

**AQUATIC ECOSYSTEM CLASSIFICATION FOR
THE GREAT LAKES WATERSHED IN ONTARIO**

G. A. Wichert
and
J. S. MacKenzie

Ontario Ministry of Natural Resources
Natural Heritage Information Centre

and

P. Staples

Ontario Ministry of Natural Resources
Geomatics Service Centre

Peterborough, Ontario

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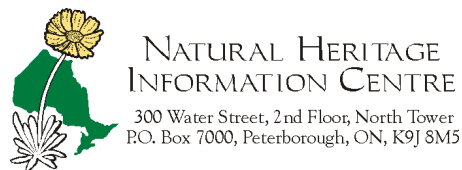


TABLE OF CONTENTS

I.	ABSTRACT.....	4
II.	INTRODUCTION.....	5
	A. STUDY AREA.....	6
	B. HISTORIC BIOPHYSICAL AND INSTITUTIONAL CONTEXT.....	8
	C. RELATED CLASSIFICATION INITIATIVES	9
III.	GROUNDWORK FOR THE AQUATIC ECOSYSTEM CLASSIFICATION	9
	A. PROJECT DESCRIPTION	9
	B. GOVERNANCE	12
	C. ONTARIO RIVERS AND STREAMS ECOLOGICAL CLASSIFICATION TECHNIQUES AND AQUATIC LANDSCAPE INVENTORY SYSTEM.....	12
IV.	AQUATIC ECOSYSTEM CLASSIFICATION: UPPER LEVELS.....	15
	A. SUBZONE: ARCTIC-ATLANTIC.....	19
	B. REGION: GREAT LAKES – ST. LAWRENCE.....	21
	C. SUBREGIONS: SUPERIOR, MICHIGAN-HURON, ERIE, ONTARIO	21
I.	AQUATIC ECOSYSTEM CLASSIFICATION: THE SUBWATERSHED LEVEL	23
	D. A CLASSIFICATION APPROACH FOR THE SUBWATERSHED LEVEL OF THE AQUATIC ECOSYSTEM CLASSIFICATION.....	24
	A. SUBWATERSHED LEVEL APPLICATION OF THE AQUATIC ECOSYSTEM CLASSIFICATION.....	25
V.	RATIONALE AND CLASSIFICATION CRITERIA FOR THE AQUATIC ECOSYSTEM CLASSIFICATION: GREAT LAKES COAST, STREAM SYSTEMS, WETLANDS, AND INLAND LAKES	27
	A. GREAT LAKES COAST	29
	1. <i>Rationale</i>	29
	2. <i>Application for shoreline and coast area</i>	30
	B. RIVERS AND STREAMS	31
	1. <i>Rationale for Rivers and Streams</i>	31
	2. <i>Application for Rivers and Streams</i>	38
	C. WETLANDS	40
	1. <i>Rationale</i>	40
	2. <i>Application for Wetlands</i>	40
	D. INLAND LAKES	42
	1. <i>Rationale</i>	42
	2. <i>Application of Inland Lake Classification</i>	49
VI.	GENERATING THE AQUATIC ECOSYSTEM CLASSIFICATION	52
	A. GEOGRAPHIC INFORMATION	52
	B. TECHNICAL METHODS	55
	1. <i>Great Lakes Coast</i>	55
	2. <i>Stream Systems</i>	57
	3. <i>Wetlands</i>	59
	4. <i>Inland Lakes</i>	60
	C. PRODUCT REVIEW.....	61
VII.	AQUATIC ECOSYSTEM CLASSIFICATION DATA SUMMARIES FOR EDU 5	63
	A. GREAT LAKES COAST	63
	B. STREAM SYSTEMS.....	64

C.	WETLANDS.....	66
D.	INLAND LAKES.....	67
VIII.	APPLICATIONS OF THE AQUATIC ECOSYSTEM CLASSIFICATION.....	68
IX.	ACKNOWLEDGMENTS	70
X.	REFERENCES.....	71
XI.	APPENDIX A. COMPARISON OF ALIS AND ORSECT.....	77
XII.	APPENDIX B: ALIS ATTRIBUTES	78

I. ABSTRACT

The Aquatic Ecosystem Classification is part of a hierarchical framework to classify aquatic ecosystems in the Ontario Great Lakes watershed. Upper levels in the hierarchy were defined by historic geo-climatic processes at continental and major drainage basin scales. Ecological Drainage Units (EDUs) within the Great Lakes watershed were defined by hydrology, climate and geology. Variation of these three variables within EDUs was less than variation among EDUs. Units at the smallest scale in this classification were aggregations of Great Lakes coastal areas and shorelines, stream segments, wetlands and inland lakes. Ecosystem components were classified by shoreline type, drainage pattern, geology, gradient, water storage potential, watershed position, wetland type, size, and shoreline morphology. Class intervals were defined using criteria that related to species richness, species distribution, types of species interactions that were reported in the literature. For each of the four system component types – Great Lakes coast, streams, wetlands and inland lakes - 50% of the Ecological Drainage Unit area was represented by 6 or fewer habitat types. In Ecological Drainage Unit 5, 95% of the Great Lakes coast was represented by 9 aquatic ecosystem unit types; for the streams, 25 types; for the wetlands, 7 types and for inland lakes, 10 types represented 95% of the drainage area. Aquatic ecosystem classification is foundational for applications that require identification and an inventory of the frequency and distribution of ecosystem units. Aquatic ecosystems units identified in this classification can be considered as sets of physical targets from which a sample of sites for conservation and protection of freshwater resources will be drawn. Other potential applications of the aquatic ecosystem classification include a guide for sample design for research and aquatic species inventories, environmental impact and monitoring, watershed based resource planning and management, and fisheries and other aquatic species assessment.

II. INTRODUCTION

In 2001 the Nature Conservancy of Canada, NCC, and the Ontario Ministry of Natural Resources, OMNR, formed a partnership to conduct the Great Lakes Aquatic Biodiversity Conservation Blueprint, GLABCB. The area of this undertaking included the rivers and streams, inland lakes, and wetlands draining into the Great Lakes and the Great Lakes coast, but not the deep water areas of the Great Lakes. The primary goal of this project was to identify representative aquatic natural features and biota in the Great Lakes region for conservation. A first step for meeting this goal required characterizing the aquatic ecosystems and aquatic biota for the study area. A second step was to design a conservation blueprint that comprises the existing network of conservation lands and protected areas, as well as other key sites that contribute to freshwater biodiversity conservation.

Key differences exist in how terrestrial and freshwater resources have been managed in Ontario. Direct management of freshwater biodiversity largely has been overlooked in the past due to a focus on managing access to exploitable resources by managing human behaviour. Second, although general guidelines for the management of freshwater resources exist, identifying and regulating protected areas for freshwater resources to date in Ontario has been largely incidental to terrestrial protection efforts. In other words, conservation planning in Ontario has emphasized terrestrial representation. In addition aquatic biodiversity is often thought of as a common property resource and is less subject to the regulations and policies relating to parcels of owned land. A provincial policy document "*Framework and Action Plan for Nature's Best*" (OMNR 1997) committed MNR to review methods to address classification of aquatic ecological diversity. An aquatic ecosystem classification would support aquatic biodiversity assessments and conservation efforts directly.

Mandrak (1998) assessed the suitability of the Ontario terrestrial classification system to protect the aquatic biodiversity throughout the province. He found weak areal correspondence between terrestrial classification regions and tertiary watersheds, and also weak areal correspondence between terrestrial classification regions and fish faunal zones. Poor correspondence between the terrestrial ecoregions and ecodistricts with tertiary watersheds and fish faunal regions suggests low potential for the terrestrial classification system to inform conservation of freshwater biota. Thus a system explicitly addressing freshwater biodiversity was required. The co-occurrence of the recognized need to consider aquatic features and biota directly and the initiation of the GLABCB prompted us to implement a GIS-based Aquatic Landscape Inventory System (ALIS) and develop an Aquatic Ecosystem Classification (AEC) for the Ontario Great Lakes watershed. Information from these tools can support numerous applications, the first of which is the Great Lakes Aquatic Biodiversity Conservation Blueprint. The AEC is a hierarchical framework that will provide classification and reporting on the number and area of stream systems, inland lakes, wetlands, and coast line types throughout the Great Lake watershed. With this information we can characterize the representation of aquatic ecosystem component classes and make informed decisions regarding conservation and protection. The AEC does not apply beyond the shoreline to the near shore and offshore parts of the Great Lakes.

The AEC is informed primarily by life history requirements and biological characteristics of fishes. An extensive electronic, geo-referenced distributional database for all fish species native to Ontario is available to develop and test the aquatic classification. We assume that although the AEC was developed from biological criteria explicitly relating to fish species, it is sufficiently general to relate to other aquatic taxa as well. As extensive databases for other aquatic taxa are developed, the AEC can be refined to relate more directly to them.

Upper levels in the AEC framework are described by individual Great Lakes watersheds and Ecological Drainage Units, EDUs. These EDUs, represent aggregations of tertiary watersheds that share similar drainage, geology and climate patterns. The lower levels of the AEC framework are referred to as subwatershed units. These subwatershed units are aggregations of classified stream segments, inland lakes, wetlands and Great Lakes coast units that were characterized through the ALIS process. Small-scale units, such as stream reaches and lake zones, should be considered part of an overall hierarchical framework but are not developed here because fine-scale remote sensing and field collected data are required but not available for large parts of the Great Lakes region.

Accomplishing an undertaking of this geographic scope required the development of automated GIS routines, inventory and organization of large quantities of physical and biological data, coordination of effort among numerous agencies and the integration of knowledge from current research, active practice, and the literature. Efforts to develop the AEC build on work of The Nature Conservancy in the U.S. Great Lakes region (Higgins et al. 1988, The Nature Conservancy 2001). Related initiatives addressing parts of the Great Lakes watershed include the bi-national Lake Huron Aquatic Habitat initiative of the Michigan Department of Natural Resources (MDNR) and OMNR, aquatic Gap analyses of the U.S. Environmental Protection Agency and the U.S. Geological Survey, and the Lake Erie Millennium Plan.

A. *STUDY AREA*

The Great Lakes basin comprises the lakes, connecting channels, tributaries and groundwater systems in both Canada and the United States that drain into the St. Lawrence River (Figure 1). The basin spans about 1200 km from west to east and lies within eight states and two provinces. Approximately 40 million people live in the basin or use water extracted from it (IJC 2000). Various land use activities including residential, industrial, agricultural, recreational, and water uses including consumption, power generation and cooling, transportation, cleaning and other industrial processes occur within the watershed. These activities influence physical habitat and water quality for the diverse freshwater biota living in the region.

A relatively young ecosystem, the Great Lakes basin was formed in its present configuration about 8,000 years ago as the Wisconsinan Glacier receded (Cudmore and Crossman 2000). Fishes from several refugia formed the nucleus of the present-day assemblage of fishes in the basin (Underhill 1986). As the glacier receded, inlets and outlets to the basin changed, allowing movement of freshwater biota in and out of the Great Lakes from adjacent basins during various periods.



Figure 1. Ontario portion of the Great Lakes watershed.

The Great Lakes are home to 142 established forms of fishes, both native and introduced (Cudmore and Crossman 2000). Of these, 26 species are considered ‘vulnerable’, ‘threatened’, ‘endangered’ or of ‘special concern’ by federal or provincial agencies (Table 1). Some 234 species either live or have lived within the Great Lakes drainage basin (Hubbs and Lagler 1981). Over the years 55 species have been introduced into one or more of the lakes – of these, 25 have become established (Cudmore and Crossman 2000). Twenty-six species have been extirpated from the lakes. Of these 26 species, four are globally extinct, three of which were endemic to the Great Lakes (Cudmore and Crossman 2000).

The Great Lakes watershed ecosystems also support 5 mollusc, 7 reptile, 6 amphibian, 9 aquatic bird, and 19 aquatic plant species listed as ‘vulnerable’, ‘threatened’, ‘endangered’, or ‘special concern’ by the Committee on the Status of Endangered Wildlife Species in Canada (COSEWIC) and the Ministry of Natural Resources.

Table ?? Number of aquatic species and communities listed in various conservation ranking processes. G- and S- ranks are assigned by Conservation Data Centres. Committee on the Status of Endangered Wildlife in Canada (COSEWIC) and Committee on the Status of Species at Risk in Ontario (COSSARO) assign ranks recognized by federal and provincial (MNR) legislation respectively.

Taxon	Number of G1-G3G4 species or communities	Number of S1-S3S4 species	Number of COSEWIC species at risk	Number of MNR species at risk (COSSARO)	Number of extirpated species
Mollusc	14	10	5	0	0
Reptile	0	7	7	5	0
Amphibian	0	4	5	4	1
Aquatic Bird	5	0	6	9	0
Fish	11	25	26	18	1
Aquatic Plant	19	28	19	9	0
Beetle (Coleoptera)	3	1	0	0	0
Mayfly (Ephemeroptera)	16	0	0	0	0
Dragonfly (Odonata)	7	7	0	0	0
Stonefly (Plecoptera)	4	2	0	0	0
Aquatic plant communities	9	13	Not applicable	Not applicable	Not applicable

B. HISTORIC BIOPHYSICAL AND INSTITUTIONAL CONTEXT

The Great Lakes have undergone profound transformations since permanent European settlements were established in the mid-19th Century (Sly 1991; Regier and Kay 1996). Early documented changes include extirpation of integrative fish species such as Atlantic salmon (*Salmo salar*) and local degradation of near shore areas and harbours, deforestation, and habitat fragmentation with dam construction for mill works and flood control. Canal construction facilitated species movements and invasion of exotics. Extensive wetland drainage for agriculture and settlement occurred throughout Southern Ontario. Fisheries and water quality issues were the emphases of early Great Lakes ecosystem rehabilitation efforts (Regier 1992). Ecosystemic connections were identified and described by the Pollution from Land Use Activities Reference Group process of the 1970s: between land and water, and between biota and water quality. (PLUARG 1980). Since the 1980s the Remedial Action Plan process supported measures to correct and reverse earlier degradation. To date Great Lakes research and rehabilitation has proceeded through a complex array of institutional arrangements and support, and a multiplicity of approaches. These efforts have produced multi-faceted perspectives on the issues and corrective measures. Parts of the Great Lakes watershed, such as recently settled areas in the Greater Toronto Area, have degraded despite corrective efforts (Wichert and Regier 1998). Continuing sources of degradation include point and non-point source inputs from agriculture, industry and human settlements, physical habitat alteration, and invasive species. Other areas of the Great Lakes watershed have improved, for example in historic settlements and agricultural areas

where state of the art mitigation and conservation measures have been practiced (Wichert and Regier 1998, Wichert and Rapport 1998). Still other areas remain relatively undisturbed, such as parts of the Niagara Escarpment and Oak Ridges Moraine in southern Ontario and tracts of land in the northern parts of the Great Lakes watershed. An application of an AEC will allow us to quantify in a spatially explicit way the amount of various types of aquatic ecosystem components and assess the conservation value of the landscape from aquatic perspectives.

C. RELATED CLASSIFICATION INITIATIVES

Busch and Sly (1992) suggested characteristics and considerations for developing aquatic habitat classification systems for the Great Lakes, connecting channels, wetlands, tributaries and inland lakes in the Great Lakes drainage area, however no comprehensive system emerged from that synthesis. An expert-derived stream habitat classification has been applied in Michigan (Seelbach et al. 1997) and for inland lakes, streams, and near shore Great Lakes throughout the US portion of the basin (Higgins et al. 1998). A stream delineation and segment characterization protocol was developed for the Lake Huron basin (Stanfield and Kilgour 2001; Stanfield and Kuyvenhoven 2002).

