Ontario

Aquatic Research and Development Section
Ministry of Natural Resources

Aquatic Research Series 2013-05

Aquatic Ecosystem Classification for Ontario
A Technical Proposal

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June 2013

Aquatic ecosystem classification for Ontario: a technical proposal

Printed in Ontario, Canada

MNR 52730
ISBN 978-1-4606-2508-8 (Print)
ISBN 978-1-4606-2509-5 (PDF)

This publication was produced by:

Aquatic Research and Development Section
Ontario Ministry of Natural Resources
2140 East Bank Drive
Peterborough, Ontario
K9J 8M5

Online link to report can be found at:
Ontario.ca/aquaticresearch

This technical report should be cited as follows:
Melles, S., N. Jones, and B. Schmidt. 2013. Aquatic Research Series 2013-05: Aquatic ecosystem classification for Ontario: a technical proposal. Ontario Ministry of Natural Resources. 52 pp.

Cover photo: James Bay
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Executive Summary

An aquatic ecosystem classification would map Ontario's aquatic ecosystem types so that resource managers can better target planning, management, and monitoring efforts across both small and large spatial scales. The foundation of the classification is an inventory database of over 2 million stream reaches and their landscape attributes. These stream reaches represent the smallest spatial unit. Using this database and various other advanced geomatics techniques, we will reduce this complexity to more manageable numbers of units produced at larger spatial scales. We propose an ecological 'master view' that will have broad applicability to resource managers and planners. This master view will be created by focusing on abiotic characteristics of the components (e.g. flow, temperature, nutrient and sediment regimes). The same method used to create the master view also allows other 'views' to be generated. A view will have cartographic representations and will be manifested in mapping products specific to a planning or management requirement.

It is widely recognized that a spatial framework and associated inventory database for aquatic assessment and policy development is needed for landscape level planning. A number of identified Ministry-wide user needs would be served by the creation of an Aquatic Ecosystem Classification (AEC) for Ontario as described in *Section 2* of this report. These needs include:

1. **Landscape-based planning tool** to support;
    a. sustainable and strategic resource use and development (e.g. renewable energy projects, forestry, and mining);
    b. community-based land-use planning initiatives in the Far North;
    c. assessment of ecological risk at regional scales.

2. **Identification of representative aquatic ecosystems** for parks and conservation reserve planning i.e. unique aquatic systems that require protection as aquatic class parks under the *Provincial Parks and Conservation Reserves Act* (PPCRA 2006, Section 8,8) and partners share a similar interest for acquiring and managing lands.

3. **Stratification of the Province into aquatic regions** for data sampling, inventory and monitoring to facilitate:
    d. the design of efficient field surveys, inventory, and monitoring of freshwater aquatic features and biota (e.g. aquatic species at risk);
    e. assessment of Broad-Scale Lakes Monitoring data;
    f. State of the Resource Reporting;
    g. Extrapolation of knowledge from data rich to data poor areas with similar aquatic ecosystem characteristics.

This report presents technical information about the proposed *AEC for Ontario*. We base the proposal on thorough reviews of the scientific and technical literature and on a detailed understanding of available provincial datasets. We recommend a multi-scale classification with five levels. Each level in the classification should stand alone and be designed to capture key processes relevant to its particular spatial scale. The spatial units at different scales will be relevant for a variety of land use planning, monitoring, and reporting purposes. A combined geo-

climatic and hydro-chemical classification is recommended because such an approach would capture the key underlying process regimes critical to aquatic ecosystem function (i.e. the streamflow, temperature, nutrient and sediment regimes); and such an approach would be based on available provincial datasets (e.g. gridded climate data, surficial geology, landcover, digital elevation data) as well as measures that capture the directional and connected nature of aquatic networks.

We briefly review the different approaches to ecosystem classification around the world (*Section 3*). We are now in a position to create a classification system for the province that will improve upon existing approaches for Southern Ontario using the most current datasets for rivers and lakes throughout all of Ontario, which have recently become available. General recommendations that apply to the classification process as a whole are summarized in *Section 4*. We propose using newly developed and more objective approaches to ecosystem identification (*Section 5*).

We then provide an outline of the proposed classification along with options for its design/implementation (*Sections 6*), as well as a brief discussion of limitations (*Section 7*), the need to validate the classification (*Section 8*), a roadmap of next steps (*Section 9*), and potential linkages to other projects (*Section 10*).

Résumé

La classification des écosystèmes aquatiques consiste à cartographier les types d'écosystèmes aquatiques de l'Ontario de sorte que les gestionnaires de ressources soient en meilleure mesure de cibler les activités de planification, de gestion et de surveillance, à petite comme à grande échelle spatiale. L'élément fondamental de la classification est une base de données d'inventaire contenant plus de 2 millions de tronçons de cours d'eau et leurs caractéristiques paysagères. Ces tronçons de cours d'eau constituent la plus petite unité spatiale. À l'aide de cette base de données et de diverses autres techniques géomatiques avancées, nous réduirons cette complexité en un nombre plus gérable d'unités produites à une plus grande échelle spatiale. Nous proposons de réaliser une « vue d'ensemble » avec un large potentiel d'applicabilité pour les gestionnaires et les planificateurs de ressources. Cette vue d'ensemble sera réalisée en misant sur les composantes des caractéristiques abiotiques (p. ex., écoulement fluvial, température, régimes nutritif et sédimentaire). La méthode utilisée pour créer la vue d'ensemble permettra aussi de générer d'autres catégories de vues. Chaque vue aura des représentations cartographiques et sera concrétisée en produits cartographiques spécifiques répondant aux exigences en matière de planification ou de gestion.

Il est généralement admis que pour la planification à l'échelon des paysages, il est nécessaire d'avoir un cadre spatial et une base de données d'inventaire associée pour les besoins de l'évaluation aquatique et de l'élaboration de politiques. Bon nombre des besoins des usagers documentés à l'échelle du ministère seraient comblés par la création d'une classification des écosystèmes aquatiques (CEA) pour l'Ontario tel que décrit à la *section 2* du présent rapport. Parmi ces besoins, citons les suivants :

4. **Outil de planification à l'échelon des paysages** pour servir les besoins suivants :
    - h. utilisation et élaboration durable et stratégique des ressources (p. ex., projets d'énergie renouvelable, de foresterie et d'exploitation minière);
    - i. initiatives communautaires d'aménagement du territoire dans la Grand Nord;
    - j. évaluation des dangers écologiques à l'échelle régionale.

5. **Détermination des écosystèmes aquatiques représentatifs** pour les besoins de la planification des parcs et des réserves de conservation, soit des systèmes aquatiques uniques qui nécessitent une protection à titre de parcs aquatiques en vertu de la *Loi sur les parcs provinciaux et les réserves de conservation* (2006, paragraphe 8.8) et les partenaires partagent le même intérêt à l'égard de l'acquisition et de la gestion des terres.

6. **Stratification de la province en régions aquatiques** pour l'échantillonnage des données, l'inventaire et la surveillance en vue de faciliter les activités suivantes :
    - k. conception de sondages efficaces sur le terrain, d'inventaires et de projets de surveillance des caractéristiques aquatiques d'eau douce et du biote (p. ex., espèces aquatiques en péril);
    - l. évaluation des données du programme à grande échelle de surveillance des pêches;
    - m. rapports sur la situation des ressources;

n. extrapolation des connaissances sur les zones riches en données vers les zones pauvres en données dotées de caractéristiques similaires en matière d'écosystèmes aquatiques.

Dans ce rapport les auteurs présentent des renseignements techniques sur la proposition intitulée *AEC for Ontario (Classification des écosystèmes aquatiques en Ontario)*. Cette proposition se fonde sur une analyse approfondie des publications scientifiques et techniques et sur une connaissance détaillée des jeux de données provinciales disponibles. Nous recommandons d'adopter une classification à différentes échelles et comportant cinq niveaux. Chaque niveau de la classification devrait pouvoir être autonome et a été conçu pour capturer les processus clés qui sont pertinents pour l'échelle spatiale concernée. Les unités spatiales des différentes échelles seront utiles à diverses fins associées à l'aménagement du territoire, la surveillance et la préparation de rapports. Une classification mixte géoclimatique et hydro-chimique est recommandée parce qu'une telle approche tiendrait compte des régimes clés sous-jacents qui sont essentiels au fonctionnement d'un écosystème aquatique (c.-à-d., écoulement fluvial, température, régimes nutritif et sédimentaire); et une telle approche serait fondée sur les jeux de données provinciales disponibles (p. ex., données climatiques maillées, géologie des dépôts superficiels, couverture végétale, données d'élévation numériques) ainsi que sur des mesures qui rendent compte de la nature directionnelle et interreliée des réseaux aquatiques.

Le rapport présente un bref survol des différentes approches à l'égard de la classification des écosystèmes à travers le monde (*section 3*). À présent, nous sommes en mesure de créer un système de classification pour la province qui améliorera les méthodes existantes pour le Sud de l'Ontario et qui se base sur les ensembles de données les plus récentes, disponibles depuis récemment, pour les rivières et les lacs de l'ensemble de l'Ontario. Les recommandations générales qui s'appliquent au processus de classification dans son ensemble sont résumées à la *section 4*. Nous proposons d'utiliser pour l'identification des écosystèmes des approches nouvellement mises au point et plus objectives (*section 5*),

Ensuite, le rapport présente un aperçu de la classification proposée de même que des options pour sa conception et sa mise en application (*section 6*), ce qui est suivi d'une brève discussion sur les contraintes (*section 7*). Viennent ensuite la nécessité de valider la classification (*section 8*), une feuille de route pour les prochaines étapes (*section 9*) et les liens potentiels avec d'autres projets (*section 10*).

1 INTRODUCTION

Generally speaking, ecosystem classification is the process of mapping ecologically distinctive areas on earth. Currently, Ontario has a land-based mapping system that identifies unique terrestrial ecosystems based on climate, geology, soil type, and vegetation cover, known as the Ecological Land Classification (ELC) system. This land-based system does not adequately represent the diversity of aquatic ecosystems in the Province. The design of an aquatic classification requires consideration of the diversity of watersheds in Ontario. Unique aquatic ecosystem classes are defined as areas that are homogeneous in the characteristics of interest. Our overall goal is to establish a comprehensive and consistent province-wide approach to aquatic ecosystem description, inventory, and interpretation that can complement the current terrestrial system. The aim is to capture the true nature of ecological processes operating in these systems. Similar classes should respond similarly to natural and anthropogenic disturbances, and thus, should respond well to class specific management.

In this report, we provide technical information about the proposed Ontario-wide *Aquatic Ecosystem Classification (AEC)* along with options for its design and implementation. As the proposed framework is based on reviews of the scientific literature (Melles et al., 2012; Melles et al., 2013; Melles et al., *in review*) and on a survey of OMNR, 'Client Needs' for an AEC (Melles et al., 2011), the reader is referred to those papers and reports for further information and background reading. Here, we first briefly review why the Province of Ontario needs an AEC. Second, we briefly review different ecological classification approaches in use around the world. Third, the majority of this technical report outlines the proposed classification and general recommendations for developing an Ontario-wide AEC. We also discuss validation of the classification and next steps from this point forward.

2 WHY DOES ONTARIO NEED AEC?

Aquatic Research and Development Section circulated a Client Needs Survey on Aquatic Ecosystem Classification (AEC) in April 2011 to ascertain how various branches and sections within the Ministry of Natural Resources could use an Aquatic Ecosystem Classification. Objectives of the survey were to: raise awareness; form an aquatic classification science team; and document the needs of our internal MNR clients. A section level response was requested and 17 sections from four divisions completed the survey. Comments were received from an additional five sections. The vast majority of respondents confirmed the utility of a province-wide aquatic classification in relation to a wide variety of user-needs including (Figure 1):

- strategic planning for resource use and development (e.g. renewable energy projects);
- surveying and inventory (i.e. monitoring) of aquatic features and biota;
- identification of sites that may support species at risk;

Indeed, more than 95% of OMNR section respondents would find an AEC 'useful' to 'somewhat useful' for these purposes (refer to Melles et al., 2011 for more details). As one respondent put it,

> "*Watershed and catchment-based aquatic ecosystem classification serves as the basis for so many aspects of resource assessment, inventory, mapping, evaluation, monitoring, research,*

planning and reporting, that the objectives stated in OMNR's broad policy statements are really only achievable if a consistent and comprehensive tool like AEC is developed".

Survey respondents also identified a number of provincial and federal acts, policies, directions, and guidelines that would be supported by an aquatic ecosystem classification (e.g. Ontario's Biodiversity Strategy, Endangered Species Act, the Far North Act, Fisheries Act, and Watershed-based Fisheries Management Planning Guidelines).

An AEC system would support landscape-level planning by:

(i) Creating a framework for reporting on aquatic ecosystems.

(ii) Stratifying the Province for assessments and summaries of broad-scale monitoring data and landscape-based assessments of aquatic ecosystem risk and sensitivity;

(iii) Helping to identify unique aquatic ecosystems that require protection under the new Provincial Aquatic Parks Class (Provincial Parks Act, PPCRA 2006, Sec.8.8);

(iv) Providing an ecological basis for community-based planning in the Far North in relation to surface waters;

(v) Supporting extrapolation from data rich to data poor areas with similar aquatic characteristics.

