogenous polygons were manually split to reflect regions with differing turbidity-producing potential.

Several small deposits of glaciolacustrine clay in southern Ontario do not generate turbidity and we do not understand why but perhaps the clay material is different from that in other areas or the geology description is not accurate. Some of these deposits exist in the Greater Toronto Area and from Campbellford to Mallorytown. In these cases, the geology polygons were removed when considering turbidity-producing potential.

Mornington Till (6) just west of St. Jacobs is composed of silty clay matrix, with moderate to high matrix carbonate content, is clast poor, and does not generate turbidity. In version 2 of the AEC this geology type will be removed from the list of geologies that can produce turbidity. Similarly, some geology types (including 4, 8, 15, and 21) will be removed because they do not generate perennial turbidity. This new grouping of geologies leaves types 24, 26, and 29, which are fine glaciolacustrine sediments (Ontario Geological Survey 1997).

Although the AEC bins turbidity as either turbid or clear, we recognize turbidity levels are a gradient across Ontario that reflect the types of geology and per cent coverage in each drainage. Many rivers are seasonally turbid (spring and fall) and some respond to summer rainstorm events. The turbidity levels in the AEC relate to summer low-flow turbidity. Many rivers are in agricultural areas in which turbidity levels are affected directly by soil erosion and indirectly through nutrient additions that promote phytoplankton. These rivers are often a khaki to jade green colour during low flow conditions in summer. Bioturbation from the activities of fish (e.g., carp), mammals (e.g., muskrats), and cattle in many streams can persistently increase turbidity levels but this may not be captured in the AEC.

Base flow index: 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: coarse and fine textured sediments, till, shallow bedrock, and organic deposits (Piggott and Sharpe 2007).

Because BFI is a measure of potential groundwater contribution to stream flow and groundwater is cold, users often interpreted the BFI levels as stream temperature. This assumption worked well in southern Ontario. This is because most streams (>90%) in southern Ontario are relatively small (<100 km^2) and are strongly influenced by local catchments characteristics. However, this approach did not work as well in Northern Ontario, particularly for larger rivers (>2000 km^2 catchment area). These rivers had large amounts of groundwater in headwater areas, which resulted in a relatively high BFI much further downstream because of the cumulative nature of this metric. On the map they appeared as very large and cold trout streams when we knew they were much warmer. This is not surprising given that, when stream size increases, the influence of BFI on their thermal character diminishes and air temperature and drainage size increasingly become the dominant drivers of water temperature. This effect can be attributed to the reduced ability of riparian trees to provide shade, allowing more of the rivers’ surface to be exposed to solar radiation that heats the water.

Proposed changes for version 2 of the classification system

Changes in version 2 will include replacing BFI values with model predicted average July temperature and refining the turbidity classification. The BFI values are abstract and more difficult to interpret than water temperature. It is well-known that water temperature is highly dependent on air temperature and drainage size (Caissie 2006) and that BFI is only part of the story. BFI values will still be provided but not used to classify. In version 2, we will attempt to predict average July water temperature for every reach. We will also use 30 years of climate data to generate 30 predictions for average July temperature to provide a distribution and the ability to estimate probabilities for each thermal class. The turbidity layer will be refined by excluding some geology types and setting different thresholds of 10, 8, 6, and 4% clay geology in the catchment for streams with respective drainage areas of <500, 500–5000, 5000–50,000 and >50,000 km^2.

Summary and conclusions

The first version of the AEC was developed over several years and involved reviewing aquatic classifications worldwide, assessing client needs, and compiling a technical proposal. As well, base data products were created, and several custom computer programs were developed to manipulate the underlying data. The many stakeholder meetings have provided a wealth of feedback and advice that can be used to fine-tune the classification.

Given the overwhelmingly positive responses to version 1 of the AEC and the documented need for this product in several business areas in MNRF and other agencies, efforts to develop a version 2 seem warranted. We have learned how we can improve the AEC in some areas and, where improvements are not possible (e.g., base data), we can document the issues and limitations for users.

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Résumé

Classification des écosystèmes aquatiques, version 1 : une révision et une orientation future

La classification des écosystèmes aquatiques (CEA), un outil scientifique, permet de catégoriser les cours d'eau de l'Ontario (rivières et ruisseaux) se déversant dans des tronçons et des segments de cours d'eau plus grands selon leurs attributs physiques et les caractéristiques du bassin versant. Cette note récapitule la conception de l'outil CEA de l'Ontario; elle documente les questions et les lacunes ressorties des consultations avec les utilisateurs finaux, et indique la nécessité d'une mise à jour basée sur les commentaires et suggestions de ces derniers.

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