The Ontario Living Legacy (OLL) Land Use Strategy is the result of an extensive planning process that began in 1997. Large parts of the Lake Superior and Huron drainage areas are included in the OLL planning area. An objective of the OLL land use strategy relates to conservation of natural resources through completion of Ontario's system of parks and protected areas (MNR 1999). To date the identification of protected areas in Ontario relied on representation of terrestrial features. The OLL work provides a rich context, legacy, and opportunity to implement the AEC and aquatic conservation initiatives. The AEC represents the first comprehensive compilation of watershed data for Ontario's Great Lakes basin.

III. GROUNDWORK FOR THE AQUATIC ECOSYSTEM CLASSIFICATION

A. PROJECT DESCRIPTION

Both the Ontario Ministry of Natural Resources, OMNR, and the Nature Conservancy of Canada, NCC, recognized the need to develop geographically extensive methods to directly assess and consider the conservation of aquatic biodiversity across the Ontario Great Lakes watershed. This realization became apparent by the growing gap in Great Lakes regional aquatic studies conducted by U.S. and Canadian agencies. Early U.S. initiatives include valley segmentation and characterization of Michigan rivers and streams flowing into the Great Lakes (Seelbach et al. 1997). This conceptual approach was applied in the Lake Huron watershed and throughout the Great Lakes watershed, e.g. TNC ecoregional plans, USGS aquatic gap, OMNR-NCC aquatic conservation blueprint. The second impetus in Ontario for proceeding with geographically extensive and comprehensive classification and aquatic biodiversity conservation was policy driven. The policy document 'Framework and Action Plan for Nature's Best' (MNR 1997) required OMNR to review aquatic classification methods and protect representative

aquatic resources. These directives spurred the creation of the GLABCB project and the attendant development of the AEC.

Although coordinated through a partnership arrangement between the Natural Heritage Information Centre, NHIC, and the NCC, the Great Lakes Conservation Blueprint project draws on expertise and resources within OMNR from Ontario Parks, Conservation and Planning, Aquatic Research and Development, and Fisheries Section for developing the AEC. The array of contributors shows the broad distribution of interest and expertise across the Ministry and the potential for diverse application of analytical tools and findings from the aquatic classification exercise. Other contributors came from NGOs, federal governmental agencies, and universities.

Aquatic Ecosystem Classification required development and adaptation of GIS routines to delineate and characterize AEUs. We defined the aquatic classification largely on biological relationships reported in the literature. The classification was implemented in a pilot area and following a peer review modified and extended throughout the Great Lakes watershed. The development process is summarized in Figure 2.

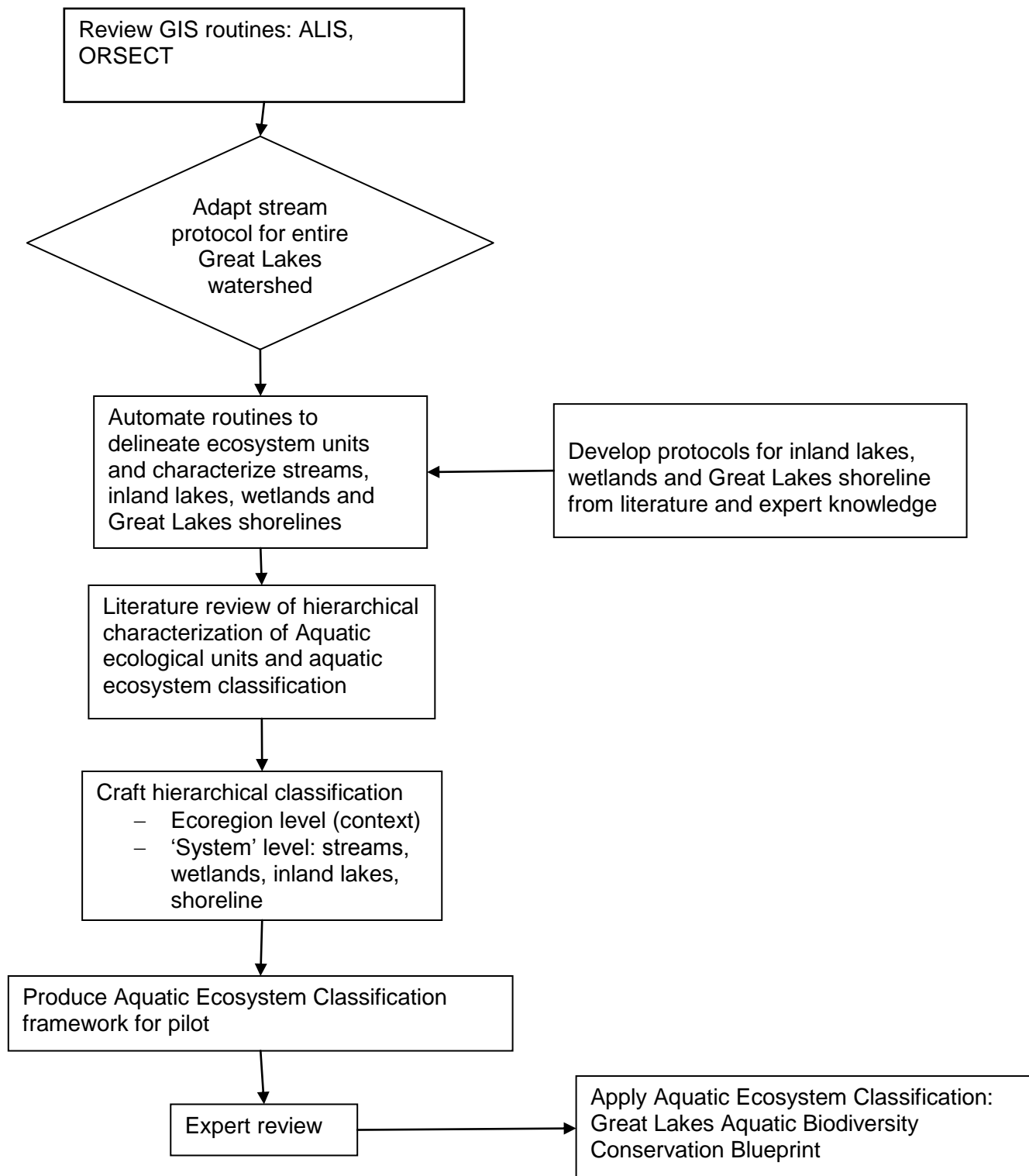


Figure 2. Key steps to develop the Aquatic Ecosystem Classification for the Great Lakes watershed. 'ALIS' means Aquatic Landscape Inventory System and 'ORSECT' means Ontario River and Stream Ecological Classification Techniques.

B. GOVERNANCE

Development of the AEC to date has occurred largely within the Aquatic Blueprint project. We assembled three teams to guide Blueprint development and production (Figure 3). The project steering committee comprises MNR managers and key NCC personnel. This group provides overall project leadership and strategic direction ensuring that project deliverables fit within the priorities of the two principal project partners.

Members of the project core team represent federal and provincial agencies, universities and key sectoral non-governmental organizations. This team ensured communication of related initiatives, and helped provide project scope in the context of ongoing and future conservation efforts. We drew science team members from federal and provincial government organizations, universities and NGOs. The science team provided guidance on technical and scientific aspects of data collection, organization, classification, interpretation, and application. A fourth team will focus on conservation issues such as assessing conservation values for locales and priority ranking locales for protection according to assessed values. This team will focus on an application of the AEC for freshwater conservation during the design of the Conservation Blueprint.

C. ONTARIO RIVERS and STREAMS ECOLOGICAL CLASSIFICATION TECHNIQUES and AQUATIC LANDSCAPE INVENTORY SYSTEM

Two river and stream segmentation applications were under development within OMNR when the GLABCB project began. The Ontario River and Stream Ecological Classification Techniques, ORSECT, application was coordinated by, Northeast Science and Technology. The Water Power project contributed significant support for ORSECT development and field testing. The Aquatic Landscape Inventory System, ALIS, supported partly by Michigan Department of Natural Resources, emerged from the Lake Huron Aquatic Habitat GIS project. Les Stanfield, Aquatic Research and Development Section, coordinated the OMNR contribution to that project.

Both ALIS and ORSECT were intended for automated characterization of watersheds. In its first iteration ORSECT was designed for delineation and characterization of watersheds upstream from user-defined (especially manually defined) points. The program was developed for and tested on northern rivers and streams but designed with flexibility for application throughout Ontario. ALIS was developed initially for application throughout the Ontario portion of the Lake Huron watershed. Although planned from the beginning, user-defined point delineation was to be added in a later version of the ALIS software. A comparison of procedures revealed that ALIS and ORSECT differed mainly in the process for identifying delineation criteria of aquatic ecosystems, validation of the GIS output through field surveys for ground-truthing, and timelines for development and extensive regional application (Appendix A).

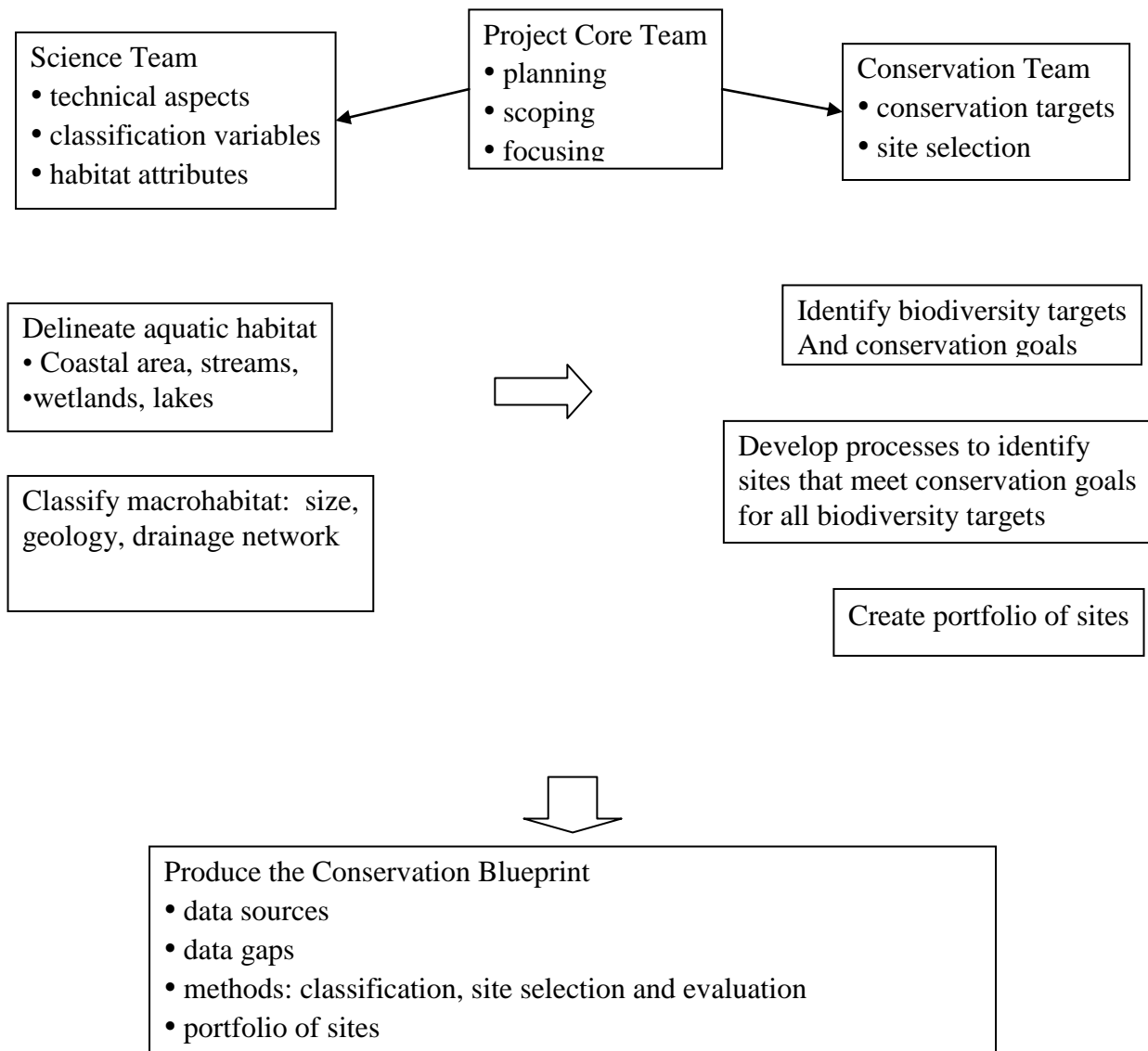
Validation of the GIS applications requires two processes: assessment of the GIS routines to ensure they represent the underlying digital landscape data accurately, and ground-truthing to assess the accuracy of the mapped data. Ensuring accurate

representation of the digital data by the GIS application was within the scope of the Conservation Blueprint project. Correcting errors associated with ground-truthing mapped information is more complicated, requiring field work and often requiring alterations to the

underlying base data, and was outside the scope of the GLABCB. The ORSECT development strategy included a comparison of GIS-derived and field-collected data from a few study areas prior to developing ORSECT for geographically extensive application. This strategy dictated a protracted development schedule that extended beyond the Conservation Blueprint project. The GLABCB project supported ALIS primarily because ALIS development timelines fit the Blueprint schedule better than the ORSECT development timelines. Ongoing revisions of both GIS applications, and the development of interchangeable computer processes for ALIS and ORSECT meant no long term penalty associated with adopting either of the two GIS applications.

Since the early development period in 2001, distinctive analytical procedures for aquatic ecosystem delineation and characterization associated with either ALIS or ORSECT have blurred because modules for specific routines have been placed into an 'application toolbox', a library for GIS analytical code, and can be incorporated readily into any number of watershed-based applications. By initially supporting two GIS applications with considerable functional overlap the OMNR has fostered creative solutions to challenges presented by aquatic ecosystem analysis at large geographic scales. That initial creativity has been refined and possible redundancy now reduced by creating a central repository of transferable computer code.

Figure 3. Governance structure and key roles for Aquatic Conservation Blueprint project teams.



IV. AQUATIC ECOSYSTEM CLASSIFICATION: UPPER LEVELS

Maxwell et al. (1995) provide a generic hierarchical framework for characterizing aquatic habitat at scales ranging from continental to stream site. Aquatic ecosystem characterization, especially as it relates to conservation, has progressed from mapping existing features that relate to species and groups of species, to reflecting understanding of some of the processes influencing ecological units at multiple spatial and temporal scales (Table 2). Knowledge of key climate and geological processes provides context for zoogeography in the recent and distant past, and thus guides present-day conservation activities. There are no clear guidelines for which era of historical zoogeography best relates to present conservation efforts but presumably links between the lengths of the zoogeographical time line into the past should be proportional to the geographic size of the conservation undertaking. For conservation at the level of the Great Lakes watershed, glacial access routes for freshwater biota, as reflected by current hydrology, and regional climate should be accounted for (Mandrak 1995). For smaller conservation efforts Holling (1985) suggested appropriate temporal and spatial scales for management should relate to the spatial requirements for all life cycle components of the species requiring the largest area and temporal management scale should be some interval of the life cycle of the longest-lived species. Minns (1995) provides information on the home range size for many fish species found in Ontario waters. These criteria may be suitable for management of smaller areas – 10s km² to 100s km² – and time frames of decades to several centuries.

Hierarchical frameworks have emerged as conceptual models identifying relationships between geo-climatic features, the area encompassed by these features, types of disturbances and associated biotic processes, and the time duration over which these changes and processes may occur (Frisell et al. 1986; Maxwell et al. 1995). These types of frameworks provide ways of organizing data from the natural sciences to allow relevant interpretations for locating and determining sizes or areas for conservation protection (Table 2).