This is not the first AEC system proposed for Ontario. Mandrak (1999) developed an aquatic classification system for Ontario applicable at an eco-regional scale (tens of thousands of square kilometres). He defined regions based on climate, bedrock geology, surficial geology, and glacial history, which were then related to regional fish community patterns (ichthyoregions), but finer scales (e.g. quaternary watersheds, ~500 km^2) were not classified. The most recent aquatic ecosystem classification in Ontario was done for the Great Lakes drainage area under the Blueprint project. The Blueprint project was a joint initiative between Nature Conservancy of Canada (NCC), OMNR, and the Natural Heritage Information Centre (NHIC), which began in 2001. The goal was to produce aquatic targets for biodiversity in the Great Lakes basin (Phair et al., 2005; Wichert et al., 2005). There are some issues with the Great Lakes Blueprint AEC that make it difficult to simply extend the approach throughout the rest of the Province of Ontario. First, the Blueprint classification is not based on variation in key aquatic process regimes like climate, hydrology, and temperature and therefore it does not adequately capture climatic variation or longitudinal patterns in stream temperatures (Chu and Jones, 2010), though these are important factors at both regional and provincial scales. Second, given the current emphasis within the OMNR on biodiversity, the Blueprint's focus on aquatic regions that correspond primarily with fish faunal distributions may be insufficient when other taxonomic groups with various dispersal mechanisms are considered (e.g. aquatic plants and invertebrates). Third, many of the attributes used to classify lakes and wetlands were defined by expert opinion. For example, the attribute 'geologic permeability' or 'permeability to cold water species' was defined as a measure of the relative contribution of precipitation to ground and surface water, and the variable was estimated based on percent cover of surficial geology (i.e. well, moderate, and poorly drained soils) in upstream contributing areas. However classification cut-points were subjectively derived and can be improved by modelling baseflow and groundwater potential as a function of geology and topology (Piggott et al., 2002; Neff et al., 2005; Borwick et al., 2006; Piggott, 2007; Olden et al., 2011).

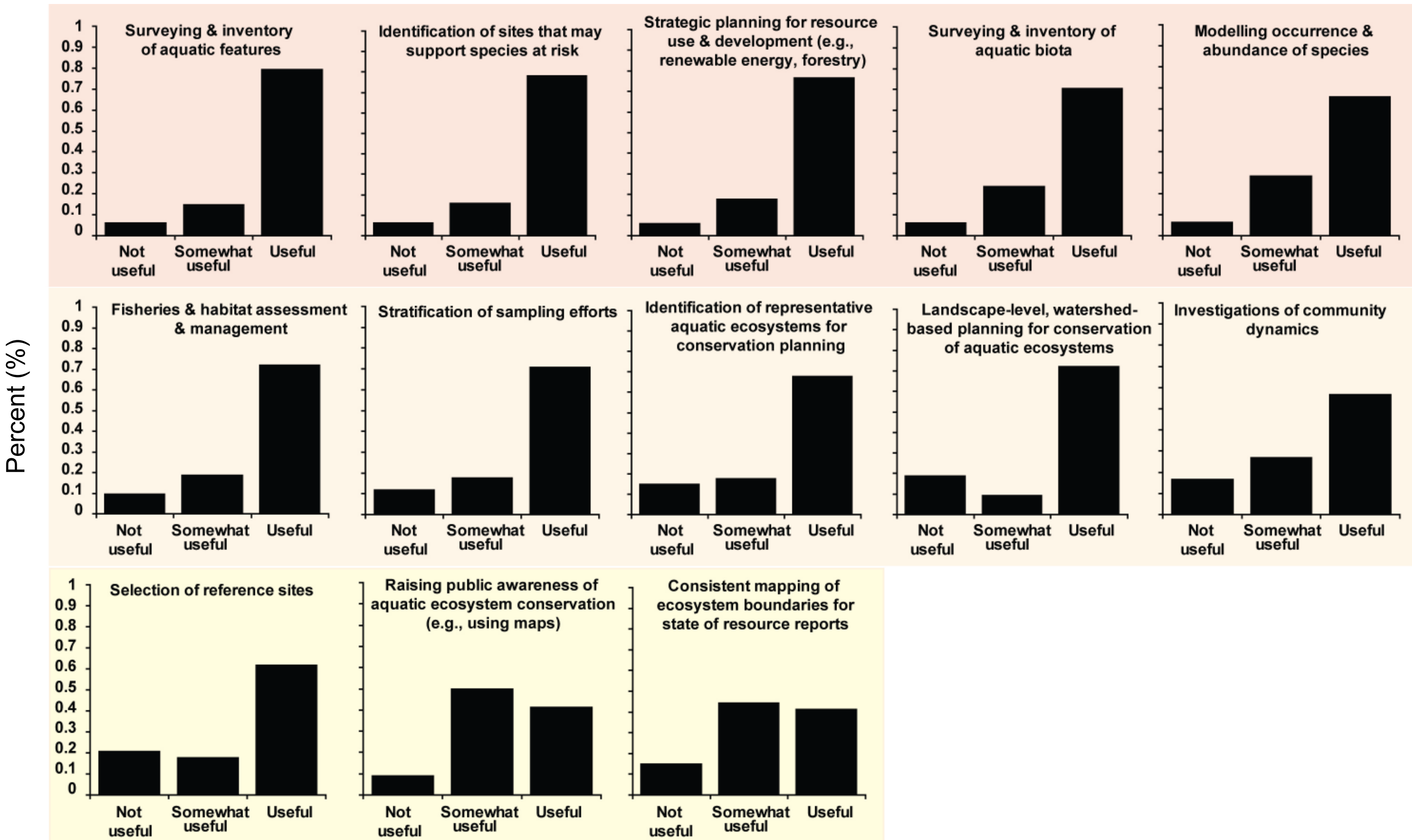


Figure 1*: Summary of responses to user needs for a Province-wide, aquatic ecosystem classification based on a sectional response (n = 17, from Melles et al. 2011). Colours (red, orange, yellow) are subjective groupings depicting higher or lower agreement amongst the sections for that particular user need.*

3 PROJECT SCOPE

Ideally, the full spectrum of diversity in Ontario's freshwater ecosystems would be represented in an all-inclusive aquatic classification. This spectrum would include five broad freshwater ecosystem types: streams, inland lakes, wetlands, the Great Lakes and the Hudson's Bay marine environment. However, for reasons of data availability and scope management we will focus on stream ecosystem classification, but we plan to integrate lakes and wetlands as follows:

1. We propose to explicitly incorporate lakes and their associated "lake-sheds" into the fundamental spatial fabric of the classification as non-divisible units, but we will not be classifying the lakes themselves in this proposal but provide the ability for future classification of lakes.
2. Lakes can be classified based on a number of metrics e.g. lake area, maximum fetch, shoreline development factor; but, without depth data for every lake, a thorough classification of lakes is not possible. In addition, the current underlying spatial fabric in GIS makes each lake, regardless of size, one unit equivalent to a stream segment. This prevents smaller scale classification of part of a lake.
3. We propose to implicitly include wetlands via the use of wetland-focused landscape descriptors, but we will not be classifying the wetlands themselves.
4. We recognize that streams feed into coastal areas of large fresh and marine water bodies (i.e. the Great Lakes and Hudson's Bay) but we will not be classifying these aquatic ecosystems or incorporating their potential upstream effect on streams. Efforts are underway to create a Great Lakes wide near-shore (i.e. coastal) ecosystem classification both in Canada and the United States under the umbrella of the recently signed Great Lakes Water Quality Agreement.

4 BRIEF REVIEW OF ECOSYSTEM CLASSIFICATION

3.1 Terrestrial Ecosystem Classification

There is a long history of ecological land classification (ELC) in Canada and the United States (Bailey et al., 1985). An ecoregion can be defined as a relatively homogeneous, ecologically distinctive area that has been shaped by a combination of factors such as geology, landform, soil, climate, water and biota (e.g. vegetation, wildlife). The Province of Ontario developed a land-based classification with six levels including ecozones, ecoregions, ecodistricts (Figure 2), as well as ecosections, ecosites, and ecoelements at finer spatial scales. The Provincial ecozones and ecoregions are largely consistent with the Federal, Canadian National ELC.

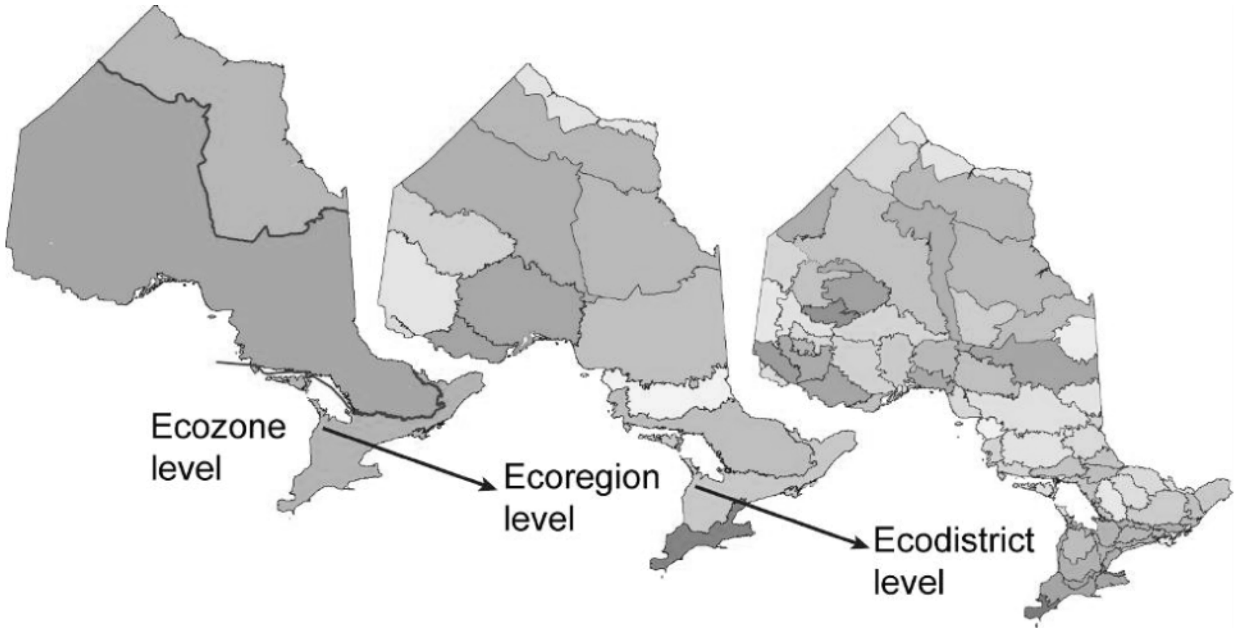


Figure 2: *The Ecological Land Classification of Ontario depicted schematically as a spatially nested hierarchy showing how upper levels completely contain, constrain, control, provide context for, and set the boundary conditions of lower levels (adapted from Crins et al., 2009 map for the ELC working group).*

Ecological land classifications are used for a multitude of purposes (e.g. parks and protected areas planning, monitoring and reporting). Currently, representation of Ontario parks is assessed at the ecodistrict scale. Within each of Ontario's 71 ecodistricts, minimum guidelines are to represent at least 1% or 50 hectares of all naturally occurring landform vegetation (LV) associations. Additionally, park class targets for ecoregions and ecodistricts include: a wilderness park, a wilderness zone, a natural environment park, and a waterway park or corridor along a waterway.

Although it is possible to use land-based ecoregional classifications to assess the potential diversity of aquatic systems and their processes (Soranno et al., 2010), there are limitations with this approach. The theoretical basis for using land-based classifications to characterize freshwater systems is the spatial interdependence of the geographic components. Aquatic systems are integrated with their surrounding valleys and landscapes through the processes of runoff, sedimentation, and migration of biotic and chemical elements (Cleland et al., 1997). Lotspeich and Platts (1997) reviewed ecological land classification schemes, noting however, that most do not attempt to integrate aquatic systems into their classification. Hawkins and Norris (2000) organized a symposium in 1998 designed to test the performance of regional land-based classifications in terms of their ability to partition the biotic variability among aquatic sites. Their main findings suggested that land-based classifications have limited application in aquatic bioassessments (see Hawkins and Norris, 2000; Omernik and Bailey, 1997 for review).

In Ontario, Mandrak (1998) assessed the suitability of the Ontario terrestrial ELC for its ability to predict aquatic biodiversity throughout the province. Consistent with findings summarized by Hawkins and Norris (2000), Mandrak (1998) found weak areal correspondence between terrestrial eco-regions and tertiary watersheds. Terrestrial ecoregions corresponded poorly with fish faunal zones suggesting that the terrestrial classification system could not be used to inform conservation of freshwater biota (Wichert et al., 2004). Chu and Jones (2010) went a step further and examined whether or not ecological land classifications of Ontario within the Great Lakes ***Basin***[1] were able to capture major differences in stream temperature at ecoregion and ecodistrict scales. Stream temperature is a critical aspect of ecosystem habitability for most species. They found that within class variation was greater than between class variation; so for example, temperatures were more variable among sites within an ecodistrict than between different eco-districts (Mandrak, 1998).

3.2 Aquatic Ecosystem Classification

In contrast to terrestrial classifications, there are fewer examples of aquatic classifications (reviews in Cowardin et al., 1979; Busch and Sly, 1992; Maxwell et al., 1995; Gordon et al., 2004; Melles et al., 2012; Melles et al., *in review*). Stream classifications based on a single variable, such as tributary confluence breaks, are the simplest form of aquatic classification (Gravelius, 1914; Horton, 1945; Mock, 1971). Most modern classifications are based on multiple environmental variables and are much more complex than this (Pennak, 1971). Complexity is generally addressed using a hierarchical or multi-scale approach in which the entire system is subdivided into groups based on various criteria that determine how objects are arranged into successively finer levels of detail (Frissell et al., 1986; Higgins et al., 2005).

There are three main approaches to multilevel, hierarchical classifications that can be found in the literature on AEC: 1) bottom-up, 2) top-down, and 3) hybrid top-down/bottom-up approaches.