Mandrak (1999) developed an aquatic classification system for Ontario applicable at an eco-regional scale (thousands of square kilometres). He defined regions analogous to eco-zones, eco-provinces and eco-regions based on 16 variables related to 5 factors – climate, bedrock geology, surficial geology, and glacial history. Principle Component Analysis showed that climate variables loaded high on the first axis and bedrock geology variables loaded high on the second axis. Variables associated with climate and bedrock geology influenced the structuring of fish communities in 5 eco-zones, 10 eco-provinces, and 15 eco-regions. Differences in bedrock geology, climate, glacial history, lake morphology, stream flow, surficial geology and water chemistry were observed among many of the eco-zones, eco-provinces, and eco-regions of Ontario (Mandrak 1999). The relative influences of biophysical processes on structuring aquatic habitat depend on temporal and geographical scales. Influences of geology, climate and large-scale drainage are associated with spatial units of 1,000s to 10,000 km² and 100s to 1,000s of years. Influences of gradient, geological permeability, water storage potential, connectivity of lakes, wetlands and streams are relevant at spatial units of 10s to 100s

Table 2. Nested hierarchy for Great Lakes basin and map units for ecological units at upper hierarchical levels.

Aquatic units	Mapping scale	Physical features	Dynamic variables	Criteria	Observed biotic processes
Subzone: Arctic-Atlantic	1:7,500,000	Basin boundaries River networks Regional climate Regional geology	Tectonics Glaciation	Fish family patterns	Speciation and extinction (Mayden 1992)
Region: St. Lawrence	1:7,500,000	Basin boundaries River networks Regional climate Regional geology	Tectonics Glaciation	Fish community patterns	Speciation and extinction (Maxwell et al. 1995; Underhill 1986)
Subregion: Great Lakes, i.e. Superior, Michigan-Huron, and Erie-Ontario	1:7,500,000	Basin boundaries River networks Regional climate Regional geology	Tectonics Glaciation	Fish community sub-patterns	Speciation and extinction, endemism (Underhill 1986; Cudmore and Crossman 2000)
River basins: individual Great Lake basins	1:2,000,000 to 1:5,000,000	Basin boundaries River networks Regional climate Regional geology	Tectonics Glaciation	Fish species assemblages (endemism)	Endemism, Speciation and extinction (Underhill 1986; Cudmore and Crossman 2000)
Sub-basins: parts of Great Lakes, major tributaries	1:1,000,000 to 1:2,000,000	Basin boundaries River networks Regional climate Regional geology	Tectonics Glaciation	Physiography and species groups	Endemism, Speciation and extinction (Underhill 1986; Cudmore and Crossman 2000)
Watersheds	1:1,000,000	Watershed boundaries Stream networks Geomorphology Local climate	Local uplift Folding/faulting Flood cycles	Genetic variation	Separation of lake trout stocks (Goodier et al. 1981)
Subwatersheds	1:500,000 to 1:100,000	Stream networks Geomorphology Local climate	Local uplift Folding/faulting Flood cycles	Genetic variation Population demographics	Structuring of communities in part by biogeography and predation (Hinch et al. 1991)

Aquatic units	Mapping scale	Physical features	Dynamic variables	Criteria	Observed biotic processes
Valley units, inland lakes	1:50,000 to 1:20,000	Valley geomorphology (flowing water) Morphometry (lakes) Climate regime Hydrologic regime	Valley filling Channel migration Stream incision	Population demographics	Local extinction and re- colonization owing to predation (MacRae and Jackson 2001; Jackson et al. 2001) Winter-kill (Tonn and Magnuson 1982)
Stream reaches, lake zones	1:10,000 to 1:20,000	Channel morphology (flowing water) Littoral, pelagic and profundal zones (lakes) Bedform/materials Bank conditions Woody debris	Peak flows Sediment transport	Population dynamics	Feeding, spawning, and juvenile refuge (Schlosser 1991)
Channel units, lake sites	Typically \leq 10m long	Habitat features Depth patterns Debris patterns Springs Inlets, outlets (lakes)	Hydraulics Scour and deposition Bed load sorting	Behavior	Feeding, spawning, and juvenile refuge (Schlosser 1991)

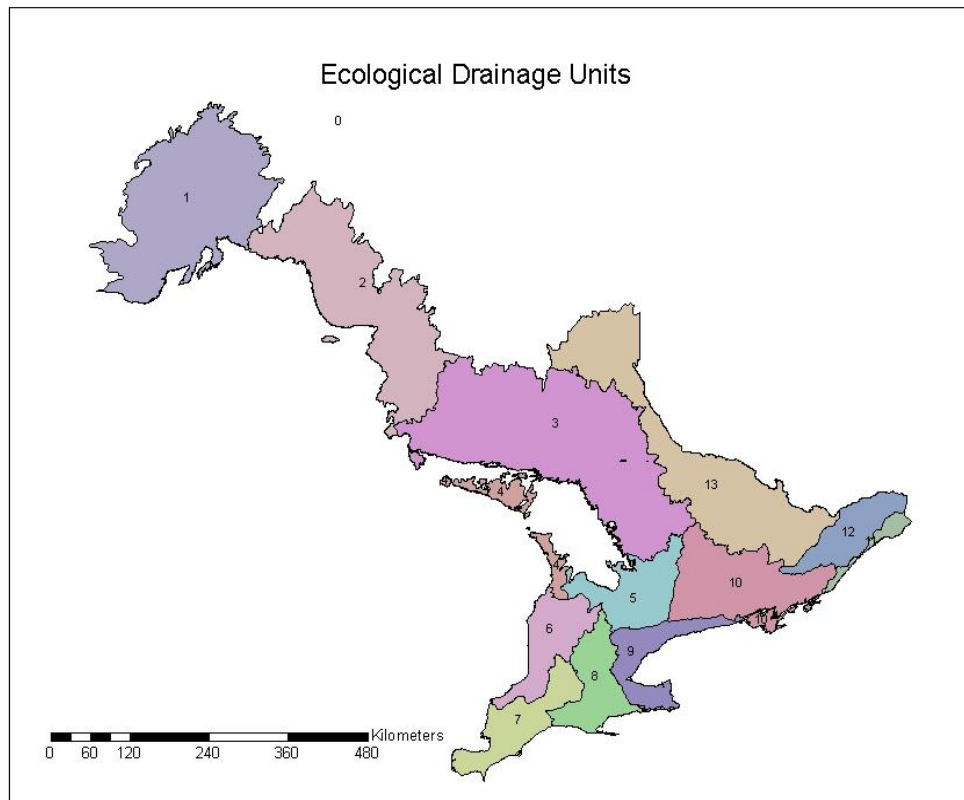


Figure 4. Ecological Drainage Units in the Great Lakes watershed.

km² and 10s to 100s of years. Scale-related influences of biophysical processes were incorporated into the AEC by delineating watershed ecosystems at three main hierarchical levels: the Great Lakes watershed; Ecological Drainage Units (EDUs), which are aggregations of tertiary watersheds; and subwatershed units – aggregations of classified stream segments, inland lakes, wetlands and coastal areas. We delineated 13 EDUs across the Great Lakes watershed based on large scale drainage patterns, geology and climate (Figure 4). Although some variation in geology and climate exists within the 13 EDUs in the Ontario Great Lakes watershed, our intent was to ensure that within EDU variance was less than the variance among EDUs. We used EDUs to stratify stream systems, inland lakes, wetlands and coastal features thus accounting for climate and glacial historic processes, such as dispersal corridors and access to glacial refugia that are observed at large spatial and temporal scales. Within EDUs we classified AECs using classification variables that indicated influential process responses occurring within mid-level ecological scales that are relevant to resource management and mapping. These variables represent processes that are thought to influence species richness and productivity of freshwater species within the classified AECs.

We used the upper ecological units described by Maxwell et al. (1995), Abell et al. (2000) and Mandrak (1999) with illustrations relevant to the Great Lakes basin from Underhill, (1986) Cudmore-Vokey and Crossman (2000) to describe AEC levels above the EDU. These upper level classes provide a context for classifying the stream segments, inland lake units, wetlands and coastline features of the Great Lakes.

Features at upper levels were formed by plate tectonics and glacial cycles and can be characterized by fish distributions; features at lower levels in the hierarchy are shaped by fluvial processes and characterized by site-specific habitat features such as substrate, depth, light penetration. The following provides an upper level nomenclature for the hierarchical structure defining aquatic habitat in the Ontario portion of the Great Lakes basin. The defining processes and some characteristics of the upper level ecological units in which the Great Lakes watershed is nested are described briefly below.

A. SUBZONE: ARCTIC-ATLANTIC

The North American continent has been divided into three subzones – the Pacific, the Arctic-Atlantic, and the Mexican transition zone (Maxwell et al. 1995). The Laurentian Great Lakes are nested within the Arctic-Atlantic subzone (Figure 5). Mountain-building processes and plate tectonics separated these subzones resulting in distinct aquatic communities in the three areas. Family patterns are the key defining biological criteria for the Arctic-Atlantic subzone. Distribution of fish fauna of the Pacific subzone was restricted leading to endemism; fishes of the Arctic-Atlantic were widespread, and those of the Mexican transition reflect both expansion and restriction (Maxwell et al. 1995). The Arctic-Atlantic sub-zone can be characterized by Cyprinidae, Percidae, Centrarchidae, Ictaluridae (Mayden 1992).

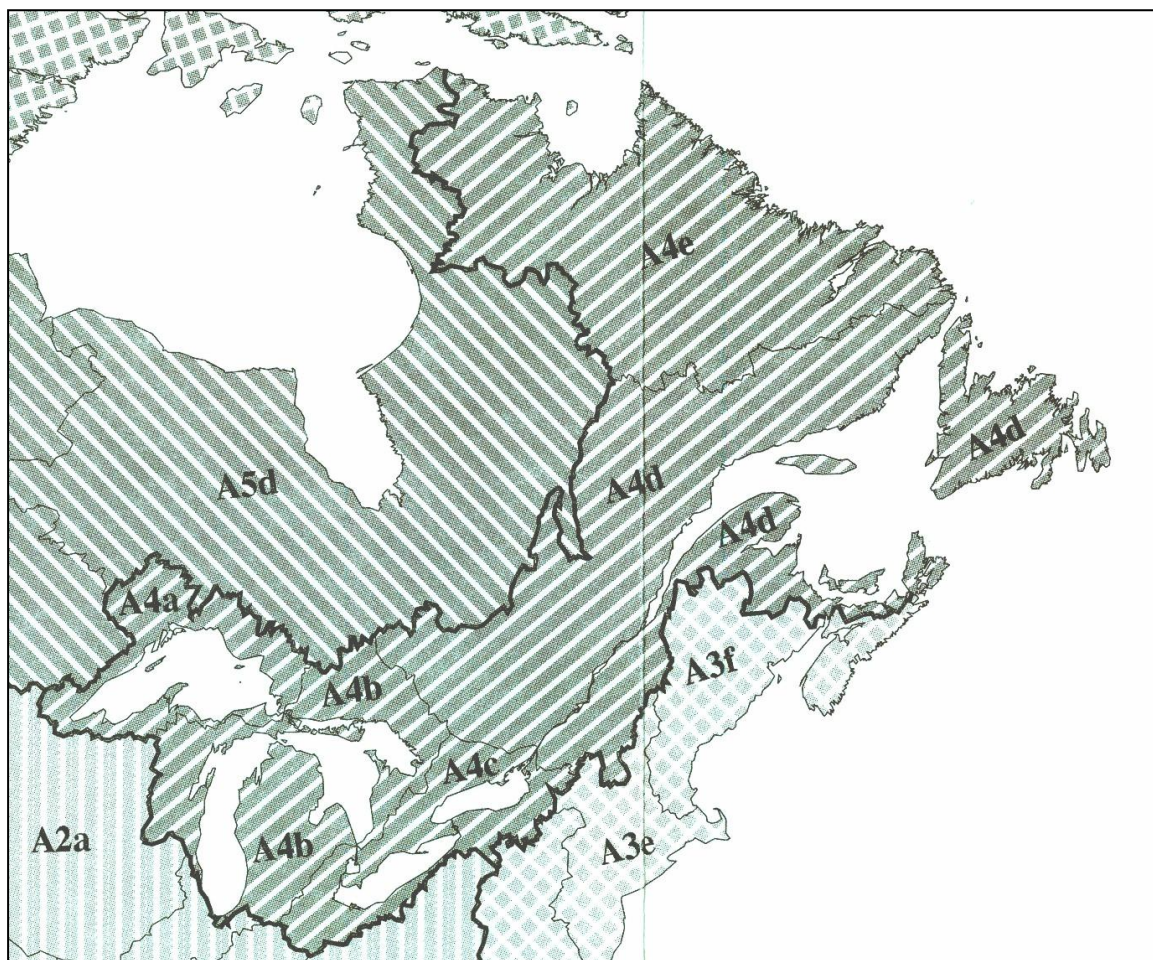


Figure 5. Great Lakes Subregions Superior (A4a), Michigan-Huron (A4b), Erie (A4c), and Ontario (A4d) within the St. Lawrence Region (A4) and the Arctic-Atlantic Subzone (A) (adapted from Maxwell et al. 1995).

B. REGION: GREAT LAKES – ST. LAWRENCE

The Great Lakes – St. Lawrence region is one of six regions in the Arctic-Atlantic sub-zone (Maxwell et al. 1995). Glacial cycles, the most recent Wisconsinan glacier in particular, formed this region. Changes in dispersal routes and isolation within subzones caused by geoclimatic factors – e.g. formation and drainage of glacial lakes and isostatic rebound – refined fish distributions in the Great Lakes region.

Fish community patterns are the key defining biological criteria for regions. Merging and separation of groups of fish caused by Pleistocene glaciation and Appalachian formation may have led to patterns of unique communities, endemism and dispersal within fish families (Maxwell et al. 1995). The mix of species in the Great Lakes – St. Lawrence basin came from the Mississippi and Atlantic drainages to the south, from a northwestern location (e.g. Yukon and Alaska) or evolved from pre-cursors (Underhill 1986).

C. SUBREGIONS: SUPERIOR, MICHIGAN-HURON, ERIE, ONTARIO

Primarily the advance and retreat of the Wisconsinan ice sheets formed the Superior, Michigan-Huron, Erie, and Ontario subregions. Maxwell et al. (1995) and Abell et al. (2000) differ on definitions for the Erie and Ontario sub-region. Historical connections to neighbouring refugia and connections among the three subregions led to observed fish community sub-patterns.

Fish community sub-patterns are the key defining biological criteria for subregions. Some general sub-patterns include endemism and unique fish communities; fauna within a subregion show common ancestry with others in the region; historic mixing and isolation of basins created the population distributions of the subregions (Maxwell et al. 1995). Regional climate and geology maintain the distinctive character of these sub-basins. Within the Great Lakes subregion, faunal similarity is greater than similarity to other parts of the St. Lawrence region (Underhill 1986). Unique taxa for each of the Great Lakes in Table 3 may relate in part to sub-basin units; coregonine fishes are endemic to the Great Lakes (Goodier 1981).

In summary, distribution patterns of fish families, communities and the observance of some endemic species demonstrates the relationships among an upper level hierarchical organization of ecological units and associated biological processes. Furthermore, EDUs stratify repeating patterns of Great Lakes coast, stream system, wetland and inland lake types across the Great Lakes watershed in terms of geology and climate.

Table 3. Unique taxa to each of the Great Lakes. N = established, native; I = established, introduced.

Lake	Taxa unique to that lake drainage	Reference
Superior	<i>Coregonus kiyi</i> (kiyi) N <i>Prosopium coulterii</i> (pygmy whitefish) N <i>Salvelinus namaycush siscowet</i> N	Cudmore and Crossman 2000 Cudmore and Crossman 2000 Cudmore and Crossman 2000
Michigan	<i>Ichthyomyzon castaneus</i> (chestnut lamprey) N <i>Lepisosteus platostomus</i> N/I ^a <i>Campostoma oligolepis</i> N <i>Notropis blennioides</i> N <i>N. chalybaeus</i> N <i>Fundulus dispar</i> N <i>Ammocrypta clara</i> N <i>Etheostoma chlorosomum</i> N <i>E. zonale</i> N <i>Percina phoxocephala</i> N	Cudmore and Crossman 2000 Cudmore and Crossman 2000; Underhill 1986 Underhill 1986 Underhill 1986 Underhill 1986 Underhill 1986 Underhill 1986 Underhill 1986 Underhill 1986
Huron	None	Underhill 1986; Cudmore and Crossman 2000
Erie	<i>Notropis buccatus</i> (silverjaw minnow) N	Cudmore and Crossman 2000
Ontario	<i>Anguilla rostrata</i> (American eel) N <i>Semotilus corporalis</i> (fallfish) N <i>Esox niger</i> I	Cudmore and Crossman 2000 Cudmore and Crossman 2000 Cudmore and Crossman 2000

^a Underhill (1986) suggests this species is native; Cudmore and Crossman (2000) suggest this species was introduced

I. AQUATIC ECOSYSTEM CLASSIFICATION: THE SUBWATERSHED LEVEL

The hierarchical classification framework provides the basis for understanding how habitat and climate influence the distribution and abundance of aquatic organisms. The Aquatic Ecological Classification, AEC, developed here classifies physical features and is conceptually analogous to terrestrial land classification in Ontario (Hills 1952; Lee et al. 1998). The field of aquatic classification is not as well developed as land classification in Ontario. We compared and interpreted terrestrial and aquatic hierarchical units, and aimed for consistent application of hierarchical classification factors associated with aquatic hierarchical units (Table 4).

The entire Great Lakes basin, individual Great Lake watersheds, Ecological Drainage Units, tertiary watersheds, and Aquatic Ecological Units (AEUs) are the terms we use to define the five hierarchical levels referred to in the Aquatic Ecosystem Classification (Table 4). The entire Great Lakes basin and individual Great Lake watersheds are the largest spatial units we consider in the AEC. These units respond to disturbance processes such as plate tectonics and glacial cycles. Approximate time for change is greater than 10,000 years and biotic processes observed at this scale are speciation and extinction (Maxwell et al. 1995). Ecological Drainage Units are aggregations of tertiary watersheds that respond to local uplift, faulting and folding, and flood cycles. Biotic processes include genetic variation and time for change is 1,000 to 10,000 years (Maxwell et al. 1995). The tertiary watersheds are convenient for watershed management and planning, but these units do not reflect the application of ecological criteria in their delineation. Aquatic Ecological Units are the smallest units we define in the Aquatic Ecosystem Classification. These units represent individual Great Lakes coastal polygons, inland lakes, wetlands, or aggregations of adjacent stream segments within the same class in terms of watershed position, gradient, permeability and water storage potential. Relevant disturbance processes for AEUs include geomorphology and local climate regimes and similar AEU types are expected to show similar population demographics. Approximate time for change in configuration of AEUs is 100 to 1,000 years (Maxwell et al. 1995).

Aquatic ecosystem delineation and characterization underlie the subwatershed level of the AEC hierarchy. Organizing and classifying variables across numerous spatial scales contributes to understanding ecological phenomena and processes. Habitat delineation refers to a set of routines, in this case automated, that direct the extraction and organization of data from various map layers – e.g. surficial geology, hydrology. These (raw) data can be used to characterize hydrological and landscape features thought to relate to the provision of functional aquatic habitat.

Habitat classification refers to the process of re-organizing the information (raw data) assembled during habitat delineation, analyzing and interpreting the information for particular applications. Examples of applications for habitat classification include:

- Site selection for research;
- Site selection for ecosystem bio-monitoring;
- Watershed-based resource planning and management;
- Fisheries and other aquatic species assessment;
- Predicting aquatic species abundance, distributions and production;

- Targeting field collections for particular aquatic species and communities; and
- Conservation of biota and habitat protection.

Table 4. Comparison between terrestrial Land Classification and proposed Aquatic Ecosystem Classification units.

Terrestrial units	Aquatic units	Spatial scale	Classification factors for aquatic units
Eco-zone	Entire Great Lakes basin	10,000s to 100,000s km ²	Continental-scale climate; plate tectonics; glaciation pattern
Eco-province	Individual Great Lake watersheds	1,000s to 10,000s km ²	Regional climate; post-glacial dynamics
Eco-region	Ecological Drainage Units	1,000s to 10,000s km ²	Consistent AEU response to hydrologic and climatic influence
Eco-district	Tertiary watersheds	100s to 1,000s km ²	Drainage based; scale appropriate for management and planning
Eco-site	Aquatic ecological units (AEU)	10s to 100s km ²	Relative uniformity within AEU with respect to hydrological properties, mappable units

D. A CLASSIFICATION APPROACH FOR THE SUBWATERSHED LEVEL OF THE AQUATIC ECOSYSTEM CLASSIFICATION

Data classification is often required for synthesis and summary and to resolve complex, multivariate data into understandable patterns. Classification also aids in the display of spatial information. Selection of class intervals is crucial to classify and analyze data and present findings. A classification system might be designed to reflect ecological or physiological requirements of organisms in a particular locale or region. In such an approach, variables for classification and class intervals are selected based on life history characteristics of key indicator species or groups of species. For example, temperature classes might reflect optimum temperatures for growth of cold, cool and warm species; substrate classes might reflect particle size requirements for members of lithophil (non-guarding fish that deposit eggs on gravel or rocky substrate), non-lithophil, phytophil (male guarders, eggs are scattered onto submerged plants) and polyphil (fish are not particular in selection of nest material or substrate) spawning guilds. Habitat classification based on ecological criteria provides high relevance to abiotic data but application is limited to the range of the species and groups of species used to define the classification variables and intervals.

Defining class intervals based on species-related criteria imparts a high degree of ecological meaning to the classification scheme. We defined class intervals using ecological information when justification for those decisions was supported in the

literature. When we found no support in the literature for ecological class intervals, we defined class intervals based on information in the literature that may relate to abiotic processes. Classification based on ecological processes and species-related criteria should be applicable in all regions where ecosystems supporting those phenomena are found.

A. SUBWATERSHED LEVEL APPLICATION OF THE AQUATIC ECOSYSTEM CLASSIFICATION

The AEC aggregates stream segments into stream system types, and classifies individual inland lakes, wetlands and Great Lakes shoreline features. Stream system polygons, inland lakes and wetlands relate to the AEU's in the hierarchy described in Table 4.

Inland lakes and wetlands are considered in two ways in the AEC. The proportion of the lake and wetland area to the total drainage of a stream system unit is an emergent property of these features and characterizes water storage potential. In addition individual inland lakes and wetlands are classified based on size, shoreline complexity, geological context and connectivity thus these features are used in different ways to characterize different components of aquatic ecosystems. Lake depth is a key variable for lake classification; however this information is available for only a small set of lakes within the study area, and therefore was not used in the AEC.

Key characteristics of numerous classification initiatives relevant to the Great Lakes region are shown in Table 5. Findings from these studies informed the AEC for the Ontario Great Lakes watershed described below.

Ricker (1934) and Hallam (1959) developed classification systems for Ontario and southern Ontario streams respectively. These two systems characterized streams at the sub-watershed level using site-level data. Ricker (1934) used site level physical features such as water temperature and flow rate, stream width, depth and substrate properties; water chemistry; and distribution of aquatic flora and fauna. Hallam (1959) focused on biotic factors including the seasonal presence of cold, cool and warm water fishes, physical features such as flow velocity, distance from source, amount of shade; and associations among "cardinal" indicator fish species and abundant macro invertebrates. These systems focus on a few integrative indicator species as the basis for aquatic habitat classification.

Portt et al. (1989) separated and grouped stream reaches based on climate, physiography, and soil drainage properties. Stream reaches classified by physiography and soil drainage were related to the presence of representative cold, cool, and warm water fish species. The classifications above outlined important factors to distinguish among streams at subwatershed and site-level scales but none gained widespread, long-term acceptance and implementation.

Johnson et al. (1977) and Marshall and Ryan (1987) characterized inland lakes by presence and abundance of Centrarchid, Percid and Salmonid communities. These indicator species are useful for specifying general habitat conditions that may be suitable for a variety of taxa.

V. RATIONALE AND CLASSIFICATION CRITERIA FOR THE AQUATIC ECOSYSTEM CLASSIFICATION: GREAT LAKES COAST, STREAM SYSTEMS, WETLANDS, AND INLAND LAKES

We considered four ecosystem components in the subwatershed level of the AEC – Great Lakes coast line, stream systems, inland lakes, and wetlands. Numerous physical, chemical, and biotic variables have been proposed and tested in previous studies for their utility in classifying aquatic habitat. We reviewed and selected variables for classification based on ecological relevance and practical consideration such as availability and comprehensive geographic representation in the study area.

Links between biological processes and physical features are observed at various scales and identified in various branches of the life sciences such as physiology, behavioural and community ecology, ecosystem studies, landscape ecology (Magnuson 1990). Possible links between fields of inquiry and observed phenomena are identified in Figure 6. Note that the processes governing physiological ecology operate sub-organismally but the effects of these processes may be observed somewhat independently of spatial scale. Some ecological and biological processes at landscape and other spatial scales, e.g. ecosystem and community ecology, and physical measures from which these processes might be inferred are provided in Table 2. Through careful consideration of site and landscape-level variables, ecological and biological processes operating at numerous spatial scales might be interpreted from the ecological units classified in the AEC.

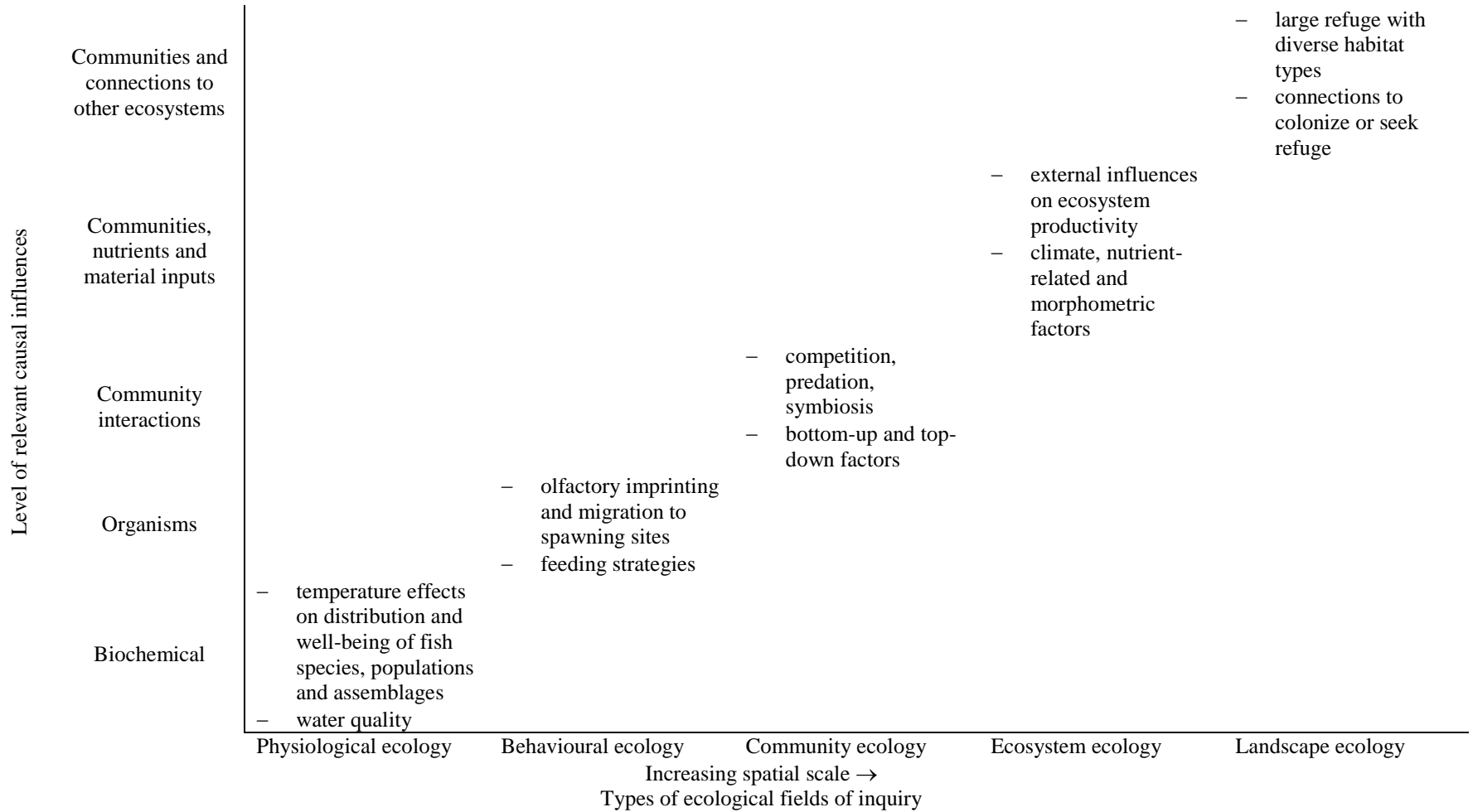


Figure 6. Types of causal links and spatial scales at which they occur for various fields of ecological inquiry. Physiological ecology operates at intra-organismal levels; physiological effects can be observed at multiple spatial scales.

Ultimately all biological communities are the net result of speciation and extinction. Numerous physical factors and biological processes shape community structure in more proximate ways. Influential physical factors readily interpreted from digital spatial data include gradient; soil type; surficial and bedrock geological features; distance from river source, mouth, or connecting water body; and land cover. This information can be used to interpret habitat heterogeneity at large spatial scales. One of the constraints for the development of the AEC at this geographical scale is that data for delineation, classification, and ecological and biological analyses must be readily available in digital format and should be spatially comprehensive. Features such as water depth, light penetration, substrate size, flow velocity, and vegetation patterns, usually require field sampling and cannot be addressed directly in this iteration of AEC development and application. Nevertheless we provide findings from studies that reported on field collected data because they can guide further AEC development.

Frequently measured water chemistry variables include pH, conductivity, alkalinity, turbidity, and phosphorus and nitrogen concentration. These variables provide insight into the nutrient status and suitability of the aqueous habitat to support various species. Although data from remote sensing is becoming more available for some water chemistry variables, most are collected from networks of sampling stations or during specific site visits. These data are not usually available for relatively large regions such as the Great Lakes watershed, but may be suitable for characterizing particular locales. Future iterations of the AEC may focus on parts of the Great Lakes watershed where detailed data exist or may utilize advanced remote sensing technology capable of providing very detailed, site-specific information. Findings from field studies reported here inform classification of detailed site-specific data.

The aim in developing the AEC was to provide a description of aquatic diversity associated with an array of aquatic ecosystem component types. Inferring predictive relationships among aquatic habitat classes and species requires in depth analyses and is beyond the scope of this AEC generation exercise. Findings from the literature guided our selection of variables and class intervals to capture the full range of aquatic diversity in the AEC.

A. *GREAT LAKES COAST*

1. **Rationale**

Numerous variables have been collected for developing classification systems for the Great Lakes coast, rivers and streams, inland lakes, and wetlands. A list of biological and physical components (Table 6) suggests the potential for complex interactions among various taxa at several trophic levels and various physical components in near shore Great Lakes waters. Aside from shoreline features, climate and stream flow patterns, and occurrences of some fish and waterfowl species, most biological and physical components of the Great Lakes near shore are not readily available for digital-spatial analyses.

The Great Lakes proper could be divided into open water and near shore units where the near shore might extend to the 5 m depth (Sly and Busch 1992). Given the constraint that interpretations must be made from available data, physical shoreline features are the only feasible variable for delineation of the Great Lakes coastal areas.

Table 6. Biological and physical components of the Great Lakes near shore ecosystem. (Adapted from Harris et al. 1982.)

Biological	Physical
Macrophytes	Water chemistry
Phytoplankton	Sediments/substrate
Zooplankton	Currents
Planktivorous fish	Seiches
Carnivorous fish	Climate patterns
Benthos	Shoreline features
Waterfowl	Seasonal water temperatures
Humans	Thermal stratification
	Fetch

Environment Canada produced an atlas that identifies 17 classes for the Great Lakes shoreline. These 17 classes were simplified into 6 types and refined further by stream drainage patterns intersecting the shore (Table 7). Coastal drainage patterns relate to species life history requirements and ‘observed centres of organization’ where rivers and shoreline intersect (Regier et al. 1989, Regier and Kay 1996, Magnuson et al. 1998, Tyson et al. 2001).