3.2.1 Bottom-up Classification

Bottom-up approaches are traditionally place-independent wherein geographic location is irrelevant to the classification of a site (Bailey et al., 1978; Hudson et al., 1992). For example, Rosgen (1994) created a classification based on geomorphic stream characteristics that is entirely place-independent, such that sections of stream with similar channel slopes can be classified as the same type regardless of where they are found (Rosgen, 1994; Snelder and Biggs, 2002). Half of the 70 stream classification studies reviewed by Hudson et al. (1992) used place-independent (bottom-up) classification methods and the other half used place-dependent methods; this 50/50 ratio was confirmed by Melles et al. (Melles et al., *in review*) for more recent aquatic classifications in use since 1980. It is also possible to create regionalized classes from the bottom-up by grouping smaller aquatic ecosystem units together under spatial contiguity constraints (Brenden et al., 2008a; Snelder et al., 2010). Although it may be technically possible to create spatially contiguous classes completely from the bottom up, we found no examples in the literature (Melles et al., *in review*). Part of the difficulty arises from scaling up from ***reaches*** to segments to larger catchments, watersheds or basins while still trying to maintain homogenous units. Headwater rivers and lakes *in different* basins often share more similar abiotic (and biotic) properties than do headwater and mainstem sections within the *same* watershed (Kratz et al., 1997; Fullerton et al., 2010; Finn et al., 2011). Though headwaters are physically connected to the mainstem by flowing water, many taxonomic groups other than fish are not restricted to movement within a basin (Green et al., 2008; Neff and Jackson, 2011). Therefore, regionalized watershed classes may contain more variation within the same watershed or basin than between different basins.

3.2.2 Top-down Classification

Top-down classifications are place-dependent. They are created by subdividing broad landscapes according to observed variation in attributes of interest (Bailey, 1976; Portt et al., 1989), resulting in regionalized areas that are spatially-nested. In practice, the upper levels of regionalized, hierarchical classifications are often sketched on the basis of expert opinion and local knowledge of ecosystem characteristics (Omernik, 1987; Kleynhans et al., 2005; Higgins et al., 2005; Seelbach et al., 1997; Seelbach et al., 2006). We want to emphasize that landscape units such as political boundaries, secondary or tertiary watersheds, and fisheries management zones, which are used for management purposes can still be used post hoc for monitoring and reporting to summarize the state of aquatic ecosystem classes in a given area. We believe, however, that such boundaries should not control the results of an ecologically based classification.

3.2.3 Hybrid Classification

Many classifications solve the difficulty of creating a multi-scale regionalized classification entirely from the bottom-up by using a hybrid approach that combines top-down expert driven classification with bottom-up clustering approaches from finer spatial scales. The result is a mixture of both regionalized and place-independent classes over a range of spatial scales (an example is the classification produced by Wichert et al. in 2004).

3.2.4 Classification Variables

Explanatory variables used in aquatic classification can be abiotic, biotic, or both. They can have any scale of measurement (i.e. nominal, ordinal, interval or ratio)

3.2.4.1 Abiotic Variables

Abiotic classifications incorporate physical and chemical characteristics including numerous parameters that attempt to describe the physico-chemical characteristics of different species' habitat, often at a variety of spatial scales. There are at least four different types of abiotic classifications: geoclimatic, geomorphic, hydrologic, and chemical.

1. Geoclimatic classification systems use climate, physiography and surficial geology as the fundamental basis for classification. These classifications are based on the premise that streams draining areas with similar climate and geology will have similar biota because climate and geology are the most important drivers of species' habitat and dispersal (Lotspeich and Platts, 1997; Portt et al., 1989).
2. Geomorphic classifications take a structural engineering approach to classification and are widely used at both the reach (Rosgen, 1994) and segment scales (Frissell et al., 1986; Maxwell et al., 1995; Brierley and Fryirs, 2000). The basic premise of geomorphic classifications is that channel morphology is governed by the laws of physics through fluvial

processes and readily observable features of stream channels (i.e. valley slope, substrate characteristics, valley characteristics, and the presence of pools/rifles (Rosgen, 1994)).

3. Hydrologic classifications use numerous indices of flow to classify streams, including: measures of flow variability, stream discharge, current speed, mean daily, seasonal, annual flow, groundwater levels, baseflow, and water source (Kim and Hawkins, 1993; Zhang et al., 2011). Many authors consider flow to be a "master variable" because it is strongly correlated with many abiotic and biotic characteristics of interest in stream classification (Poff et al., 1997; Gordon et al., 2004). Source of flow influences water temperature (i.e. ground water or surface water), and flow can limit the distribution and abundance of many riverine species thereby regulating ecological integrity (Poff and Ward, 1989; Poff et al., 1997; Wichert et al., 2004).
4. Chemical or water quality based classifications are often designed to assess the physical and chemical characteristics in streams according to criteria established by various environmental protection agencies (Ahl, 1994; Dodds et al., 1998; Gordon et al., 2004). The criteria of interest attempt to capture the condition (i.e. degree of eutrophication as reflected by nutrient levels such as nitrogen and phosphorus) and toxicity of stream pollutants that negatively affect human and ecosystem health.

3.2.4.2 Biotic Variables

Biotic classifications group observational units predominantly on the basis of the presence of various taxa such as: game fish (Huet, 1959; Illies, 1961), benthic invertebrates (Wright et al., 1984; Biggs et al., 1990), aquatic plants (Pennak, 1971), and riparian vegetation (Pennak, 1971). Biotic classifications are appealing when the objective is to manage the biota (e.g. fisheries resources), but classifications based on sport or game fish alone will likely be inadequate for broader applications beyond fishes (Portt et al., 1989).

3.2.4.3 Scales of Measurement

Many variables useful for aquatic ecosystem classification are measured on a continuous gradient (e.g. the gradient of a stream reach can be any value between 0 and 90 degrees). There are two ways to address the continuous nature of such variable when classifying. Classes may be formed by binning the continuous nominal attributes using expert driven cut-points (e.g. low, medium, high stream gradient) or class boundaries may be found more objectively using the raw continuous variable as input to clustering methods that do not require *a priori* knowledge of cut-point thresholds or the number of classes.

4 GENERAL RECOMMENDATIONS

4.1 An ecological view

Based on our review of aquatic ecosystem classifications around the world (Melles et al., 2013), it is apparent that there are many perspectives on how an aquatic classification system should be developed. Indeed, any classification should be designed to allow adequate flexibility to accommodate the multitude of possible management goals and this is a guiding principle of the proposed AEC. At the same time, we recognize the need for a general, all-purpose classification that would provide a universally applicable ecological framework for Ontario. Such a framework would allow resource managers to organize their efforts more effectively across the many agencies responsible for aquatic ecosystem health in Ontario. Towards this end, we are endeavouring to create a 'master ecological view' for Ontario, one that will describe streams using the abiotic template in terms of the most basic habitat conditions that all lotic organisms share (e.g. streamflow patterns, stream temperature patterns, nutrient availability and sediment supply). This generalized 'master view' could then be interpreted more specifically. For example, one could focus on unique aspects of the abiotic template that identify ideal brook trout habitat (e.g. baseflow predictability, cold water temperatures, riparian shading, and water clarity (Stanfield et al., 2006).

If a specific management objective can not be accommodated by the 'master view', then the inherent flexibility of this AEC could be called upon to develop a 'custom view' specifically designed for the task or question of interest. For example, managers may be interested in a classification that shows which aquatic systems are likely to have high biodiversity and connectivity (Eros, 2012). Others might be interested in setting water quality criteria which is very difficult without an understanding of underlying regional variation and cumulative network effects. It is our intent that the River and Stream Ecology Lab would assist any client in the development of their custom views in order to maintain consistency and continuity in the AEC's application

4.2 The reach attribute database

We propose building a landscape characteristics database that enables the creation of the 'master view' and also provides the necessary data to assemble any 'custom views' (Wang et al., 2011; Melles et al., 2011). This database will use interconfluence reaches and their channels, reach contributing areas and upstream contributing areas as fundamental spatial units to collect the landscape characteristics (Figure 3)(Wang et al., 2011).

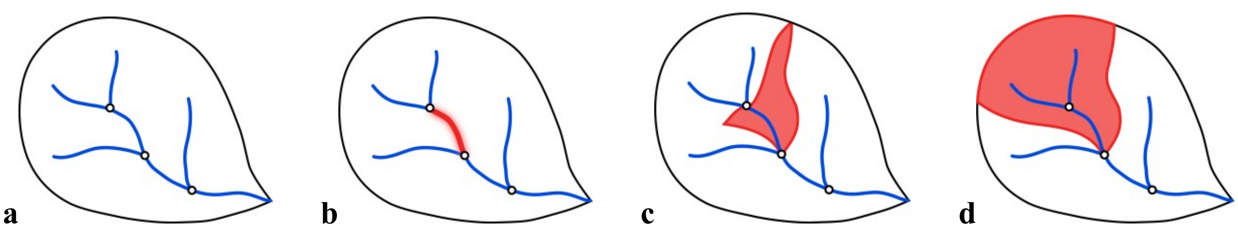


Figure 3: *a) A hypothetical stream network including its confluence points and watershed boundary; b) An interconfluence reach channel; c) A reach contributing area; d) An upstream contributing area.*

The database will be populated by attributing each reach with a wide variety of landscape variables via GIS (e.g. channel characteristics, thematic summaries, zonal statistics, model-derived variables, and anthropogenic factors known to influence aquatic ecosystems: like road network densities). Supporting GIS layers could also include a series of ecological and political spatial boundaries (e.g. Ecoregions, Fisheries Management Zones, Ecological Drainage Units, Primary, Secondary and Tertiary watersheds). This database will allow users to extract and analyze information as required. The advantage of this holistic landscape approach is that it considers both terrestrial and aquatic ecosystem components and the linkages between them. It has long been known that aquatic ecosystems are influenced by the landscapes that surround and support them (Hynes, 1975). Similarly, terrestrial landscapes are shaped and sustained by the linkages and flows that aquatic ecosystems provide (Poole, 2010). This interconnectedness is also reflected in Aboriginal traditional knowledge, which does not distinguish between land and water. So there are very good scientific and cultural reasons to use an approach that integrates information from the land (e.g. abiotic contributing area variables) and models their relationships with key aquatic process regimes. The merits of this approach are discussed in more detail in Melles et al. (2012).

4.3 Data availability

There are practical advantages to the abiotic approach, which are related to data availability and the cost of information required. All of the process variables we recommend either exist already or can be mapped using predictive methods (e.g. modelling and interpolation). Much of the abiotic information is currently available and these datasets are constantly updated from remotely sensed satellite platforms or existing monitoring networks (e.g. climate stations, hydrometric gauges). These datasets permit the modelling and identification of aquatic characteristics at multiple spatial scales. In contrast, classifications based on biota require detailed knowledge of species abundance and distributions as well as their natural history and habitat characteristics. This type of information is generally not available across vast areas like the Province of Ontario – and particularly not in the Far North; nor is it easy or economical to obtain comprehensive and reliable biotic data.

4.4 Network complexity

We originally intended to focus on attributing 2nd order reaches or higher by simply removing 1st order streams from the stream network. The Blueprint Project mentioned earlier took a similar approach by omitted 1st and 2nd order streams from that classification. However, removing all 1st order streams will remove reaches that can vary substantially in length, particularly when different geologies are compared (*see* Hughes and Omernik, 1983). Stream order can also be considered a subjective measure for a variety of reasons: assignment of stream order varies depending on selection of a particular mapping scale; it is difficult to map the origin of perennial streams; and stream reaches of the same order can have considerably different discharges (Poole, 2010). Thus, we now plan to use upstream catchment area as removal criterion in place of stream order in aquatic classifications (e.g. Snelder et al., 2007; Brenden et al., 2008b; Soranno et al., 2010). This is a less subjective approach because the streams that are removed are more likely to be similar in size. However, one technical question remains: the choice of the area threshold below which streams are removed. The challenge is to select a single threshold that can be applied optimally across all of Ontario to account for the differences in underlying geomorphological conditions. Another option is to use a hybrid approach where a first selection pass identifies 1st order streams and then a subsequent pass identifies streams below a contributing area threshold of the 1st pass sub-set.

Regardless of the method used there are several advantages to reducing network complexity by weeding out low-order stream reaches: (i) the number of interconfluence reaches would be reduced by as much as 50% (assuming all 1st order streams are removed), thereby reducing processing time or allowing larger areas to be analyzed at once; (ii) photogrammetric interpretation errors of omission and commission become less common as stream order increases, and therefore, there is increased confidence in the mapping of those streams; (iii) the size of stream vectors better matches the resolution of cell size of the hydrologic base data. The disadvantages to removing low-order streams include increases in inter-confluence distances, which results in an increase in the length of stream lines and the size of reach contributing areas. Increasing the size of headwater reach contributing areas will likely increase the number and heterogeneity of landscape variables within these areas. Additionally, removing low-order streams means they will not be represented in the reach level database. At the fine mapping scales of 1:10,000 and 1:20,000, this should not be an issue, and the attributes of low-order drainage areas will still be captured in higher order stream reach units.

4.5 Scale and spatial nesting in aquatic systems

Water flows downstream within branching watersheds that are directionally nested and resemble trees: they have a crown (the headwaters) and a trunk (main channel). As spatially contiguous stream reaches flow and converge from the headwaters to the watershed outlet, there comes a point when the abiotic characteristics of the stream will be very different compared to any of the headwaters that merged to form it. In contrast, headwater reaches in separate watersheds may have much in common (Kuehne, 1962; Savage and Rabe, 1979; Hawkins et al., 1993; Whiting and Bradley, 1993; Bryce and Clarke, 1996). Therefore, larger watershed are likely to contain more variation within the same watershed than between different watersheds. This relationship will limit the spatial scale to which a bottom-up approach can aggregate smaller units into large units without introducing more and more undesirable heterogeneity as a result. To address this limitation, larger watersheds can be used as new ‘containers’ within which the spatial configuration of valley segment classes are summarized. These summaries will then be used to identify groupings of watersheds with similar internal configurations. This process essentially resets the fundamental landscape ‘container’. For the finer spatial scales (Figure 8: Reach and Segments levels) of the classification the fundamental ‘container’ is the inter-confluence reach. The fundamental unit of the coarser scales (Figure 8: Watershed and Zone levels) now becomes the quaternary watersheds (or their equivalent).