2. Application for shoreline and coast area

Shoreline features shown in Table 7 were used to distinguish and characterize coastal areas. These areas, likely important for spawning, rearing young, refuge, adult feeding and growth, were identified and the proportion of the total shoreline comprised by each type was estimated. Future studies may identify relationships among species associations and coastal types using existing data and detailed local investigations.

While analyzing and displaying the AEC for Great Lakes coast and stream system polygons we observed a set of coastal polygons that were not placed into any category in our initial classification system. Further investigation revealed that this set of polygons sloped toward the Great Lakes coast and may encompass inland lakes and wetlands but showed no surface water flow in defined linear watercourses. We named these polygons collectively as ‘Great Lakes coastal polygons with no defined surface flow’ and characterized them in terms of geological permeability with intervals similar to those used for stream systems and inland lakes (Table 8).

Table 7. AEC categories and classes for the Great Lakes coast.

Category	Class	Comment
Shoreline	Gently sloping shoreline gradient	High or low bluffs with beach; sandy beach/dunes; coarse beach dunes/ bay mouth-barrier beach; bedrock
	Abrupt shoreline gradient	High or low bluff without beach; sandy/silty banks; clay banks; bedrock; composite
	Low riverine coastal plain	Connecting channels and river mouths
	Open shoreline wetlands	Subject to wave action
	Semi-protected wetlands Artificial or unclassified	Not subject to wave action
Drainage pattern	$\leq 3^{\text{rd}}$ order stream (small streams)	Concentration of key life cycle processes where lake and river ecosystems meet (Stephenson 1988, Regier and Kay 1996, Willis and Magnuson 2000)
	$\geq 3^{\text{rd}}$ order stream (large streams)	
	Mixed – large and small streams	
	None	

Table 8. AEC categories and classes for the Great Lakes coastal polygons with undefined surface flow.

Category	Class	Interval	Rationale
Permeability	High	>2.34	Geological permeability values range from 1 to 3 on a continuous scale.
	Intermediate	>1.67 to ≤ 2.34	
	Low	≤ 1.67	Observed cold water species distribution

B. RIVERS AND STREAMS

1. Rationale for Rivers and Streams

Many studies characterized streams based on site and landscape level features and biological processes (Table 9). Although relevant, many of these biological and site-level variables are not feasible for this study because they require field sampling to collect the required data. We used remotely sensed data for this study because they provide the best representative information for the entire Great Lakes basin. We described findings from a wide range of studies here because this information may inform future applications of the AEC at a site scale or utilizing more detailed data.

Pennak (1971) provides a framework including 11 variables for stream classification (Table 10). Wright et al. (1984) shows that streams can be discriminated on the basis of topography, hydrology, channel shape, substrate size, in stream vegetation,

and water chemistry (Table 11). The variables considered by Pennak (1971) and Wright et al. (1984) with the exception of distance from source, and altitude of site, related to site-level analyses and require intensive field sampling. Most variables considered by Pennak (1971) and Wright et al. (1984) were ecologically relevant but Wright et al. (1984) did not provide class intervals for discriminating variables and most intervals suggested by Pennak (1971) were arbitrary (Table 10).

Table 9. Aquatic habitat features at site and landscape scales.

Features	Site level	Landscape level
Physical	Substrate Flow velocity Temperature Within and among site habitat heterogeneity Gradient	Gradient Distance from source (or mouth) Longitudinal zonation Lateral zonation Connections to lakes and wetlands
Chemical	pH Conductivity Alkalinity Turbidity	pH and conductivity inferred from geology
Biological Processes	Competition Predation Extinction	Predation Colonization Speciation

Table 10. Classification variables and class intervals for streams from Pennak (1971). We assigned ecological relevance based on Pennak's rationale for classification variables and intervals.

Variable	Ecological relevance for class intervals	Rationale for variable and class intervals
<i>Site scale (Pennak 1971)</i>		
Width	Low	<ul style="list-style-type: none"> – Allochthonous and autochthonous energy inputs are ecologically relevant but it is unclear how energy input relates to the suggested width categories – Complexity of bottom faunas – Width to depth ratio
Flow	High	<ul style="list-style-type: none"> – Two categories – intermittent and permanent – that relate to the possibility to support instream aquatic biota
Current velocity	Low	<ul style="list-style-type: none"> – Five categories that relate to visual perceptions: imperceptible, slow, moderate, swift (or flood flow), and torrential. Each class is associated with numerical values (km/hr).
Substrate	Moderate	<ul style="list-style-type: none"> – Considered a factor of great biological significance – Classes loosely based on biotic density of fish and invertebrates for trout and bass streams
Maximum summer temperature	High	<ul style="list-style-type: none"> – Three intervals based on optimal temperatures for growth of cold, cool and warm water species; – Two classes based on tropical streams, and high altitude or Arctic streams
Minimum winter temperatures	Low	<ul style="list-style-type: none"> – Many lotic habitats above 35° N latitude have winter temperatures below 5°C
Mean turbidity	Low	<ul style="list-style-type: none"> – Class intervals may relate to visual perceptions: exceptionally clear, clear, slightly turbid, turbid, and highly turbid
Total dissolved inorganic matter	Low	<ul style="list-style-type: none"> – May index stream productivity and standing crops
Total dissolved organic matter	Moderate	<ul style="list-style-type: none"> – Provides food source for aquatic bacteria directly, and indirectly for grazers and filter feeders – Extreme classes related to alpine brooks and recovery zones of heavily polluted streams

Variable	Ecological relevance for class intervals	Rationale for variable and class intervals
Water hardness	Low	<ul style="list-style-type: none"> – Related to total dissolved inorganic matter, all other things being equal, hard-water streams have a richer bottom fauna than soft-water streams – Similar class intervals used by several researchers
Dissolved oxygen	Moderate	<ul style="list-style-type: none"> – Dissolved oxygen concentrations may relate to water pollution – Upper and lower classes defined by pristine (absence of pollution) and severely polluted criteria – Intermediate classes “moderate pollution” and “heavy pollution” seem arbitrary
Rooted aquatic vegetation	Low	<ul style="list-style-type: none"> – Spatial and food niches are provided by aquatic vegetation – Class intervals are arbitrary, but related to provision of aquatic habitat and food
Stream side vegetation	Moderate	<ul style="list-style-type: none"> – Stream side vegetation provides breeding habitat for terrestrial insects and allochthonous food inputs – Class intervals based on provision of stream shade (trees), fish cover (over-hanging grasses and shrubs), and erosion and turbidity (lack of streamside vegetation)
<i>Valley unit scale (Seelbach et al. 1997)</i>		
Segment catchment size	None provided	<ul style="list-style-type: none"> – Longitudinal gradient has been used as a classification variable
Segment position	None provided	<ul style="list-style-type: none"> – Proximity to downstream potential source populations can influence fish community composition
Connection to Great Lakes	High	<ul style="list-style-type: none"> – The presence or absence of a barrier dam indicates potential for fish movement for spawning and colonization – 2 classes
Hydrology: discharge patterns	None provided	<ul style="list-style-type: none"> – Class intervals based on a series of six commonly observed discharge patterns representing tradeoffs between groundwater and surface runoff sources for stream flow – 9 classes

Variable	Ecological relevance for class intervals	Rationale for variable and class intervals
Water chemistry	Moderate	<ul style="list-style-type: none"> – Categorized as oligotrophic, mesotrophic or eutrophic based on interpretation of soil, land cover and surficial geology – Categories subdivided based on effects from upstream lakes, wetlands and land cover type – 8 classes
Water temperature	High	<ul style="list-style-type: none"> – Class types based on distributions of brown trout and smallmouth bass – 3x3 matrix characterizing July weekly mean temperatures and July weekly temperature variation – 9 classes
Valley slope	High	<ul style="list-style-type: none"> – 3 classes based on the likely presence of pools without riffles, some riffles, and riffle-pool sequences
Valley character	None provided	<ul style="list-style-type: none"> – 8 classes describing the degree of channel confinement by coarse-textured morainic features, old glacial-fluvial channel walls, or deeply incised alluvial channel walls – Based on elevation, topography, surficial geology patterns, and wetland patterns
Channel character	None provided	<ul style="list-style-type: none"> – 3 classes – Single meandering; braided; or channelized

Table 11. Rankings of 23 variables for four discriminant functions. Data were collected from rivers in Great Britain. Blank cells represent rankings less than 10. (Summarized from Wright et al. 1984.)

Variable	Function 1	Function 2	Function 3	Function 4
Distance from source				9
Slope at site	2			
Altitude of site	7		6	10
Discharge category for site	3			5
Mean channel width from survey area	4			1
Depth category of survey area		6	9	
Mean width of water in sampling area	10			8
Mean depth of water in sampling area		4		
Minimum velocity of surface water in sampling area		8		
Median velocity of surface water in sampling area			7	3
Mean substrate size category in sampling area	6		2	
Minimum dominant particle size in sampling area		9	3	
Maximum dominant particle size in sampling area	9	10		
Median dominant particle size in sampling area			5	
Maximum % macrophyte cover in sampling area		5		4
Minimum % macrophyte cover in sampling area		3		
Mean % macrophyte cover in sampling area		1	10	
pH	8			2
Dissolved oxygen			8	6
Total oxidized nitrogen		7	4	
Chloride		2	1	
Dissolved orthophosphate	5			
Alkalinity	1			7

Seelbach et al. (1997) considered the sampling unit represented by the “segment” or “valley segment” the most appropriate for management of aquatic organisms and communities. Segments, or valley units, delineated by Seelbach et al. were 1-15 km long, or encompassed entire small inland lakes; the smallest units that could be distinguished from large-scale maps (1:50,000 to 1:100,000) (Seelbach et al. 1997). Units of this size often include suitable habitat to support various life cycle stages – spawning, rearing young, foraging areas, daily and seasonal refuges – for fish (Schlosser 1982). Stream segments are distinguished by hydrologic regime, gradient, size of stream or catchment, and connection to other habitat types, i.e. confluence of stream with wetland or lake (Seelbach et al. 1997, Higgins et al. 1998, Stanfield and Kilgour 2001). Osborne and Wiley (1992) showed high correlation between d-link, a measure of the size and position of a stream in the watershed and species richness. They argued convincingly that a first order stream connected to another small stream in a headwater locale showed fundamentally different characteristics from a first order stream connected to a large river in the downstream portion of a watershed. Vannote et al. (1988) suggest class intervals for stream size based on energy and carbon source, its flow and utilization in flowing waters (Table 12). These observations were based on studies of small to

medium-sized rivers (orders 1-7 or 8) in temperate regions. Findings from these studies provided a guide to distinguish stream systems by watershed position.

Table 12. Some characteristics of rivers (adapted from Vannote et al. 1980).

Stream size (order)	Energy source and temperature	Biotic community
Small, order 1-3	<ul style="list-style-type: none"> – Influenced strongly by riparian vegetation – Allochthonous detritus – Low temperature, low daily fluctuation 	<ul style="list-style-type: none"> – Macro invertebrate shredders and grazers – Cold and cool water fish, invertivores
Medium, order 4-6	<ul style="list-style-type: none"> – Reduced allochthonous detritus and enhanced autochthonous primary production – Cool to warm temperature, high daily fluctuation 	<ul style="list-style-type: none"> – Macro invertebrate collectors and grazers – Diverse cool and warm water fishes, piscivorous and invertivorous
Large, order > 6	<ul style="list-style-type: none"> – Upstream fine particulate organic matter – Autochthonous primary productivity – Warm temperature, high daily fluctuation 	<ul style="list-style-type: none"> – Macro invertebrate collectors – Piscivorous, invertivorous and planktivorous fishes

2. Application for Rivers and Streams

Using ALIS we delineated streams based on changes in surficial geology, stream size, connection to other water bodies, and presence of barriers to flow (Table 13). These variables relate to thermal regime, water chemistry, island biogeography, and generally to provision of habitat for biological functions including reproduction, feeding, refuge from predators and adverse seasonal conditions, and adult growth. For application in the AEC stream segments were classified with respect to geology, gradient, water storage potential and watershed position using data collected during the ALIS segment delineation and attribution process (Table 14). These variables loaded high in a principal components analysis of stream segments for some Great Lakes streams (Wichert, unpublished data) and relate to water temperature and base flow, energy dynamics, and system level water quality and flood flow dynamics.

In summary, ALIS delineated streams into segments based on confluence with adjoining streams, change in surficial geology, connections with other water bodies, i.e. lakes, wetlands, and presence of barrier dams or waterfalls. Each segment was characterized in terms of gradient, hydrologic regime, size, position in the watershed and type of connection to adjacent water bodies, catchment area, and surficial geology. Where the initial version of ALIS characterized the drainage area and land cover for each segment based on the entire upstream drainage, we modified the process to characterize only the catchment of the segment of interest. That is the portion of the drainage associated with each individual segment and not the catchments associated with upstream segments. We used characteristics related to permeability, gradient, water storage potential, and watershed position to build the AEC. Class intervals were assigned based on ecological characteristics for species distributed widely in the Great Lakes watershed.

Table 13. Delineation criteria for streams used for ALIS GIS processing.

Variable	Criteria
Hydrography	Stream size, i.e. when stream order changes Confluence of a tributary to the main stem Confluence with a wetland Confluence with a lake
Geology	Change in surficial geology. These changes are often interrelated with changes in sinuosity, gradient, valley and channel morphology
Barriers	Abrupt changes in slope, i.e. dams and waterfalls

Table 14. AEC categories, classes and class intervals for Great Lakes rivers and streams.

Category	Class	Interval	Rationale
Permeability	High	>2.34	Geological permeability values range from 1 to 3 on a continuous scale. Observed cold water species distribution
	Intermediate	>1.67 to \leq 2.34	
	Low	\leq 1.67	
Gradient	Low	\leq 0.20%	Substrate size composition Gordon et al. (1992)
	Medium	>0.20 to \leq 2.0%	
	High	>2.0%	
Water storage potential: lake and wetland area in catchment	High	\leq 10% of catchment	Water quality and peak flow thresholds (Detenbeck et al. 2003)
	Low	>10 % of catchment	
Watershed position	Headwater	\leq 100 upstream 1 st order streams	Relate to differences in species richness (Osborne and Wiley 1992) Energy and nutrient dynamics (Vannote et al. 1980)
	Medium	>100-1000 upstream 1 st order streams	
	Main channel	>1000 upstream 1 st order streams	

C. WETLANDS

1. Rationale

Wetlands provide important habitat for fish and wildlife. Some species thrive on the moisture and vegetation gradients provided by wetlands. Other species utilize wetland areas for part of their life cycle. Wetlands on inland lakes in Ontario can boost fish yields above base levels of about 2.0 kg/ha/yr (Whillans 1988). These ecosystems provide habitat for plant, amphibian, reptile, invertebrate and bird species that require a freshwater component to complete their life history cycle. Through water and nutrient retention, wetlands also influence water flow and nutrient regimes. Dramatic seasonal changes in fish community composition are related to utilization of marshes for reproduction (Stephenson 1990). Surveys of coastal marshes in the Greater Toronto Area showed that 89% of the 36 species encountered at any time in these areas used the marshes for spawning (Stephenson 1990). Wetland area and the highly correlated area of emergent vegetation are strong predictors of fish yields from central Ontario lakes (Whillans 1988). Wetland size also relates to bird species richness (Boström and Nillson 1983) and the presence of particular bird species (Environment Canada et al. 1998). These findings suggest the importance of wetlands for providing habitat for aquatic species and that wetlands serve as significant centres of biological activity in the aquatic landscape of coastal waters, rivers and streams, and inland lakes.