5 THEORETICAL BASIS

The theoretical basis for the proposed AEC assumes that biotic communities in flowing waters are largely shaped by abiotic aspects of aquatic systems and their drainage networks (Poff et al., 1997; Jones et al., 2010). Generally, aquatic systems that drain areas with similar climate and geology are expected to have similar biota or biota with similar ecological traits. The key underlying process regimes in aquatic ecosystems regulate the availability of different habitat types that vary spatially and seasonally. The flow regime regulates the availability of free-flowing, standing, and ephemeral waters, which are consistently shaped and modified over years to decades (Poff et al., 1997). From an evolutionary perspective, the relative success of a variety of species depends on spatial and temporal regime dynamics, which create breeding, shelter, and foraging habitats. This is the "habitat template" described by Southwood (1977), which creates subtle and profound differences in the natural histories of species and which is shaped by the environmental heterogeneity and harshness (Poff et al., 1997; Jones et al., 2010). Process regimes influence species distributions and abundances as well as ecosystem function (Southwood, 1988; Townsend and Hildrew, 1994). Following the habitat template approaches of Southwood (Southwood, 1977; Southwood, 1988) and of Townsend and Hildrew (1994), we propose to classify based on environmental gradients, including flow, temperature, sediment, and nutrient regimes (Jones et al., 2010).

5.1 Abiotic regime based classification

5.1.1 Flow regimes

In 1997, Poff et al. wrote a highly influential paper on the importance of the flow regime for the functional integrity of riverine ecosystems. A number of ecologically important stream-flow characteristics constitute the natural flow regime, including the magnitude and seasonal patterning of flows; the timing of extreme flows; the frequency, predictability, and duration of floods or droughts and intermittent flow; daily, seasonal, and annual flow variability; and rates of change in hydrologic conditions (Poff and Ward, 1989; Poff et al., 1997). We intend to approach flow regime type using two different but complementary methods.

Approach 1: In Ontario, there is considerable variability in groundwater inputs and the surface water inputs of wetlands and lakes, both of which provide base flow to rivers and contribute to flow stability over time. In addition, these inputs have different thermal conditions: in summer lakes are generally warm whereas groundwater is cold (see section on *Thermal regimes* below). The baseflow index (BFI) developed by Neff et al. (2005) for a variety of surficial geologies can be used to predict groundwater discharge potential across much of Ontario. This BFI index varies between 0 and 1 and provides an indication of the proportion of baseflow relative to stream flow for each geologic type. Higher values indicate greater base flow potential (Piggott et al., 2002; Piggott et al., 2005; Piggott, 2007). The contribution to baseflow from lakes and wetlands can be assessed by examining stream hydrographs in relation to lake position and storage potential within the watershed (i.e. stream-lake network metrics and percent lake and wetland cover). Increasingly, the effects of lakes and wetlands, and their position in a watershed, are being recognized as having a large effect on the natural flow regime and the basic ecology of streams (Jones, 2010).

Figure 4 depicts an idealized view of the expected effects of watershed surface storage capacity (low or high lake and wetland cover) and ground-water input (high or low groundwater baseflow) for equivalently sized catchments. The relative position of the curves on the y-axis represents flow stability rather than absolute magnitudes, with a higher plotting position indicating higher stability.

- The lower left quadrant represents catchments with high surface-water storage potential but low groundwater contributions. Flows are modified by the surface-water buffering capacity which dampens high-flow events, maintains baseflow and relatively warm and stable temperatures. Even though baseflow is relatively stable in such watersheds, surface waters are susceptible to prolonged drought conditions and therefore are less dependable than groundwater sourced baseflow.

- The upper left quadrant represents watersheds with low surface storage capacity and low groundwater inputs. Streams in this type of watershed will likely be intermittent and flashy, varying widely and responding quickly to precipitation or spring thaw events. Water temperatures may also vary widely in such streams in response to rain and drought events because of the lack of buffering cold groundwater inputs. As a result, the environment will likely be harsh. The biota found here may have short generation times, small body size, and good colonizing ability.

- A contrasting scenario is depicted in the upper right quadrant. Here, ground water contributions are high, primarily due to high soil permeability and hydraulic conductivity of the geology. Under such conditions, precipitation can percolate down easily and flow relatively quickly through the geologic sub-surface strata feeding streams with a steady supply of cold groundwater. The lack of surface storage means no warm surface baseflow inputs are mixing with the cold groundwater inputs resulting in colder water temperatures. Such watersheds are likely to support species that prefer very predictable baseflow and cold stable temperature environments (e.g. brook trout).

- Watersheds, of the type represented by the lower right quadrant, reflect conditions when both surface storage capacity and groundwater inputs are high. These watersheds will have very stable flows with a stable cool to warm temperature regime.

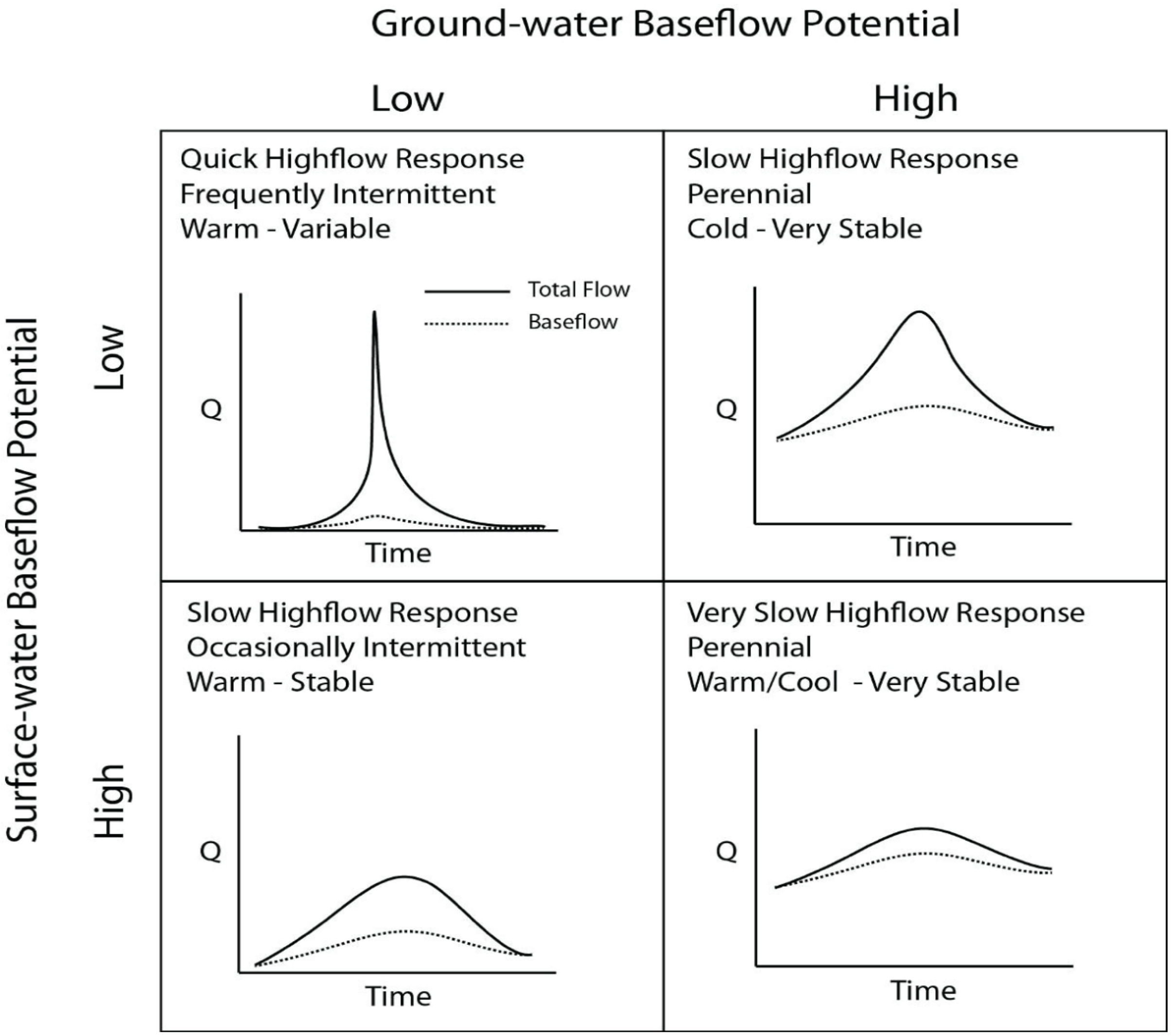


Figure 4*: Idealized flow and thermal regimes depicting a heavy rain event given varying watershed storage capacities and groundwater contributions. Watersheds with little storage capacity or infiltration have rapid runoff response, frequent floods, and warm temperatures, but with considerable diel variability. Watersheds with no lakes but high soil infiltration/geologic conductivity have a stable and cold flow regime which is similar to what is seen in watersheds with many lakes. While an abundance of lakes and groundwater can lead to similar flow regimes, their thermal regimes will be very different: warm and cold, respectively. Growing degree-days will modify temperature responses across the province. Among these idealized extremes in flow and thermal regime depicted above there are many intermediate forms along the continuum.*

Approach 2: In 2010, Poff and Zimmerman summarized the consensus view of an international group of riverine scientists concerned with classifying rivers into a few distinctive flow regime types that are expected to have different ecologic characteristics. They suggest: 1) calculating a variety of hydrologic indices from stream hydrographs; 2) arranging them into summary measures of flow to capture the ecological characteristics of river flow regimes (Poff and Ward, 1989); 3) cluster analyses to identify the variety of stream flow types based on selected hydrologic indices; and 4) predictive modelling of associated flow regime types using catchment characteristics. The basic data required to develop hydrographs that summarize natural flow regimes in Ontario are available. Research is currently underway to create a flow regime predictive model for Ontario.

5.1.2 Thermal regimes

The importance of climate and thermal regimes has been noted by numerous authors (e.g. Neuheimer and Taggart, 2007). Climate influences temperature and precipitation, growing degree-days, frost-free days, water deficits, and the timing of floods or freshets within a region. Magnuson et al. (1979) stressed that temperature is an ecological resource, and he showed that most temperate freshwater fish can be grouped into three thermal guilds: cold, cool, and warm water fishes. For aquatic biota, water temperature is a key factor influencing physiology (Fry, 1971), life histories, distribution and abundance patterns (Welsh et al., 2001; Wehrly et al., 2003). The thermal regime of aquatic systems is influenced by numerous factors including: ground-water inputs, tributary inflows, surface water runoff over variable land covers, channel morphology, morphometry (lake size and depth), incoming solar radiation at different latitudes, amount of shading, and elevation (e.g. Mohseni et al., 2002; Webb et al., 2008; Chu et al., 2009). In forested temperate regions, summer stream temperatures vary longitudinally with cooler waters in headwater systems and warmer waters downstream (Poole and Berman, 2001). In much of Canada, the formation, persistence, and break-up of river ice are important aspects of the physical character of streams (Prowse, 2001; Power, 2002; Jones et al., 2010).

In this classification, thermal regime will be characterized by base flow index from Environment Canada (Piggott et al., 2002; Piggott, 2007), which represents the cold contribution to flow, and by the number, size, and position of surficial storage areas (e.g. lakes, wetlands) that represent the warm contribution to flow (Figure 4). In addition, climate measures including growing degree days (GDD) and mean annual temperature will be used to approximate regional differences in the potential temperature of surface waters and to provide estimates for the growth and development of ectotherms during the growing season (Shuter et al., 1983; Jones et al., 2003; Neuheimer and Taggart, 2007; Venturelli et al, 2010).

5.1.3 Nutrient and turbidity regimes

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 (or other related water chemistry parameters), broadly akin to the Morphoedaphic Index (MEI) developed by Ryder (Ryder, 1965; Kwak and Waters, 1983; Krueger and Waters, 1983; Scarnecchia and Bergersen ,1987; Chételat et al, 1999). The morphoedaphic index is the most widely used index of potential lake productivity and is derived by dividing a lake's total dissolved solids (TDS in mg/L) by its mean depth in meters (Ryder, 1965; Henderson et al., 1973). TDS is generally proportional ($r^2 \sim 0.8$) to one or both of the limiting nutrients, nitrogen and phosphorus, albeit salinity has an affect on the slope of the relationship (Henderson et al., 1973; Chow-Fraser, 1991).

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). Indeed, algal biomass (Chl *a*) in rivers of southern Ontario and western Quebec was strongly correlated with total phosphorus ($r^2 \sim 0.6$) and conductivity (r^2 ~ 0.7) (Chételat et al, 1999). But riparian shading and turbidity can disrupt this relationship because high levels of turbidity lead to a reduction in potential photosynthesis as suspended particles absorb more heat and block the amount of light penetrating the water. Even relatively small turbid tributaries can strongly influence the nature of large mainstem rivers.

Specific conductance is often used to calculate MEI when an estimate of TDS is not available because conductivity is generally highly correlated with TDS (r^2 ~ 0.9, (Foster et al., 1981; Chow-Fraser, 1991)). Conductivity provides an estimate of the ability of water to carry an electrical charge (microsiemens per centimetre) and is both easy to measure and is used to evaluate relative productivity of aquatic ecosystems (Ryder, 1964). Neff and Jackson (2011) found strong differences in conductivity between on-shield and off-shield regions of Canada, and these differences were related to changes in the invertebrate community. We will develop models of conductivity for unsampled watersheds in Ontario based on a variety of explanatory variables (e.g. geology, soils, watershed position, and climate). Conductance data from OMNR field work, Ministry of the Environment, Department of Fisheries and Oceans, and the broad scale lakes database will be used.

Turbidity meters are used to assess water clarity by the passage of light (or scatter) through water (Bin Omar and Bin Matjafri, 2009). Like conductivity, turbidity is strongly related to geology, landscape position, and climate in the surrounding watershed. We will develop models of turbidity for un-sampled watersheds in Ontario based on these explanatory variables. It may also be possible to assess lake water clarity using Landsat data (r^2 ~ 0.8, (Olmanson et al., 2008)).