2. Application for Wetlands

The Southern Ontario Wetland Evaluation System (OMNR 1994), the Northern Ontario Wetland Evaluation System (OMNR ?), the Ecological Land Classification (Lee et al. 2001), and the Northwest Ontario Wetland Ecosystem Classification (Harris et al. 1996) have been developed and applied in various parts of Ontario. The southern and northern Ontario Wetland Evaluation Systems combine classification and evaluation procedures. In both the northern and southern evaluation systems wetlands are classified into one of four types – bog, fen, swamp and marsh – and then assessed in terms of provision of ecosystem functions – biological, social, hydrological and special features. Differences between the two systems are few and minor and tend to reflect alterations in scoring for ranges for some values. The Ontario Wetland Evaluation System was developed primarily to serve the needs of Ontario's planning process. Wetland classification and evaluation requires detailed mapping and field surveys.

Wetland classification is also a component of the multi-scale Ecological Land Classification (ELC) developed for Ontario. The key purpose of the ELC is to provide analytical standards to meet forest management and land use planning requirements (Lee et al. 2001). Wetlands are delineated and classified based on water table dynamics, seasonality and depth of standing water, and plant species composition such as percent emergent vegetation. In the ELC approach, wetland classification depends on detailed information obtained through site-level field surveys.

An aim of the Wetland Ecosystem Classification for Northwestern Ontario (NWO WEC) is to provide an understanding of wetland ecosystems thus facilitating resource management activities (Harris et al. 1996). In particular the NWO WEC enables

resources managers to make informed decisions especially with respect to biodiversity conservation and ecologically sustainable resource management. The NWO WEC is appropriate for describing wetland eco-elements at a scale of 1:10,000 or less for wetland classification, evaluation, and inventory, for example inventory of rare plant habitat (Harris et al. 1996). Wetlands are delineated and defined based on hydrologic features that persist long enough to promote wetland processes including poorly drained soils, hydrophytic vegetation and various kinds of biological activities that are adapted to wet environments (National Wetlands Working Group 1988).

One or more of the detailed wetland classification processes listed above have been applied to a small subset of wetlands in the Great Lakes watershed. One of our aims in developing an aquatic ecosystem classification was to develop a comprehensive dataset that would allow assessment of conservation values and prioritization of locales for conservation in large regions such as the Great Lakes watershed. Although wetland attributes such as water source, water chemistry, water colour, floral and faunal composition, and soil type are important modifiers of wetland types, these variables are difficult to collect and interpret over the spatial scale of the Great Lakes watershed in Ontario. Owing to project time constraints and the geographic scope of the undertaking, we classified wetlands based on information available from existing digital layers that encompassed large portions of the Great Lakes watershed. Classification variables and rationale relate to spatial attributes recorded in Table 15.

Table 15. Wetland types, classes and class intervals identified within the Great Lakes watershed.

Type	Class	Interval	Rationale
Marsh	Small	≤ 100 ha	– 10-100 ha supports species such as Black Tern, Forster's Tern, Short-eared Owl; >100 ha support Least Bittern and King Rail (Environment Canada et al. 1998)
	Large	>100 ha	
For marshes, swamps, fens, bogs and muskeg	Unconnected	0 inflows or outflows	– Presence and absence of connections relates to island biogeography theory and habitat isolation (Magnuson et al. 1998)
	Connected	>0 inflows or outflows	

D. INLAND LAKES

1. Rationale

Two types of studies classifying lakes in the Great Lakes drainage area have been conducted. One type of study relates fish species richness was related to various factors and processes (e.g. Minns 1989, Tonn and Magnuson 1982). Other studies relate species associations with lakes exhibiting various morphometric and chemical characteristics in numerous regional contexts (e.g. Johnson et al. 1977).

a) Species richness

Minns (1989) found significant relationships between regional, local, anthropogenic and methodological factors, and fish species richness in Ontario lakes (Table 16). Tonn and Magnuson (1982) found strong seasonal contrast in species richness for lakes with Centrarchid and Cyprinid dominated assemblages (Table 17). Marshall and Ryan (1987) showed that fish species richness reached an asymptote at a size of 56,000 ha and depth greater than 10 m for northern Ontario lakes (Figure 7) but Shannon-Wiener diversity was maximized in lakes 4-10 m deep. Eadie and Keast (1984) found that local factors such as shoreline complexity, lake size, and habitat heterogeneity influenced species richness.

b) Species associations

A survey of central Ontario lakes showed that lakes deeper than about 10 m contained lake trout and shallower lakes did not (Johnson et al. 1977). As the area of deep lakes increased, other species were added to the lake trout community (Table 18). Combinations of bass, pike and walleye dominated shallow lakes of various size, and nutrient status in warm and cold climatic settings. Secchi depth provides a weak distinction between lakes containing only bass or only pike. Historical records showing introductions of smallmouth bass or migratory pathways after the most recent glacier may provide more robust criteria for distinction among lakes of those size and depth and nutrient conditions.

Table 16. Variables contributing to fish species richness (Summarized from Minns 1989).

Factor	Variable	Relationship with species richness
Regional scale	Species richness in tertiary watershed	+
	Elevation	-
Local scale	Lake area	+
	Mean depth	+
Methodological	Survey year	+
Anthropogenic	pH	+

Marshall and Ryan (1987) found fish communities changed from those dominated by salmonids to those dominated by percids along depth and area gradients for boreal forest lakes (Figure 7). Various other thermal, physical, and biological features characterized lakes into different depth categories (Table 19).

Water depth is an important variable to classify lakes but was not used here because depth data was not available for most lakes in the study area. Area and depth data from a sample of 9780 Ontario lakes suggest that further stratification of small inland lakes is possible (Table 20). If lakes were grouped based on geological setting and watershed position, strong area-depth relationships might be identified within and among groups. Based on such relationships, future studies could model depth for lakes for which only area data are available, and inland lakes could be placed into depth categories.

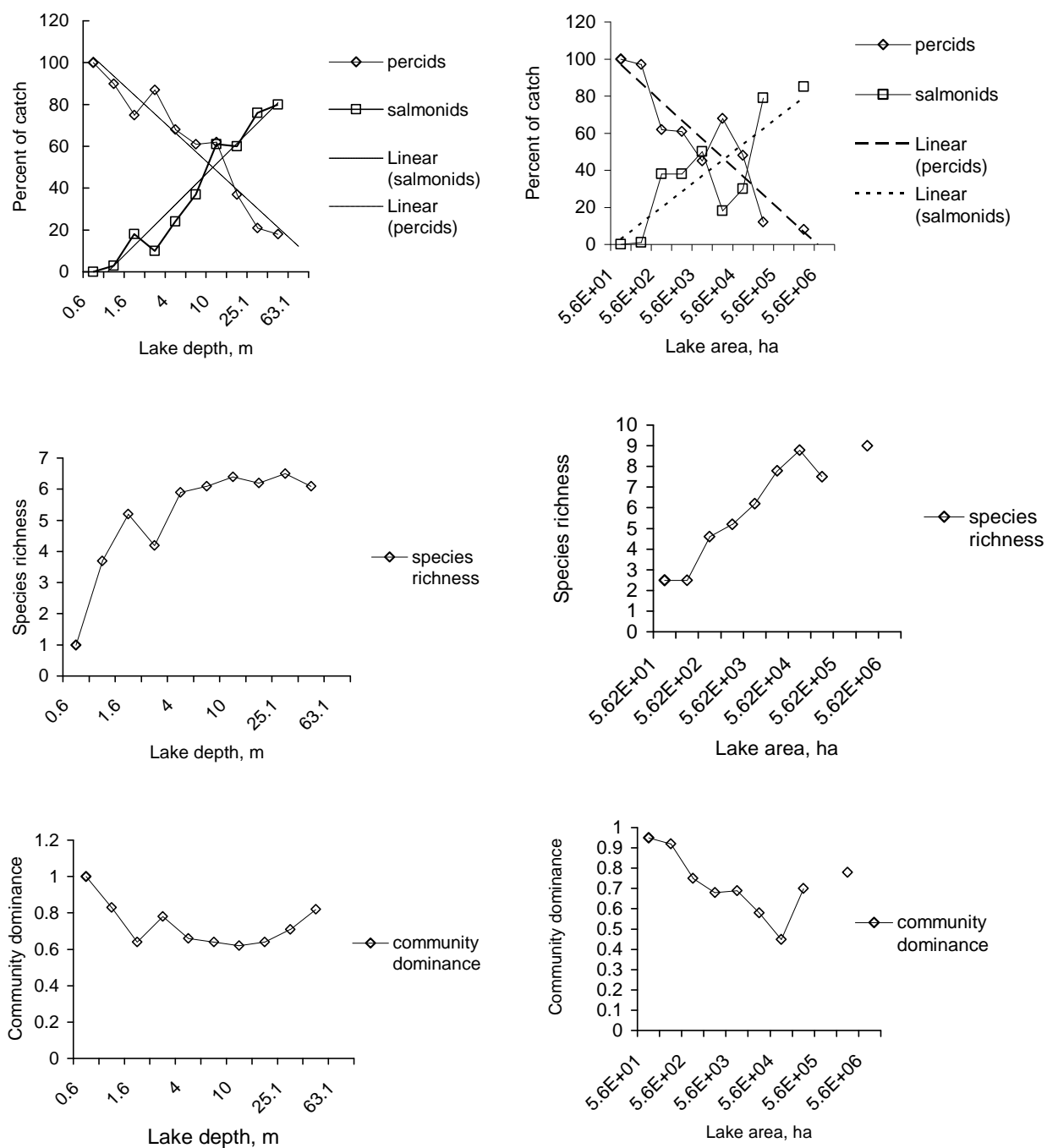


Figure 7. Properties of fish communities related to depth and area of lakes in northwestern Ontario (adapted from Marshall and Ryan 1987).

Table 17. Correlations between species richness and morphometric and limnological variables during summer and winter seasons. “+” represents a positive relationship; “-“ represents a negative relationship; a blank represents no relationship. (Summarized from Tonn and Magnuson 1982).

Season	Independent variable	All lakes (N=18)	Centrarchid – <i>Esox</i> lakes (N=12)	<i>Umbra</i> – cyprinid lakes (N=6)
Summer	Log (lake area)	+	+	+
	Log (maximum depth)	-		
	Log (connectdeness + 1)	+	+	
	Log (alkalinity)	+	+	
	Log (conductivity)	+	+	
	PH	+	+	
	Log (total dissolved solids)			
	Log (winter oxygen + 1)			+
	Substrate diversity			
	Vegetation diversity	+	+	+
	Depth diversity			
	Depth and substrate			
	Depth and vegetation	+	+	+
	Substrate and vegetation	+		+
Depth, substrate and vegetation				
Winter	Log (lake area)			
	Log (maximum depth)		+	
	Log (connectdeness + 1)			
	Log (alkalinity)			
	Log (conductivity)			
	PH			
	Log (total dissolved solids)			
	Log (winter oxygen + 1)		+	
	Substrate diversity			
	Vegetation diversity			
	Depth diversity			
	Depth and substrate			
	Depth and vegetation			
	Substrate and vegetation			+
Depth, substrate and vegetation				

Table 18. Characteristics and associated fish communities for Ontario inland lakes (Johnson et al. 1977).

Depth	Area	Total Dissolved Solids	Secchi Depth	Climate	Key fish species	Locale
Deep	Small	Low	High	Cold	Lake trout	NW Ontario, Algoma to Temagami, Algonquin highlands
Deep	Small	Low	High	Warm	Lake trout – Black Basses	Algoma, Algonquin Highlands
Deep	Intermediate	Low	High	Cold	Lake trout – Pike	NW Ontario
Deep	Intermediate	Low	High	Warm	Lake trout – Pike – Black Basses	NW Ontario, Algoma to Temagami
Deep	Large	Low	High	Cold	Lake trout – Walleye – Pike	NW Ontario
Deep	Large	Low	High	Warm	Lake trout – Walleye – Pike – Black Basses	NW Ontario, Algoma to Temagami, Parry Sound
Shallow	Small	High	Intermediate	Warm	Black Basses	Sault Ste. Marie to Temagami, south to Algonquin highlands, scattered throughout the south
Shallow	Small	High	Low	Warm	Pike	Scattered throughout clay belt in north, generally scattered throughout the south
Shallow	Small	High	Intermediate	Warm	Pike – Black Basses	South of Sault Ste. Marie, Kirkland Lake, common in eastern Ontario
Shallow	Small	Intermediate	Low	Cold	Walleye	Scattered in N Ontario
Shallow	Large	Intermediate	Low	Cold	Walleye – Pike	N Ontario, south to Wawa and Kirkland Lake
Shallow	Large	Intermediate	Intermediate	Warm	Walleye – Pike – Black Basses	South of Espanola and Kirkland Lake, NW Ontario
Shallow	Large	Intermediate	Intermediate	Warm	Walleye – Black Basses	South-central Ontario, North Bay, south to Haliburton and Kawartha lakes

Table 19. Selected abiotic and biotic characteristics of three classes of boreal forest lakes. (Adapted from Marshall and Ryan 1987).

Characteristic	Mean depth		
	< 4 m	4-10 m	> 10 m
Thermal regime	Continuous cold polymictic	Discontinuous cold polymictic	Dimictic
Disturbance regime, in terms of nutrient supply	Predictable, often	Unpredictable, fairly often	Predictable, seldom
Benthos biomass	High	Low	High
Zooplankton biomass	Low	High	Low
Fish community	Percid	Mixed	Salmonid
Lake herring	Low	High	Low
Community mean weight (of individuals)	High	Low	High
Species richness	Low	High	High
Shannon-Wiener diversity	Low	High	Low
Life strategy	k-selected	r-selected	k-selected

Table 20. Mean, 25th and 75th percentile area for lakes in three depth classes. The depth classes relate to those in Table 19. Inland lake data were taken from 9870 lakes in the Ontario inland lake survey with suitable data.

	Depth classes		
	<4 m	4-10 m	>10 m
Mean	35	60	160
25 th percentile	7.5	16	65
75 th percentile	120	160	500

Cross and McInerny (1995) showed that abundance of individual species and groups of species were related to lake size and watershed area in Minnesota lakes. These species lake and watershed size relationships were modified by land use activities (Table 21). Catch per unit effort for black bullhead, black crappie, common carp, and yellow perch, each of which are found in the Great Lakes drainage area, were associated with agricultural land use.

In a study conducted in northwestern Ontario Bendel and McNicol (1982) found that provision of particular habitat functions might be related to the size of lake drainage area and connections to other aquatic habitat (Table 22). Presence of cyprinid species comprising lithophilous (non-guarding fish that deposit eggs on gravel or rocky substrate) and non-lithophilous reproductive guilds was distinguished by the mean size of the drainage associated with cyprinid lakes. The mean size of lake watersheds containing lithophils was greater than 300 ha. Non-lithophils were found in lakes with watersheds less than or equal to 245 ha. These findings show that the presence of lithophils was not related to size of the lake, rather lithophils were added to the assemblage as drainage area (watershed) associated with the lake increased. Quinlan et al. (2003) noted water chemistry shifts and altered resilience to perturbation and changes in aquatic communities associated with lake size. Thus lakes with larger drainage areas may provide a greater diversity of functional habitat than those associated with smaller watersheds.

These findings suggest that both species richness and some details about aquatic species associations can be inferred from physical features interpreted from available map layers. When regional factors such as climate and historical glacial processes are controlled, lake area and depth relate positively to species richness. At regional scales, climate and glacial history are also relevant to species richness.

Table 21. Correlation among fish catches (CPUE) and watershed factors. (Summarized from Cross and McNerny 1995.)

Species groups and individual species	Watershed size	Lake size (volume)	Land use (cultivation to forest cover ratio)
Black bullhead – Black Crappie – Common Carp	+	–	+
Yellow Bullhead – Sunfishes – Largemouth Bass – Northern Pike	-	+	-
Walleye – Yellow Perch – White Sucker	+	0	0
Sunfishes	0	+	0
Northern Pike	-	0	0
White Sucker	+	0	-
Yellow Perch	+	0	+
Walleye	0	-	0

2. Application of Inland Lake Classification

Table 22. Reproductive guild associated with seven cyprinid species found in northwestern Ontario lakes (Bendel and McNicol 1982).

Species	Reproductive guild	
	Lithophilous	Non-lithophilous
Northern redbelly dace		X
Finescale dace		X
Fathead minnow		X
Pearl dace		X
Common shiner	X	
Creek chub	X	
Blacknose dace	X	

Climate, bedrock, and glacial history factors are influenced by large scale spatial and temporal processes. We classified inland lakes in terms of size, permeability, shoreline complexity and whether streams fed or drained the lake (Table 23); class intervals were based on ecological criteria reported in the literature. The shoreline complexity index (shape index) was calculated using Equation 1. Eadie and Keast (1984) showed a positive relationship between species richness and shoreline complexity index for southeastern and northern Ontario lakes. Depth data were available for few inland lakes in the study area, thus we could not classify lakes into depth categories.

Equation 1

$$ShapeComplexity = perimeter / 2\sqrt{\pi area}$$

In summary, connectivity, size, shoreline complexity, and geologic setting characterized lakes. Inland lakes were not divided into sub-units, rather each lake was considered as one unit. Thus there were no delineation criteria for lakes at the sub-lake level. Additional variables such as pH and depth should be considered in future refinements of the AEC. We assigned class intervals based on ecological criteria reported in the literature. The preceding account describes some of the aquatic biota and system dynamics associated with various inland lake types in numerous settings. Our aim in classifying lakes as shown in Table 23 was not to predict aquatic species and communities that likely occur in lakes of each type and in each geographic region. Rather findings from the studies described above provide some guidelines for classifying inland lakes to improve the likelihood of capturing representative aquatic diversity in the Great Lakes watershed. Future work may include correlating species occurrences by lake type thus providing ecological meaning to the classification.

Table 23. AEC categories, classes and class intervals for inland lakes in the Great Lakes watershed.

Category	Class	Interval	Rationale
Connectivity	Unconnected	0	Presence and absence of connections to the water flow relates to island biogeography theory and habitat isolation (Magnuson et al. 1998)
	Connected	>1	
Size	Small	≤200 ha	Piscivores and small-bodied fish do not co-exist (Jackson et al. 2001)
	Medium	200 to ≤1000 ha	Cool and warm water fish associations dominate (Johnson et al. 1977; Marshall and Ryan 1987); low concentration of major ions, susceptible to acidic deposition (Quinlan et al. 2003)
	Large	>1000 ha	Transition from cool to cold water communities (Johnson et al. 1977; Marshall and Ryan 1987); high concentration of major ions, less susceptible to acidic deposition (Quinlan et al. 2003)
Shape	Round	0.97 to 1.5	Shape index likely relates to extent of littoral zone and thus influences aquatic species abundance (Hinch et al. 1991) and species richness (Eadie and Keast (1984); 1.5 is the median for EDU 5
	Irregular	>1.5	
Permeability	High	>2.34	Geological permeability values range from 1 to 3 on a continuous scale. Observed lake trout distribution in EDU 5
	Intermediate	>1.67 to ≤2.34	
	Low	≤1.67	

VI. GENERATING THE AQUATIC ECOSYSTEM CLASSIFICATION

An automated GIS-based Aquatic Landscape Inventory System was crafted based on a protocol to delineate and characterize streams in the Lake Huron watershed and then throughout the remaining parts of the Great Lakes watershed (Stanfield and Kilgour 2001; Stanfield and Kuyvenhoven 2002). The initial version of ALIS comprised GIS processes to delineate and characterize flowing water. Inland lakes and wetlands connected to the water flow layer were identified in the stream segmentation process but these features but processes to not characterize water polygons were not included in the initial version of ALIS. Unconnected lakes and wetlands were not identified in the initial version of ALIS. We developed additional routines to characterize wetlands, inland lakes, and the Great Lakes coast and applied them across the Ontario Great Lakes and Ottawa-St. Lawrence watershed. Data from ALIS were used to create an Aquatic Ecosystem Classification, AEC, for the Ontario portion of the Great Lakes watershed. Here we report on the creation of and results from this Aquatic Ecological Land Classification, some potential applications and prospects for application of the classification techniques in other parts of Ontario.

A. GEOGRAPHIC INFORMATION

Topographic, geologic, and hydrologic information was synthesized to implement the ALIS GIS routines and then generate the AEC (Table 24). GIS routines to delineate and characterize rivers and streams were implemented first. When the GIS processing of those features was underway, we developed modules to characterize inland lakes and wetlands. Care was given to sequencing the processing of watersheds in southern Ontario because the digital elevation models, digital elevation models, DEMs, for some areas were not available when we began implementing ALIS.

Table 24. Information layers required to generate ALIS.

Coverage	Scale	Source	Comment
Quaternary Geology	1:1,000,000	Land Information Ontario, LIO	
Bedrock Geology	1:1,000,000	LIO	
Watershed Polygons	1:10,000 for south, 1:20,000 for north	Natural Resources Values Information System, NRVIS	Data south of the French River are higher resolution than north; produced by the Water Resources Information Project, WRIP
Water flow Network	1:10,000 for south, 1:20,000 for north	LIO	Data south of the French River are higher resolution than north; produced by WRIP
Water polygons	1:10,000 for south, 1:20,000 for north	NRVIS	Data south of the French River are higher resolution than north
Land cover	25 m pixel resolution	MNR	For wetlands south of the French River; 28 landcover classes
Digital Elevation Model	10 m pixel resolution for south, 20 m pixel resolution for the north	LIO	Produced by WRIP; higher resolution south of the French River
Climate: mean maximum daily August air temperature	1:100,000	Bioclimatic Mapping of Ontario, MNR	
Climate: mean annual precipitation	1:100,000	Ontario Forest Resources Institute	
Forest Resources Inventory	1:20,000	MNR	For wetlands north of the French River

Evaluated wetlands	1:10,000	NRVIS	For wetlands south of the French River
Great Lakes coast	1:50,000	Environment Canada Spills Atlas	Classification of the shoreline into 17 categories

B. TECHNICAL METHODS

1. Great Lakes Coast

Classification of the Great Lakes aquatic ecosystem revealed a set of coastal polygons that drained toward the Great Lakes but showed no defined water flow. Attributes for these areas were not characterized during the first application of ALIS because attribution was dependent on water flow drainage characteristics and water flow for the coastal polygons was undefined. For this reason we defined two types of coastal units. Shoreline units referred to the land water ecotone and coastal polygons to the areas adjacent to the Great Lakes with undefined flow (Figure 8).

a) Shoreline

The Great Lakes shoreline was classified according to the criteria listed in Table 8. We refer to each classified section as a shoreline unit. The Great Lakes shoreline coverage (arcs) was buffered to produce narrow polygon units along the shore. Buffering was required because Environment Canada and OMNR shoreline data were not completely aligned. We then overlaid the shoreline data with the water flow network to relate the size of streams (Strahler stream order) to the shoreline units. Analysis was preformed using an Arc Macro Language (AML) program to assign each shoreline unit to 1 of 24 shoreline types shown in Table 25.

b) Coastal polygons

Coastal polygons were characterized in terms of geology and size in a subsequent iteration of ALIS processing. Geology, as an indicator of permeability, provides an indication of the contribution of precipitation in coastal area to the groundwater or surface water components of the hydrological cycle. Coastal polygons were classified into 1 of 3 classes according to the criteria in Table 9.



Figure 8. Examples of Great Lakes shoreline and coastal area AEU types in EDU 5. Great Lakes shoreline was classified according to shoreline ecotone features, presence and size of intersecting streams; coastal area was classified by permeability.

2. Stream Systems

The water flow network created by the Water Resources Information Project (WRIP) was used as the base data for stream system analysis. The water flow layer is a GIS coverage of arcs that represent streams and rivers. These features have been attributed with flow direction. The Aquatic Landscape Inventory System (ALIS) application was used to break the water flow network into stream segments. The six criteria for breaking the network were: adjoining streams, lakes, surficial geology (hydraulic conductivity), barriers, wetlands, and Great Lakes. The ALIS application then populated a Microsoft (MS) Access database by delineating and characterizing watersheds for the water flow segments. Characteristics include: drainage area, surficial geology, land cover, connectivity, link (accumulation of first order streams), and slope (see Appendix B). We developed modules and queries in an MS Access database to assign each water flow segment to 1 of 54 system types described in Table 27. Through this process adjacent water flow segments with similar class membership were aggregated into stream systems (Figure 9). The system type attributes were transferred to the water flow network arcs and converted to a raster line grid. The source line grid was then used with a flow direction grid (derivative of the Digital Elevation Model (DEM)) to create stream system polygons that represent the area contributing to the stream systems. The resulting GIS layer is a grid coverage of classified stream systems including the terrestrial land that drains into them (subwatershed).

Manual editing of the water flow network was required along the Great Lakes coast. Delineation nodes were added where streams entered the Great Lakes to imply a break in connectivity in the water flow. These breaks were required for estimates of stream order and stream size used in the AEC.

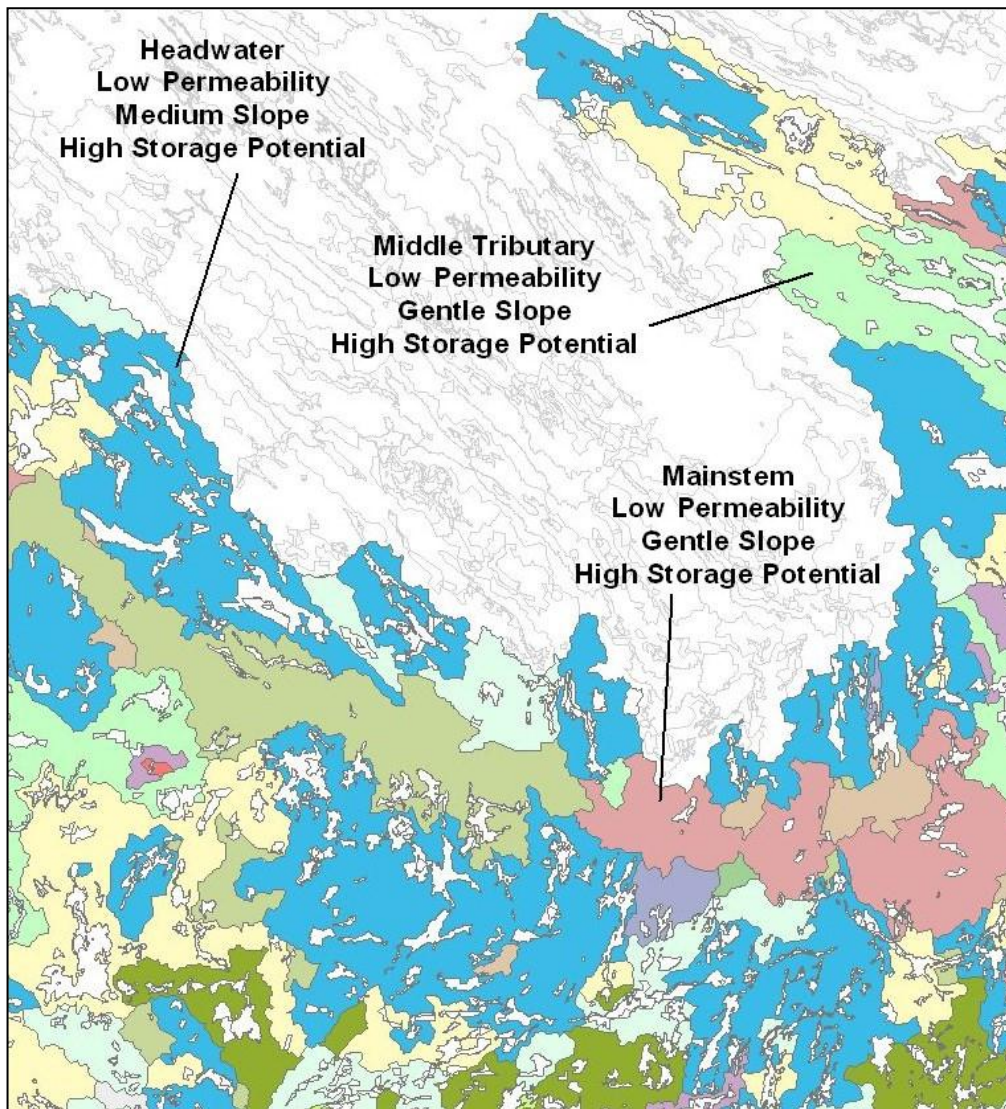


Figure 9. Examples of stream AEU types in EDU 5. Water flow was classified by watershed position, permeability, gradient, and water storage potential.

3. Wetlands

A raster grid of wetlands was converted to a polygon coverage and overlaid with the water flow network. Wetland attributes used in the classification included wetland type, hydrologic connectivity and size Table 15 (Figure 10). Additional wetland attributes collected but not used for classification included: shape (shoreline complexity), geology (hydraulic conductivity), and mean August air temperature (Wichert 2004). Wetland attribution represented additional development of ALIS. We analyzed data from the attribute table of the wetland coverage to assign each wetland to 1 of 14 wetland types shown in Table 28.

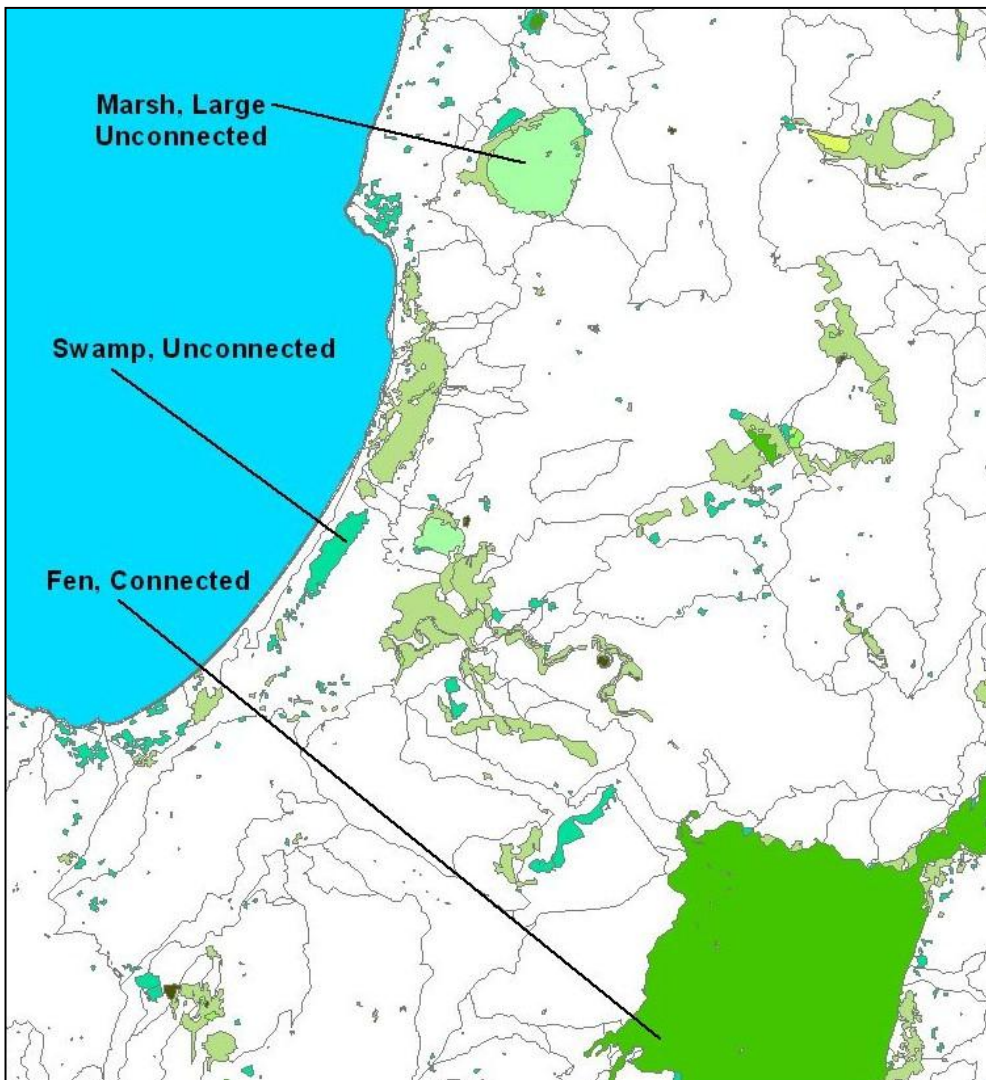


Figure 10. Examples of wetland AEU types in EDU 5. Wetlands were classified by type, size and connectivity.