5.1.4 Aquatic network structure and function

As discussed earlier in section 4.5, the physical structure of aquatic networks dictates that headwater systems are different than mid- and lower- order systems (Fullerton et al., 2010). Mean annual discharge, channel size, temperature, and turbidity all increase in a downstream direction. Headwater systems tend to be occupied by a suite of different biota, such as colonising specialists with excellent dispersal abilities and species with the ability to withstand more unstable environmental conditions, than downstream systems (McGarvey, 2010). This suggests that variability in headwater, mid- and lower- order systems may best be captured using a segment level classification that incorporates longitudinal network patterns (Benda et al., 2004b; Grant et al., 2007; Chu and Jones, 2010).

The importance of network position has not gone unnoticed in aquatic ecology, but incorporating these ideas into aquatic classification has traditionally focused on longitudinal trends rather than on network dynamics (Melles et al., 2012). Benda et al. (2004a; 2004b) recently proposed the Network Dynamics Hypothesis to describe how stream habitat heterogeneity is a function of the spatial arrangement and relative size of tributaries, confluences, and stochastic watershed processes. Jones (2010) suggested that lake effects need to be explicitly incorporated into stream ecology and aquatic classifications, and limnologists would likely benefit by incorporating streams into their thinking. A comprehensive aquatic network approach would help unify the study of aquatic ecosystems, which is needed for the successful management and conservation of our aquatic resources.

5.1.4.1 Network measures

Confluences and lakes form different kinds of breaks in a directed aquatic network, and these breaks can be represented by different kinds of 'nodes' in network theory and analysed accordingly (Newman, 2003) (Figure 5). Inter-confluence stream reaches have been represented as network links of different magnitude or stream order since Horton introduced the law of stream numbers in 1945. Over the years, a number of measures have been developed to summarize aquatic networks and there has been a recent push to apply and develop more measures based on network theory since Benda et al. (2004a) proposed the *Network Dynamics Hypothesis*. Measures developed in the field of graph and network theory should prove useful in the analysis of aquatic networks (Grant et al., 2007; Jones, 2010).

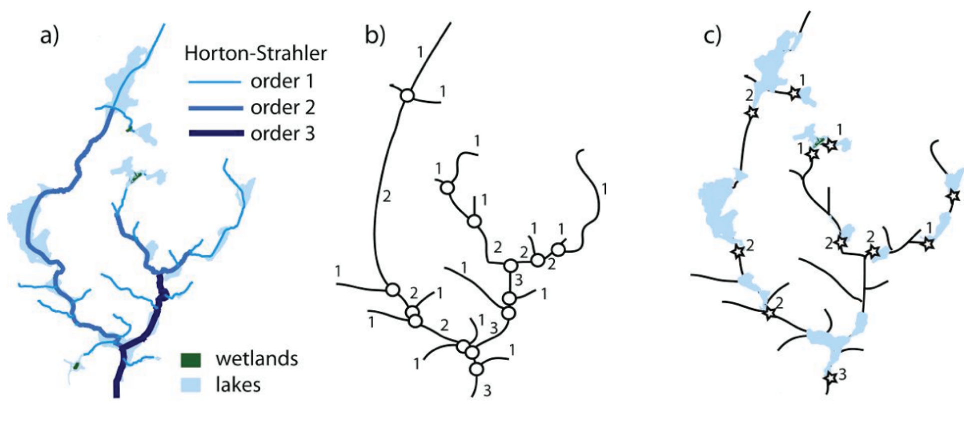


Figure 5: *Example network depictions of the stream lake network in a small portion of the Black River watershed in south-central Ontario. a) GIS map of lakes, wetlands, and streams; b) simplified network representation showing streams as links between confluences (nodes). Horton-Strahler stream orders (numbers) are also shown; c) simplified depiction of the network showing lake order (numbers) at lake outlets (stars). Lake inlet nodes are not shown.*

Network measures can be divided into three categories (Table 1), including: I) measures that summarize the characteristics of each element in the aquatic network such as lakes, confluences, and stream reaches; II) measures that summarize watershed or basin-wide characteristics; and III) measures that summarize network characteristics such as average inter-confluence distance. We will test a variety of these measures for their ability to capture key aquatic properties of interest once the reach inventory database is complete.

Table 1: *Summary of network measures that attempt to quantify network structure and function.*

Structural level	Measures	Properties of interest
Element (e.g. lake, segment, confluence)	Element area; width; fetch; perimeter; shape index; fractal dimension; radius of gyration; contributing area (CA); perimeter to area ratio; area relative to circumscribing circle; degree (# incoming and outgoing tributaries); in degree (incoming tributaries); out degree (outgoing tributaries); stream order; lake order; Lake index (Snelder et al., 2004); in components (e.g. # upstream lakes); out components (# downstream lakes); node in- & out-flux; dispersal in- & out-flux; confluence symmetry ratio (tributary CA relative to mainstem CA ratio); lake symmetry ratio (lake CA relative to mainstem CA); stream-lake path; lake proximity (to outlet) index; betweenness centrality (up & downstream - U&DS); flow betweenness; random walk betweenness; closeness centrality (U&DS); eccentricity (U&DS); current density; quality-weighted area; modified incidence function.	Focused on measures of an individual element's structural properties that might account for some of its' physical and biological characteristics (e.g. circulation patterns, relative accessibility, recruitment potential, likelihood of dispersers, influence on neighbouring downstream elements, influence from neighbouring upstream elements)
Basin or watershed wide	Basin area; shape measures such as Horton's form factor (Horton, 1941); Schumm's elongation ratio (Schumm, 1956); Benda's modified form factor (Benda et al., 2004a); width function or distance area function; topological width function; lake width function or lake distance area function; percent cover of lakes & wetlands; % lake by order; # isolated lakes and wetlands; Shannon and Simpson's index (element diversity).	Focused on measures that capture basin shape, diversity, and composition as well as the relative position of features within it, given stream distances. Such measures are expected to be related to key aquatic process regimes such as flow, temperature, nutrients and sediment.
Network	Bifurcation ratio; stream length ratio; drainage density or connectance; drainage density by stream order; confluence density; degree distribution & exponent (based on stream order or lake order); network diameter; network or link magnitude (Shreve, 1966); dendritic connectivity index; mean inter-node geodesic (shortest) distance (U & DS); mean lake to outlet distance.	Focused on measures that capture overall network structure, overall connectivity between different types of nodes (lake to lake, lake to outlet, confluence to confluence), and scaling of features within basins and watersheds. These measures are expected to be related to how aquatic networks function for the species living in them.

5.1.4.2 Lake effects

Kratz et al. (1997) suggested that a lake's landscape position (including a lake's hydrologic position) will determine the degree and type of influence that the surrounding landscape has on the receiving lake and that it could be used as a predictive tool to help explain which lakes have greater species diversity. Lakes can have strong effects on downstream hydrologic, chemical, thermal, and material regimes (Ward and Stanford, 1983; Jones, 2010). Conversely, rivers can have strong influences on lake turnover, productivity, and plankton composition and abundance (Brook and Woodward, 1956; Kling et al., 2000; Jones, 2010). Martin and Sorrano (2006) found that lake order – a reflection of stream order – was strongly related to lake water chemistry and clarity.

One of the few examples of aquatic ecosystem classification that assessed the influence of lakes on river flow dynamics is an index developed by Snelder et al. (2004). These authors used a lake index, which takes both lake size and the volume of water passing through a lake into account, in relation to the total volume coming from the catchment. Where data are available, we can explore a variety of such element level measures (Table 1). At watershed wide scales, the moderating influence of lakes may be captured by a variety of measures. For example, as with stream order (Horton, 1945; Strahler, 1957), aspects of the frequency (or degree) distribution of lake orders (Figure 5c) should prove useful for summarizing watershed-wide lake effects on flow and temperature regimes(Figure 6).

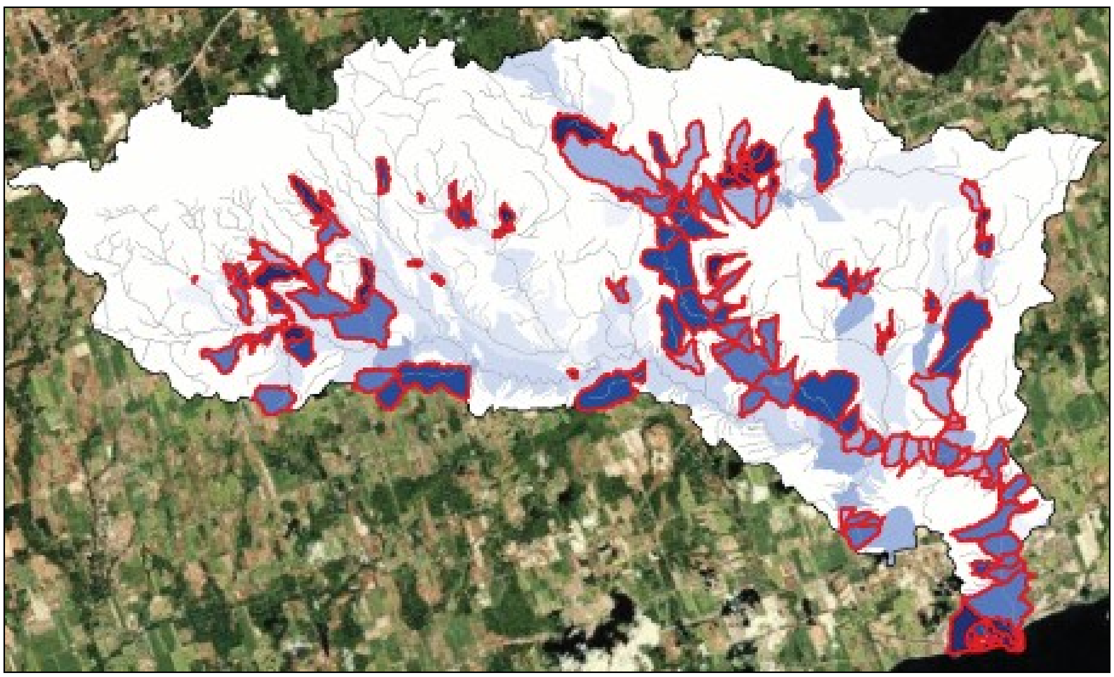


Figure 6: *Percent coverage of lakes within upstream catchment areas (UCAs) plotted for all reach contributing areas (RCAs) in the Ganaraska River watershed of Southern Ontario. Polygons shaded in blue represent reach contributing areas that are influenced by upstream lakes/impoundments to some degree (darker blue indicates higher degree of percent lake coverage). Polygons outlined in red are reaches where the ratio of upstream lakes area to upstream catchment area is greater than 1/500 (i.e. > 0.2% UCA lakes coverage).*

5.1.4.3 Integrating lakes into the spatial fabric

As described in Jones (2010), it is crucial that any aquatic ecosystem classification designed for Ontario embeds lakes at the fundamental level of the classification's spatial fabric. The proposed method of using inter-confluences reaches as the fundamental unit of the classification creates a dilemma when considering that 'virtual reaches' connect lake inlets to its outlet. The confluences of these virtual connectors are currently treated the same as real confluences when delineating reach contributing areas (OMNR, 2012). Clearly this is undesirable because they do not represent real entities in the landscape (Figure 7a). The solution to this issue is theoretically simple but more difficult to implement in practical terms. Additional nodes (i.e. breaks) need to be added into the stream line network at the inlets and outlet of all lakes. This would result in "lake-sheds" that are linked to the lake outlet within the spatial database. The proposed structure would allow modelling the influences of individual streams (and consequently the contributing landscape) discharging into lakes. The 'lake-shed' area can be used to characterize the influence of the landscape draining directly to a lake and assist in lake classification efforts. Additionally, inlet and outlet points could also be used to store attribute information in the spatial database (e.g. angle of inflow to outlet, inlet/outlet/lake area ratios (Jones, 2010)).

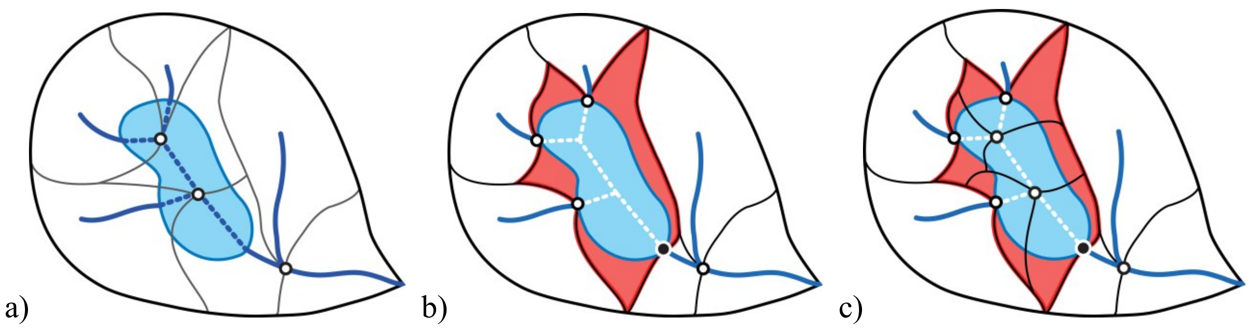


Figure 7: ***a)*** *Illustration of the current spatial data structure of the Ontario stream network including confluences (white points), virtual connector lines (blue dashed line) and reach contributing areas (RCAs outlined in grey). Notice that the lake shoreline is ignored.* ***b)*** *The proposed spatial data structure would add lake inlets (white points) and an outlet (black point) creating a 'virtual multi-reach' composed of multiple lines within the lake (white dashed lines). This 'virtual multi-reach' would be relationally linked to the lake outlet in the spatial database. The landscape area draining directly to a the 'virtual multi-reach' is called the "lake-shed" (red area).* ***c)*** *An alternate data structure that would introduce inlets and outlets plus maintain the virtual confluences within the lake, as a result creating individual 'virtual RCAs'. These 'virtual RCA's would be treated like real interconfluence RCAs within the spatial database. Later in the classification process these virtual RCAs would be aggregated into "lake-sheds" during the reach-to-segment clustering procedure (red area).*

If the data structure illustrated in Figure 7b proves to be impossible to implement because of constraining database rules (e.g. multi-reach lines for a single-reach lake contributing area not allowed), then an alternative as illustrated in Figure 7c could be implemented, essentially creating virtual reach contributing areas for the virtual reaches inside a lake (i.e. the landscape areas draining to each virtual reach (read areas outlined in black). These virtual reach contributing areas could later be aggregated into a single "lake-shed" during the valley segment clustering process. However, this data structure will increase the complexity of the spatial fabric (i.e. total number of reach units). For example, in the illustrated example of Figure 7c, five virtual reach contributing areas would result, compared to the single "lake-shed" structure of Figure 7b. This increase in complexity may prove to be a technical challenge and requires further consideration.

Either of the proposed integrated lake data structures will require considerable development resources to implement (i.e. funding and person-hours). We have been in communication with the Water Resources Information Program and they are currently assessing the scope of this work.

5.1.4.4 Considerations for wetlands and coastal areas

Unlike lakes, wetlands will not be explicitly integrated into the spatial fabric of the classification. Although we realize that wetlands can influence the abiotic template of streams, we plan to include their influence implicitly via wetland focused landscape attributes of the reach database. There are several reasons for this decision:

- The current state of mapping of wetlands across Ontario is often incomplete and inaccurate, especially in the Hudson Bay Lowlands and Canadian Shield ecozones.
- The state and function of wetlands is variable over relatively short periods of time (e.g. annual wetting /drying cycles, succession of plant communities, beaver dams etc.).
- Where mapping does exist, wetlands are often 'complexed' with lakes in very convoluted ways.
- Wetland type requires site knowledge of hydrology.
- Wetland classification systems already exist (Jeglum et al., 1974, Warner and Rubec, 1997). These classifications are based on intensive field work, highlighting the fact that remotely sensed data is inadequate to classify wetlands at the provincial scale.

Coastal near-shore areas will not be integrated into the classification. As mentioned previously, in-land lakes will be considered as non-divisible ecological units in the context of the proposed classification. Efforts are underway to create a Great Lakes wide near-shore (i.e. coastal) ecosystem classification both in Canada and the United States under the umbrella of the recently signed Great Lakes Water Quality Agreement. We have been in communication with the groups leading both initiatives to facilitate integration of our classification with these emerging near-shore frameworks. It is unclear if the coastal classification will include near-shore areas of the large inland lakes (e.g. Nipigon, Nipissing, Simcoe). As it stands, we plan to treat these larger lakes in the same way as all other lakes while developing our classification.

6 PROPOSED MULTI-SCALE CLASSIFICATION

We recommend a multi-scale classification with five levels, including: Zones, Watersheds, Segments, Reaches, and Sites (Figure 8), created largely by clustering smaller spatial units into increasingly larger units from the bottom-up. A multi-scale approach should be able to meet the needs of different users across different scales (Melles et al., 2011). As a strategic land-use planning tool, mid to upper scales of an aquatic classification can be used to select reference systems and assess the capabilities or sensitivities of these systems to the broad impacts of various development projects (Zone and Watershed levels). The coarse provincial and regional scale levels are useful for summarizing broad-scale trends (e.g. related to climate change) or for generalizing and reporting on trends for use in strategic corporate documents. Finer spatial scales (Segment and Reach levels) correspond more to characteristics like species occurrence patterns where biotic data has been collected at fine spatial scales (e.g. within headwaters, river segments).

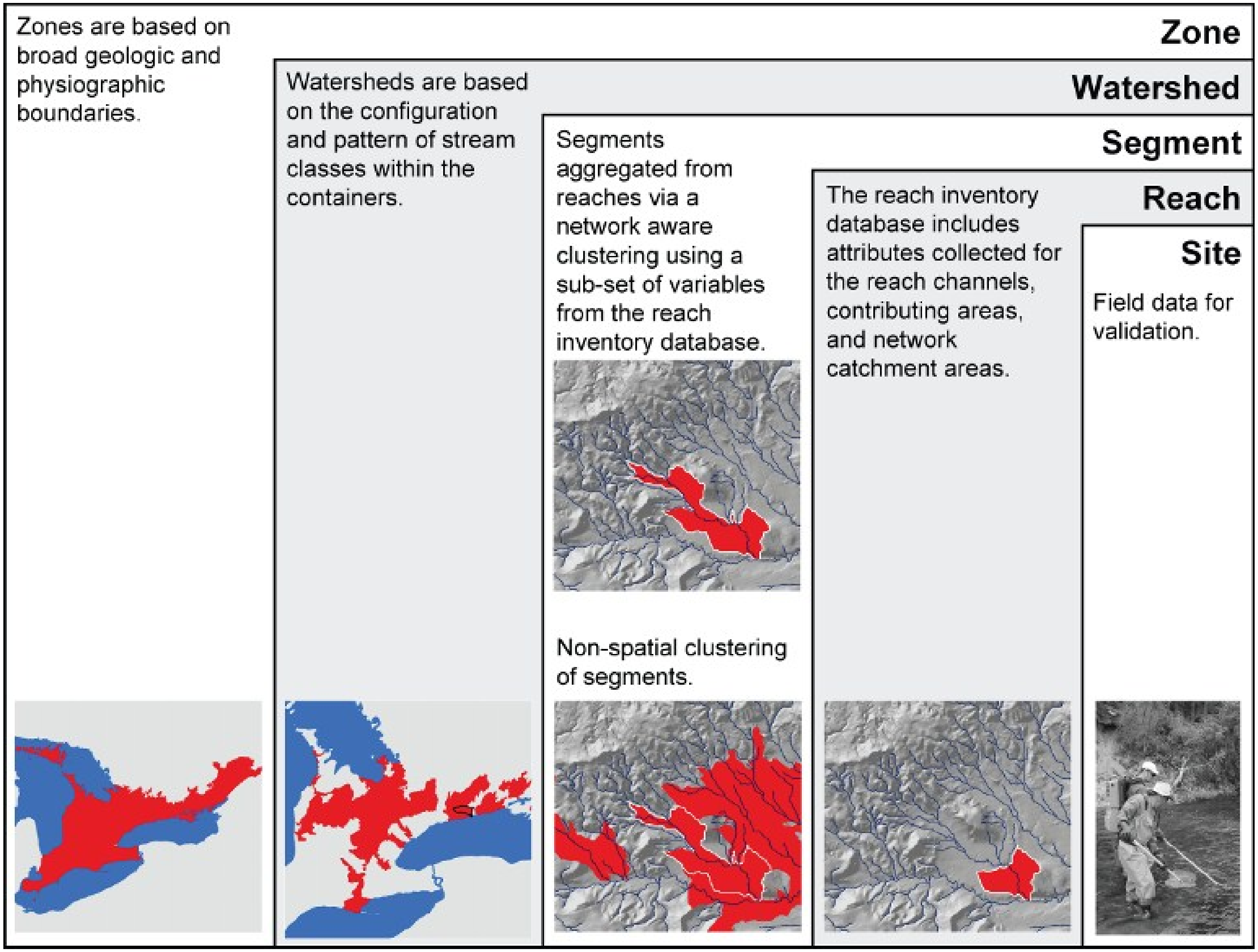


Figure 8: *Schematic overview of the proposed multilevel aquatic classification for Ontario. See text for description and discussion (network catchment areas are synonymous to upstream catchment areas).*

6.1 Sites

The site level will be the classifications finest scale of interest, providing point-based linkages to information on species as well as detailed environmental characteristics via linkages between the AEC inventory database and established field-based datasets and monitoring programs such as the *Provincial Broad Scale Monitoring Lakes database (BSM), the Aquatic Resource Area Survey (ARA), Ontario Benthos Biomonitoring Network (OBBN), Fishnet, past Aquatic Habitat Inventory Surveys (AHIS)* and *Ontario Stream Assessments Protocol (OSAP)*. The AEC inventory database could be designed to include special tables of unique identifiers that link it with existing survey datasets as well as provide placeholders for any future data collection initiatives. Another option for linking databases is GIS spatial joining.

Such detailed site level data cannot be detected remotely (i.e. using remotely sensed imagery) and must be collected on a point-by-point basis in the field. Given the cost of acquiring site-level data on aquatic biota, these datasets cover a limited number of sites across Ontario, and rivers are often not well represented in datasets. The lack of adequate data coverage is one of the primary reasons biotic data cannot be effectively used to develop an Ontario-wide AEC. However the classification, once developed, will provide much guidance on where future sampling should take place, for example, to investigate sites where expected diversity is low or high and to validate the classification. This should prove particularly useful when field budgets are small and the chance for ineffective and redundant sampling efforts is high.

6.2 Reaches

Inter-confluence reaches and their local contributing areas are well suited to be the fundamental spatial units of an inventory database and classification because they are easily identified by physical breaks in the network at confluences (Benda et al., 2004b), and because they are fundamentally integrated into hydrographic GIS databases (Maidment, 2002), which are widely used by several of Ontario's public water resource management agencies. Moreover, their small size at the AECs mapping scale translates into a relatively homogenous landscape character within them.

The reach level will serve as the basic inventory of attributes necessary i) to support the development of our proposed general ecological classification, our 'master view', and other 'custom views' (*see Section 4.1*); ii) allow for revisions to datasets as they occur through time; and iii) can be linked to a variety of land management goals and spatial scales (Wang et al., 2011). Each record (i.e. row) in the database would represent a single reach with fields (i.e. columns) summarizing a large array of attribute information about the reach channel, the reach contributing area and upstream catchment area (*see Section 4.2, Figure 3*). Virtual reaches that connect lake and wetland inlets to the outlet will be included in the database to enable hydrologic analysis and modelling by allowing otherwise disconnected stream sections (separated by lakes and wetlands) to remain flow connected (*see Section 5.1.4.3, Figure 7*). The proposed spatial framework and reach inventory database would provide users with the capability of conducting analyses, developing management scenarios, and tracking results at a variety of scales (Wang et al., 2011).

There are some examples in the fluvial classification literature for Michigan and Ontario that have created additional breaks in the aquatic network based on: sharp changes in channel slope (indicating falls or impassable rapids); changes in surficial geology; boundaries in landform or soil infiltration classes; and at changes in stream sinuosity (Stanfield et al., 2006; Seelbach et al., 1997). Seelbach et al. (1997) used expert judgement to identify these additional breaks, whereas Stanfield et al. (2006) used an automated approach. We reason that either of these approaches would add unnecessary and unjustifiable complexity to the reach level inventory. Expert methods tend to be pedantic and they lack objectivity, which limits their potential utility (Brenden et al., 2008a). They are also impractical to implement across the whole province. Automated approaches tend to create many small and irrelevant line segments, and this approach is highly dependent on the scale and accuracy of the spatial data used to create the breaks. The spatial scale of stream network data and landscape data are often incompatible. For instance, there are often large spatial uncertainties in the location of break points due to mapping errors and the generally fuzzy nature of geologic or soil class boundaries. Moreover, there seems to be little evidence to suggest that flow or other process regimes in a river change significantly or immediately at all transitions of surficial geology (Devito et al., 2005).

Therefore, we will not be using geologic breaks or other landscape variable breaks for stream segmentation. Furthermore, we will not use barriers to place breaks into the network. The available information on barriers in Ontario is poor (e.g. man-made and beaver dams, perched culverts, rapids) and barriers are variously permeable to different species. The permeability of a barrier is dependent on river discharge, water velocity, vertical height, longitudinal length of the barrier, species and size, and water temperature. It should be noted that large dams and reservoirs will create breaks in the stream network by default because they will be effectively treated as artificial lakes along the stream network.

Even so, we do not propose to ignore the effects of these types of changes along the aquatic network either. Their effects of these landscape characteristics and entities will be implicitly integrated into the classification by including them into the reach inventory database.

In summary, the reach level inventory is the foundation for all other levels in the AEC. This level ties together information from different AEC levels such that:

- biotic data collected within a given aquatic reach can be easily identified;
- relevant abiotic data (*Appendix 1*) are summarized and inventoried within associated reach contributing areas and upstream network contributing areas at a spatial scale that is suitable for a wide variety of land-water modelling purposes;
- reach breaks match current hydrologic and GIS analysis tools such as Arc Hydro that preserve to and from node network consistencies; and,
- abiotic similarities between reach characteristics can then be used to find unique aquatic units with meaningful boundaries, rather than relying on geomorphic breaks that may have no ecological relevance.

6.3 Segments

Without analysis and classification, the basic inventory of inter-confluence reaches will represent no more than an unorganized list. Such reaches are simply delineated based on the presence or absence of bifurcations in the aquatic network at confluences and at lakes. What is more difficult to assess is whether these geomorphic breaks have ecological relevance. For example, not all confluences are associated with significant changes in flow or sediment discharge (Benda et al., 2004b). Fish communities have been shown to respond the best to segment scale phenomenon, as opposed to reach and sub-catchment scale (Wang et al., 2011). For ecosystem classification and management purposes, it is important to establish ecologically relevant aquatic segments, i.e. groupings of stream reaches that are likely to be homogeneous in their hydrology, water chemistry, channel morphology and riparian characteristics (Seelbach et al., 1997; Brenden et al., 2008a, 2008b). The process of creating segments thus involves grouping neighbouring reaches together into ecologically meaningful segments. This is where the classifying really begins. Segments are a natural ecological unit of organization that reflect the spatial scale of many physical and biological processes occurring in river systems (Seelbach et al., 1997; Brenden et al., 2008a). Virtual reaches within lakes can be grouped into 'lake-shed' segments so that these features can be analyzed as a whole as well (*see Section 5.1.4.3, Figure 7*).

The segment level involves two steps: 1) grouping similar and spatially connected reaches together, and 2) classifying the resulting segments together that are not spatially connected. In the following two subsections, we describe each of these steps in detail.

6.3.1 Spatially constrained clustering of reaches

Recently, Brenden et al. (2008a) developed a software tool that takes an objective approach to finding similar and spatially contiguous stream reaches by clustering reaches together. This tool is called the Valley-segment Affinity Search Technique (VAST). VAST uses a non-hierarchical clustering algorithm similar to *K*-means to create groups by adding reaches one at a time into an open cluster. A reach is linked to an open cluster only if it is spatially adjacent and if it meets similarity criteria defined by a user-specified, 'affinity threshold'. The affinity threshold determines how similar two reaches need to be before they are joined and varies according to the similarity metric selected (e.g. Bray-Curtis, Jaccard's, Simple Matching). Similarity metrics summarize the similarities between neighbouring reaches based on how closely attributes match for the reach channel, reach contributing areas (RCA) and upstream contributing areas (UCA).

Tributary streams modify the river continuum and the magnitude of adjustment depends on tributary size relative to the main-stem as well as the physical, chemical and biological characteristics of the tributary (Bruns et al., 1984; Rice et al., 2001; Brenden et al., 2008a, 2008b). Research suggests that changes in discharge (Miller, 1958) downstream of a confluence can result in consistent changes in river characteristics (Roy and Woldenberg, 1986). Not all tributaries are large enough to cause a substantial change in characteristics and the relationship between the two confluent streams can be quantified by their confluence symmetry ratio.

The confluence symmetry ratio refers to the relationship of the two upstream catchment areas of two confluent streams (i.e. at a junction of a main channel and a tributary). The influence a tributary can potentially exert on the larger main channel into which it drains increases as the confluence symmetry ratio approaches unity (i.e. one). A threshold may occur when the confluence symmetry ratio approaches 0.6 to 0.7, above which changes in river morphology are generally evident (Leopold et al., 1964; Rhoads, 1987).

Based on this research, we propose to modify the Valley-segment Affinity Search Technique algorithm to use confluence symmetry ratio (CSR) rather than Shreve's link ratio to model tributary effects and to determine whether segments should contain branching tributaries, or whether tributary branches should form significant breaks in the network. Confluence symmetry ratios are easier to interpret than Shreve order link ratios, which are susceptible to subtle changes in drainage density or mapping scale. Areas of high drainage densities can quickly result in large Shreve order streams, even when their respective drainage areas are relatively small. Moreover, Shreve orders are sensitive to mapping biases, which are potentially introduced by photogrammetric interpretation errors and with changes in surficial geology (Hughes et al., 2011). During clustering, we imposed mandatory breaks at large confluences (i.e. at confluences of 3rd order or greater streams having confluence symmetry ratios > 0.4). These mandatory breaks represent points along the stream network where, regardless of the landscapes homogeneity upstream, the streams' abiotic template would change due to an increase in water volume alone. In other words, imagine a landscape that was entirely homogenous in character with only its topographic variation directing water down-stream through the watershed. In such a landscape, the character of the stream would still change simply due to the physical differences resulting from the ever increasing volume of water in the channel and time spent in contact with the stream bed (e.g. geomorphology, temperature, nutrients).

Deciding which attributes best describe the ecological similarity of stream reaches can be challenging. Brenden et al. (2008a) used physicochemical variables to create segments in their network of Michigan streams (i.e. $\log_e$ UCA, predicted temperature, percent lake, percent wetland, percent moraine, mean RCA slope, and predicted baseflow). Their approach has been tested by Warrner et al. (2010) who found that (fish) habitat variability within valley segments was less than variability between valley segments of Illinois streams. The attributes we select for Ontario may be similar to those used by Michigan researchers, but we intend to include more relevant lake effect network metrics given the importance of lakes in Ontario (Table 1). This process of determining which attributes to select for Ontario will likely be iterative and involve review by members of an AEC technical science team (Melles et al., 2011). We recommend using attributes that capture aspects of the four key aquatic process regimes (temperature, flow, sediment, and nutrients), depending on the resolution of the data and the scales at which these process regimes vary (Section 5.1).

6.3.2 Segment clustering and classification

Once segments are created by joining reaches, their segment attributes will be assembled into a sister segment database. Each record (i.e. row) in this new database represents a newly formed valley segment. The fields (i.e. columns) represent a summarized attribute (e.g. mean, median, majority) based on the individual reach attributes that formed the segment. Segments can then be clustered into classes using the summarized attributes and variety of clustering algorithms

(Jackson et al., 2010; Legendre and Legendre, 2012). Multivariate classification and regression trees may be used as an alternative approach to create classes (Martin et al., 2011).

Figure 9 shows an example of an experimental classification exercise performed on the Ganaraska watershed. In this exercise, stream segments were created using the Michigan's Valley-segment Affinity Search Technique with inputs of BFI, percent UCA forest cover, reach channel slope and log(UCA) and the resulting segments were then clustered aspatially using *K*-means clustering.

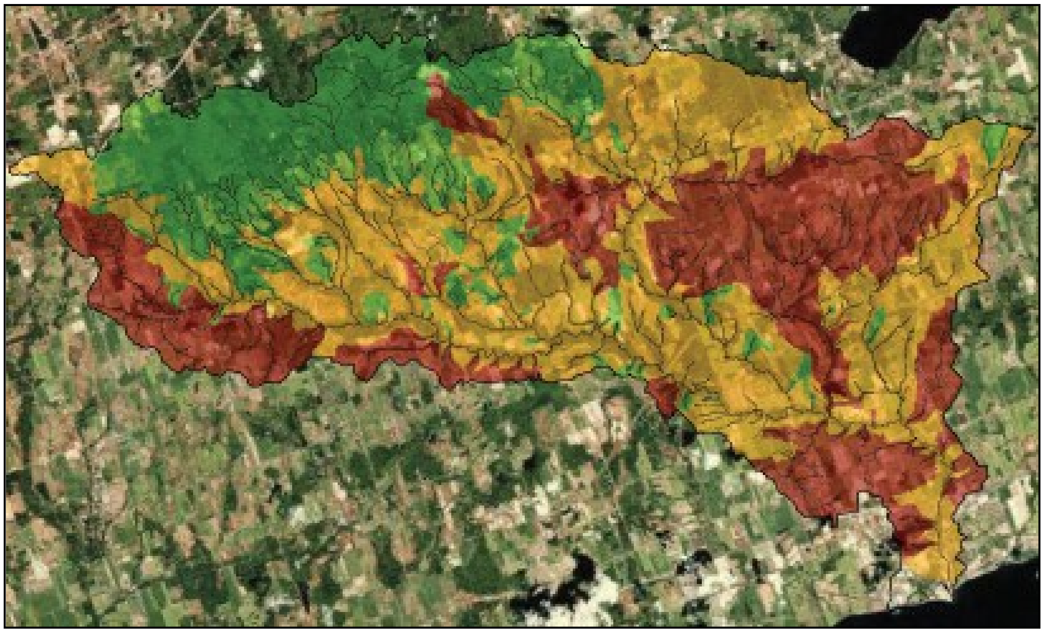


Figure 9: *Example of classification based on experimental multi-scale clustering of stream reaches segments on the basis of BFI, UCA percent forest cover, and reach channel slope and log(UCA) in the Ganaraska watershed of Southern Ontario.*

In summary: Classification of homogeneous aquatic segments in Ontario is most relevant to allocating sampling efforts in monitoring programs, summarizing information for local community watershed reports, prioritizing protection and restoration efforts, and modelling the distribution and abundance of aquatic species. Such a system should allow us to target areas where un-sampled populations of species at risk (SAR) might occur. In the Far North, classification at the sub-watershed scale should aid the process of community-based planning because rare segment types could be targeted for conservation and protection or further study. In combination with regional climate modelling, classification at this level could help to predict potential rates of aquatic invasive species spread.

6.4 Watersheds

Watersheds will be classified based on segment class patterns, where the segment classes are located in the watershed, and other watershed network measures. Quaternary watersheds are the smallest recognized watershed units in Ontario tessellating the entire area of the province. Digital spatial data of the quaternary watersheds already exist for a large part of the province with the remaining area in the far north currently in development (WRIP, pers. comm. 2013). Figure 10 depicts this 'class pattern' approach wherein watersheds *a & b* would be classified together, c) would classify out on its own, while watersheds *d-f* would classify together as a separate type (*see Section 4.5 for more details on how watersheds act as 'containers' for clustering*).

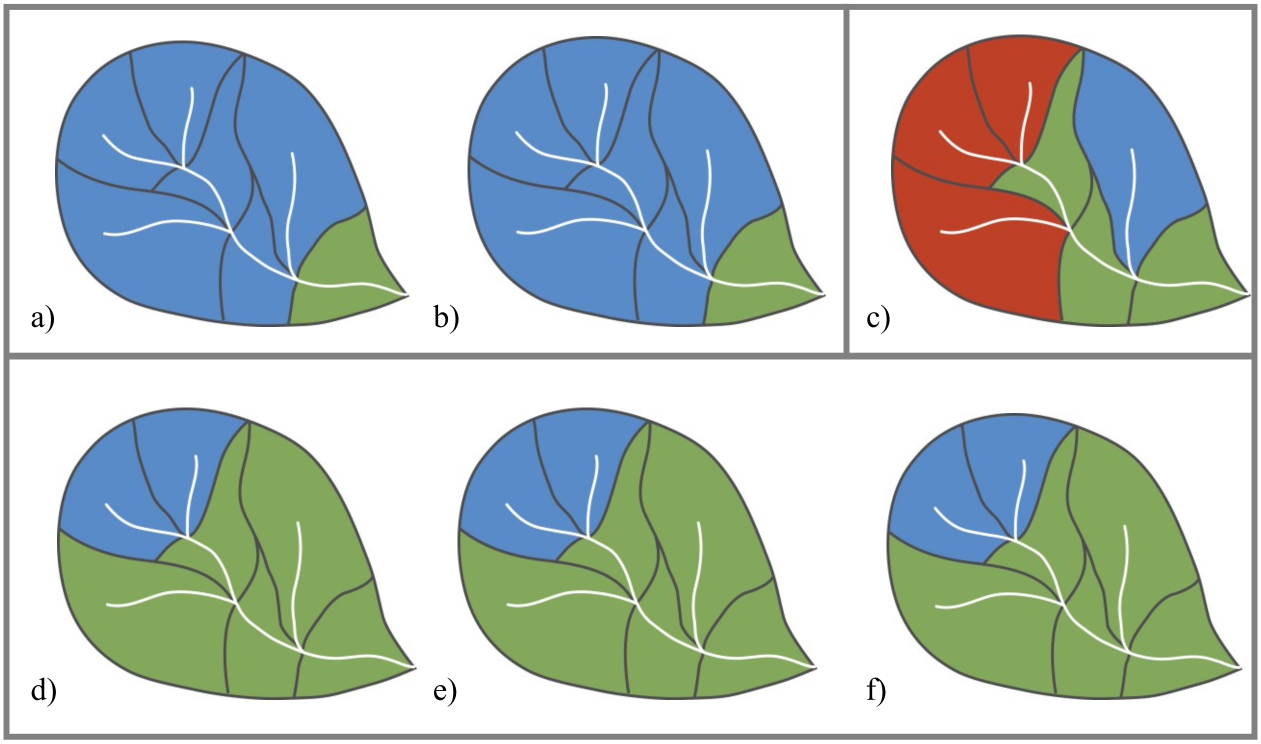


Figure 10: *Schematic illustration of three watershed types grouped on the basis of the unique configurations of the segment classes they contain.*

In summary: We propose to classify the over 2000 quaternary watersheds in Ontario into unique type classes on the basis of the configurations of the segment classes they contain, which in turn is thought to reflect the differences in the fundamental aquatic process regimes. This regional scale classification should prove useful for a variety of applications, such as:

- Protected areas planning
- Cumulative effects modelling using up- and downstream linkages to evaluate risks
- Community-based watershed planning
- Optimal sampling strategies for risk-based monitoring
- Ease of reporting in 'State of the Resource' series
- Selection of representative aquatic class parks and protected areas
- Selection of reference watersheds for comparison to impacted watersheds

Watersheds across Ontario could be viewed in terms of their sensitivity to various resource use practices (e.g. waterpower) and their sensitivity to climate change.

6.5 Zones

We propose to integrate aquatic zones with current terrestrial ELC zones as much as possible. However, as discussed earlier land-based zone boundaries do not necessarily respect watershed boundaries and key aquatic ecological processes. Fifteen terrestrial ecozones can be found across Canada, three of which are found in Ontario. These were delineated from the top-down (expert driven) according to broad physiographic and ecological similarities in climate, human activity, vegetation, soils, geology, and physiographic features (Ecological Stratification Working Group, 1996; Marshall and Schut, 1999; Crins et al., 2009

We suggest using a combination of expert knowledge and segment attribute/classification data to define zone boundaries between the Mixedwood Plains, Ontario Shield, and Hudson Bay Lowlands. Moreover, boundary watersheds that straddle two or more zones may have unique properties and these may need to be placed in a watershed class of their own.

Zone level information will provide a broad geoclimatic context for watershed classification so that reference watersheds and sampling can be stratified by zone. Zones can be used as a framework for reporting in *State of the Resource Reports* at provincial, national, and international levels i.e. to summarize biodiversity, species at risk, and conservation area targets (e.g. Canadian Biodiversity Ecosystem Status Trends Report (Federal, Provincial and Territorial Governments of Canada, 2010)). In addition, zones will help guide Ontario Provincial policy development and aid strategic planning for land-water management, conservation, resource and renewable energy development.

7 LIMITATIONS

7.1 Scale and accuracy of the input data

In Ontario, data are more limited in the Far North, and much of these data that do exist are collected at coarser resolutions compared to the southern portions of the province. However there are a number of base datasets that are just now coming online (2012), including: the Ontario Integrated Hydrology Data suite of products which present the opportunity to finally create a provincially complete AEC for the entire province of Ontario. A new Far North landcover data has recently been developed including satellite derived disturbance mapping layers.

7.2 Fuzzy boundaries and temporal variation

The creation of ecosystem classes inherently implies that relatively distinct boundaries exist and can be identified by a discrete set of variables. The reality is that aquatic systems are innately complex with multiple river branches interspersed by lakes, longitudinal and lateral linkages to the surrounding landscape, and vertical linkages with groundwater aquifers that are generally difficult to observe.

Aquatic systems are highly variable throughout time. They change cyclically between seasons and stochastically from year-to-year. Episodical changes induced by geo-climatic disturbances can also occur. Hence the boundaries between apparent fluvial patches are often indistinct or better portrayed as continuous functions (Naiman et al., 1988; Cleland et al., 1997). The intrinsic connectivity and variability of aquatic systems are fundamental and essential properties, but these properties make placement of enduring classification boundaries difficult (Bailey, 1983; Naiman et al., 1992).

All classifications suffer from their lack of ability to deal adequately with temporal change. However, this depends on spatial scale. At fine spatial scales (e.g. pools and riffles), many aspects of the abiotic environment are highly ephemeral, and we would not attempt to map them; whereas at larger spatial scales, we expect aquatic characteristics to be spatially and temporally stable and thus stand the test of time.

8 VALIDATION

Ecological classification is largely hypothesis-based, founded on a strong legacy of pure and applied ecological science (Bailey, 1983; Snelder and Biggs, 2002). The resulting classification represents how we think ecosystems behave. We assume that the boundaries we create represent meaningful differences in the distributions of flora and fauna. As a hypothesis-based modelling approach, the process of ecological classification and mapping is necessarily iterative. As we learn more about the functions and processes of ecosystems through monitoring, the collection of improved data, models, and advances in research, we improve the framework and thereby the quality of our management responses to problems and issues (Hughes et al., 1994). AECs also assume that ecosystems within the same class should respond similarly to management actions (Bailey, 1983). These assumptions must be put to the test. Aquatic ecosystem classes should be treated as hypotheses rather than paradigms.

One generally accepted way to test classification performance is to use an index of classification strength based on community composition data (Van Sickle, 1997; Van Sickle and Hughes, 2000). Classification performance can be determined by measuring the difference between mean within-class and mean between class similarities. First, information on the spatial distribution of biota needs to be collected either from existing datasets or by fieldwork (e.g. Ontario Benthos Biomonitoring, broad scale lakes monitoring). Next, various community similarity indices are calculated between all sampled sites (e.g. Jaccard's, Bray Curtis, Sorenson-Dice, Gower's index; (Legendre and Legendre, 2012)). The mean index of similarity within each class is calculated and permutation tests are used to determine whether the within class means are smaller than the between class means.

Validation could also come from sampling select watershed types in Ontario. For example, if we found that there were 10 different classes of watersheds in Ontario then we could strategically sample, using segment classes as guidance, representative watersheds of each class. Watersheds would be sampled over several years to understand their physical chemical and biological characteristics. Such a validation step would complement the broad-scale monitoring program by including flowing waters in aquatic watershed networks.

We believe that it is critical to discuss the maps and classification levels with experts across various branches and sections of the OMNR, as well as with conservation authorities, aboriginal communities, Parks Canada, and Department of Fisheries and Oceans. This would facilitate the transfer and exchange of scientific and traditional knowledge and information, which would serve to verify, improve and modify the classification.

Ultimately this classification will serve to better manage our natural resources in Ontario. Once completed, the opportunity for research and collaboration with partners at universities and fellow government agencies will no doubt present themselves, further improving our collective understanding of aquatic ecosystems in Ontario.

9 ROAD MAP OF NEXT STEPS

(Figure 11)

1. **Database development v 0.1**
    a. This is the reach level inventory with attribute information (e.g. landcover, geology, climate) from associated reach and upstream contributing areas.
        i. Create reach level inventory using Archydro GIS and attribute data suggested in Appendix 1.
        ii. Use spatial framework of broad-scale secondary watersheds to ensure up- and down-stream flow connections in ArcHydro sessions
        iii. Ensure attribute data are spatially aligned and depicted at appropriate resolutions
            1. e.g. troubleshoot new landcover class (LCC) & DEM base data layers
        iv. Integrate connections between reach segments and Great Lakes coastal areas (e.g. use virtual segments and pour points)
        v. Integrate attribute information for virtual lake segments
            1. i.e. summarize data for lake contributing areas
        vi. Prepare inventory database for distribution and hosting via Land Information Ontario (LIO)

2. **Develop software tool** to group neighbouring reaches together into segments based on similarities in their attributes.
    a. Modify existing publically available code written in Excel (Visual Basic, VBA) to a more suitable platform (e.g. *Matlab* or *R*)
        i. Migrate code and modify it to create added flexibility (e.g. user inputs based on confluence symmetry ratios)
        ii. Integrate lake influences based on network measures (e.g. size of upstream lake, Table 1)
    b. Develop code to automate calculation of selected network measures listed in Table 1.

3. **Develop segment classification v 0.2**
    a. Use software tools developed in step 4 on ArcHydro sessions within secondary watersheds
    b. Summarize attribute information for ecologically relevant aquatic segments and create sister database to reach level inventory (v 0.2)

c. Perform segment level classification
    i. Cluster segments using various statistical algorithms
    ii. Test validity and consistency of segment classes (statistically using randomization tests and related methods by comparing results of different algorithms)
d. prepare classification for distribution and hosting via LIO

4. **Classification modelling at multiple watershed scales.** Classify watersheds into types based on characteristics of the flow regime at quaternary watershed scales. Perform similar watershed analyses for stream temperature, nutrient and sediment regimes.
    a. Determine hydrologic (flow) regime types in Ontario
        i. Use available models of baseflow based on geology for southern Ontario (Piggott, 2007)
        ii. Cluster hydrologic metrics that capture flow characteristics of Environment Canada gauged watersheds
    b. Model relationships between existing conductivity and turbidity data to examine how soil edaphic factors affect river nutrients and sediments
    c. Use climate data (e.g. GGD) and baseflow estimates to summarize aquatic temperature regimes
    d. Assess the predictive ability of network measures (Table 1), calculated within pilot watersheds. Can they be used to help predict regime classes?

Long-term phases

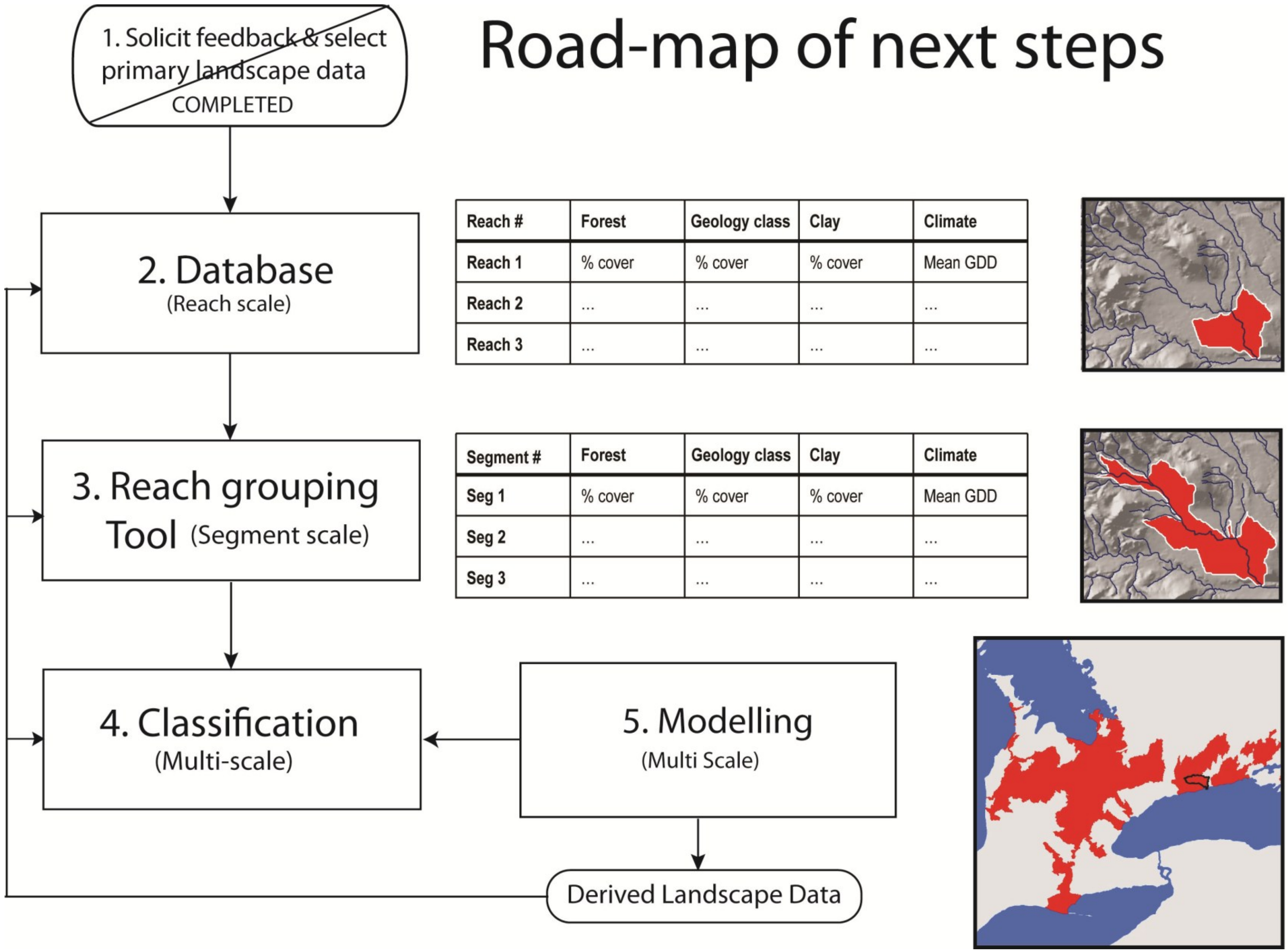
1. **Evaluate and test classification.** Validate segment level groupings and watershed level classification results in a pilot area using available biotic data (e.g. fish and benthic community data)

2. **Revise classification** to ensure that most recent and up to date data layers are used to attribute reach inventory, segment database, and classification.

3. Research to **improve future iterations**.

10 LINKAGES AND DEPENDENCIES

- In 2008, the Water Resources Information Project (WRIP) completed development of a seamless Provincial waterflow base map data layer (v2.x). This map of Ontario streams and rivers delineates their relative size (stream order), flow direction, flow connections through lakes, as well as local and upstream catchment areas. This base map enables watershed analysis within quaternary watersheds of Southern Ontario (~500 km^2) at a fine resolution (10 m). Watershed analysis in the Far North is still limited with this dataset.
  - WRIP is now (2012-2013) completing a revised version (the Integrated Hydrology Data Suite) that updates the waterflow layers, makes corrections, and is designed to facilitate watershed analysis within all of the large secondary watersheds (~38,000 km^2) of Ontario at a medium resolution (30 m).
  - The advantages of the new Integrated Hydrology data are that watershed analysis can also be performed in areas of the Far North where Quaternary watersheds are not available. Watershed analysis will be integrated across larger spatial extents, thus honouring the hydrologic connections in large areas of the Far North (and southern Ontario). The coarser resolution also allows for improved GIS processing time.
- New version of the Ontario Flow Assessment Tool (OFAT)
  - OFAT v1.0 was completed in 2002 and this tool estimates flow information for watersheds in Ontario
  - The new version of OFAT is currently being developed by WRIP and this tool will allow users to extract summary landcover and geologic information in addition to flow estimation within user-defined watersheds. Preparation of data layers for OFAT is consistent with AEC project needs and the two projects could combine efforts with anticipated cost savings as a result.
- Completed water body data (including differentiation between lakes and double line rivers)



Reach #	Forest	Geology class	Clay	Climate
Reach 1	% cover	% cover	% cover	Mean GDD
Reach 2	...	...	...	...
Reach 3	...	...	...	...

Segment #	Forest	Geology class	Clay	Climate
Seg 1	% cover	% cover	% cover	Mean GDD
Seg 2	...	...	...	...
Seg 3	...	...	...	...

Figure 11: *Flow chart of next steps for Aquatic Ecosystem Classification in Ontario.*

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11 APPENDIX 1

Landscape Descriptor	Source Data	Extent	Resolution	Date
Thematic Class Summaries	Landcover 28	Provincial	25m	1991-1998
Thematic Class Summaries	Far North Land Cover (FNLC)	Far North	30m	2005-2009
Thematic Class Summaries	Landcover 2000 (LC2000)	N Shield	25m	1999-2002
Thematic Class Summaries	S.ON Land Resource Information System (SOLRIS)	S Ontario	10m	2000-2002
Primary Material Thematic Class Summaries	Surficial Geology of Southern Ontario (MRD128)	S Ontario	1:50k - 1:250k	1950-2003
Permeability Thematic Class Summaries	Surficial Geology of Southern Ontario (MRD128)	S Ontario	1:50k - 1:250k	1950-2003
Material Thematic Class Summaries	Quaternary Geology of Ontario	Provincial	1:1M	various
Soil Drainage Class Summaries	Soil Landscapes of Canada v3.2	Provincial	1:1M	2011
Soil Drainage Class Summaries	Soils Ontario (Soil Survey Complex)	S Ontario	1:50k - 1:250k	since 1945
Physiography Type	Physiography of Ontario (MRD228)	S C Ontario	1:50k	2007 digital
Mean Annual Temperature	Canadian Forestry Services	Provincial	1km	various
Mean Annual Precipitation	Canadian Forestry Services	Provincial	1km	various
Cumulative Growing Degrees Days	MNR	Provincial	1km	various
Elevation Summaries	Integrated Hydrology Data	Provincial	30m	2012
Slope	Integrated Hydrology Data	Provincial	30m	2012
Stream Order (Strahler and Shreve)	Integrated Hydrology Data	Provincial	1:10:20k:50k	2012
Percent Lakes of UCA	Integrated Hydrology Data	Provincial	polygons	2012
Baseflow potential (Neff et al. 2005)	Quaternary Geology of Ontario	Provincial	polygon	2005
Baseflow potential (Piggott et al. 2007)	Quaternary Geology of Ontario	S. Ontario	polygon	2007
Turbidity (RSEL will develop the model)	-	Provincial	500m	-
Conductivity (RSEL will develop the model)	-	Provincial	500m	-

MNR 52730
ISBN 978-1-4606-2508-8 (Print)
ISBN 978-1-4606-2509-5 (PDF)