4. Inland Lakes

Lake polygons were overlaid with the water flow network and quaternary geology data. The Water Body Attributing System application within ALIS was then used to populate an MS Access database. We characterized water bodies connected to rivers or streams and unconnected water bodies (Figure 11). Attributes of inland lakes that were used for classification included: connectivity, size, shape (shoreline complexity), and geology (hydraulic conductivity) (Table 23). Mean August air temperature was also estimated but not used explicitly in the classification (Wichert 2004). Lake attribution represented additional development of ALIS. We developed modules and queries in the database to assign each lake to one of 36 lake types shown in Table 29.

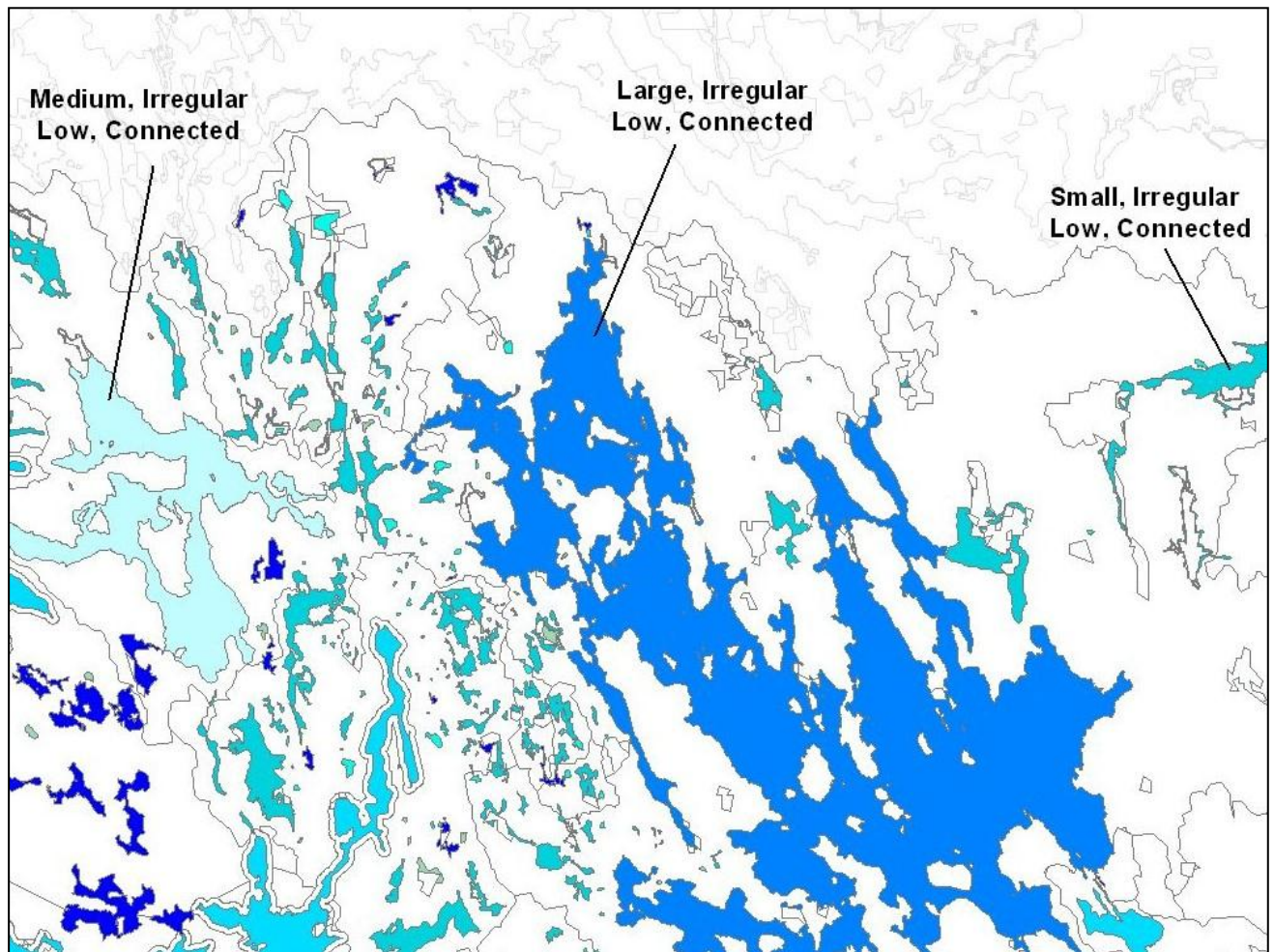


Figure 11. Examples of inland lake AEU types in EDU 5. Inland lakes were classified by size, shape, permeability, and connectivity to the water flow.

C. PRODUCT REVIEW

Reviews of results of the aquatic ecosystem classification processes revealed the sensitivity of the ALIS process and the subsequent classification to underlying data anomalies. Automated ALIS routines were designed so that streams were traced to the headwaters; delineation and attribution proceeded in a downstream direction. During the attribution process, if data for any of the attributes for a particular segment were missing, or anomalous, attribution for that segment would terminate without populating any of the associated databases and ALIS would begin processing the next segment. In EDU 5, the first region classified as part of our pilot study, stream polygons with missing data were concentrated in the complex transition zone between the Canadian Shield and the glacial deposits immediately to the south. The principal source of missing data was the geology layer. These missing geology attributes were assigned using a manual process and the EDU was processed again.

Missing data were also biased toward large lakes and wetlands. Here also the main source of missing data was the geology layer. Data characterizing the geology under many of the large inland lakes did not exist. We characterized the geology of lakes and wetlands with missing data according to the geology of adjacent stream system polygons.

We implemented two rounds of reviews for the AEC: its rationale, framework and map products. For the first round one of the authors (Wichert) conducted personal interviews with science team members well-versed in our effort to delineate, characterize, and classify aquatic ecosystem components. Wichert showed maps depicting classified water flow, inland lakes, wetlands, and coastal areas for EDU 5, 1 of 13 EDUs. Comments from these interviews helped us focus the review for a wider group of peers. The second phase of the review process consisted of consultations with the science team, regional experts from within MNR and knowledgeable peers from federal organizations, universities, and Canadian and U.S. NGOs.

For the second review we circulated maps depicting classified water flow, inland lakes, wetlands, and coastal areas for EDU 5. The rationale for the aquatic ecosystem classification, including the classification variables and class intervals, accompanied the maps. The rationale was followed by an early version of this manuscript. EDU 5 was the first of four EDUs that we designated for a pilot to test the classification process. As the other pilot EDUs – 2, 7 and 13 – were complete, we posted them on the NHIC website and requested reviewers to comment on those maps as well. All comments from reviewers were considered and appropriate changes were made to the document and the accompanying aquatic ecosystem classification maps. When we were satisfied with how each of the maps represented each individual ecosystem component – coastal areas, water flow, wetlands and inland lakes – we incorporated these features into a set of maps on which the four components were displayed on the same layer. The classification and mapping process, minus the external review, was extended to the remaining parts of the Great Lakes watershed. After review Great Lakes coast, streams, wetlands and inland lake AEUs were combined in a single layer (Figure 12). Aquatic ecological units identified and classified by the AEC will form the basic units for assessing and prioritizing locales for a collection of aquatic conservation sites.

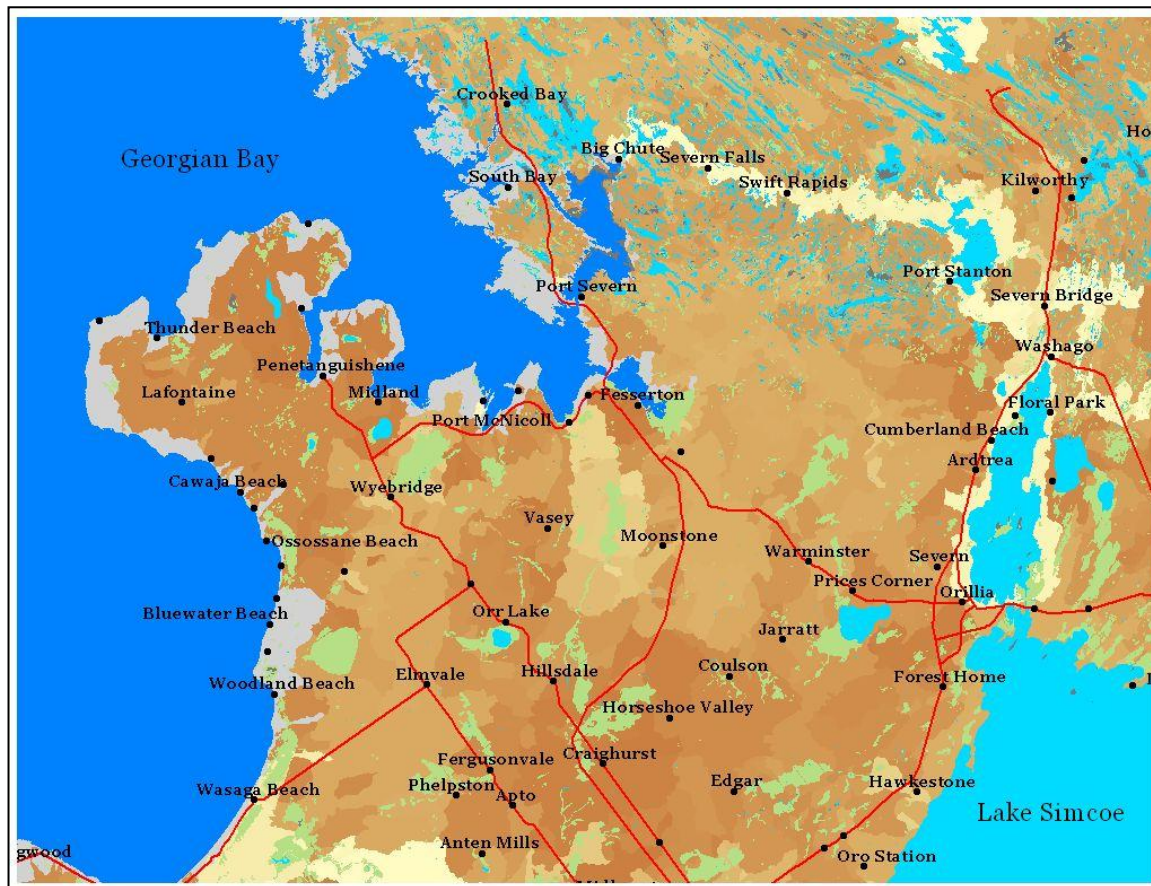


Figure 12. Great Lakes coast (grey), stream systems (brown to yellow), wetlands (green) and inland lakes (blue) combined in a single layer.

VII. AQUATIC ECOSYSTEM CLASSIFICATION DATA SUMMARIES FOR EDU 5

A. GREAT LAKES COAST

Three different shoreline types comprise 53% and 9 types comprise 95% of the total Great Lakes coast in EDU5. About 50% of the Great Lakes coast in EDU 5 slopes gently away from the shore and about 20% of the coast consists of open shoreline wetlands. About 20% of the coast in this EDU is artificial or unclassified (Table 25) and 9 shoreline types were not represented in EDU 5. Nearly 65% of the coastal area was relatively impermeable and about 25% of the area was highly permeable (Table 26).

Table 25. Summary data for Great Lakes shore in EDU5. Classes are defined in Table 7.

ID	Shoreline type	Drainage pattern	Percent area
C01	Abrupt shoreline gradient	small streams	0.7
C02	Abrupt shoreline gradient	large streams	0.0
C03	Abrupt shoreline gradient	large and small streams	0.6
C04	Abrupt shoreline gradient	no streams	6.0
C05	Gently sloping shoreline gradient	small streams	27.2
C06	Gently sloping shoreline gradient	large streams	2.8
C07	Gently sloping shoreline gradient	large and small streams	7.2
C08	Gently sloping shoreline gradient	no streams	14.9
C09	Low riverine coastal plain	small streams	0.0
C10	Low riverine coastal plain	large streams	0.0
C11	Low riverine coastal plain	large and small streams	0.0
C12	Low riverine coastal plain	no streams	0.0
C13	Open shoreline wetlands	small streams	10.9
C14	Open shoreline wetlands	large streams	0.1
C15	Open shoreline wetlands	large and small streams	0.2
C16	Open shoreline wetlands	no streams	9.4
C17	Semi-protected wetlands	small streams	0.0
C18	Semi-protected wetlands	large streams	0.0
C19	Semi-protected wetlands	large and small streams	0.0
C20	Semi-protected wetlands	no streams	0.0
C21	Artificial or unclassified	small streams	5.6
C22	Artificial or unclassified	large streams	0.5
C23	Artificial or unclassified	large and small streams	3.7
C24	Artificial or unclassified	no streams	10.2

Table 26. Summary data for Great Lakes coastal polygons in EDU 5.

ID	Coastal polygon type	Percent
C25	High permeability	23.4
C26	Intermediate permeability	12.9
C27	Low permeability	63.7

B. STREAM SYSTEMS

Only a few headwater types accounted for most of the stream system area in EDU 5. The 6 largest stream system types comprised about 50% of the area. The 10 largest types comprised two-thirds of the EDU 5 drainage area. About 25% of the area was a type of middle tributary and about 5% of the EDU 5 area was a type of mainstem. All headwater types of streams were represented in EDU 5; 10 middle tributary and mainstem types were not represented (Table 27).

Table 27. Summary data for stream system polygons in EDU5. Classes and class intervals are defined in Table 14.

ID	Watershed position	Permeability	Gradient	Potential	Percent area ¹
S01	Headwater	High	Steep	High	0.3
S02	Headwater	High	Steep	Low	3.7
S03	Headwater	High	Medium	High	5.3
S04	Headwater	Medium	Steep	High	0.3
S05	Headwater	High	Gentle	High	2.8
S06	Headwater	High	Medium	Low	12.9
S07	Headwater	Medium	Steep	Low	1.6
S08	Headwater	Medium	Medium	High	3.3
S09	Headwater	Low	Steep	High	0.4
S10	Headwater	Medium	Medium	Low	9.8
S11	Headwater	Medium	Gentle	High	3.0
S12	Headwater	Low	Steep	Low	0.5
S13	Headwater	Low	Medium	High	6.8
S14	Headwater	Low	Gentle	High	4.2
S15	Headwater	High	Gentle	Low	2.7
S16	Headwater	Medium	Gentle	Low	2.3
S17	Headwater	Low	Medium	Low	5.8
S18	Headwater	Low	Gentle	Low	2.2
S19	Middle tributary	Low	Gentle	Low	9.9
S20	Middle tributary	Low	Medium	Low	1.2
S21	Middle tributary	Low	Gentle	High	4.8
S22	Middle tributary	Medium	Gentle	Low	1.8
S23	Middle tributary	Low	Steep	Low	0.0
S24	Middle tributary	High	Gentle	Low	2.2
S25	Middle tributary	Medium	Medium	Low	0.9
S26	Middle tributary	Medium	Gentle	High	0.3
S27	Middle tributary	Low	Medium	High	1.1
S28	Middle tributary	Low	Steep	High	0.0
S29	Middle tributary	Medium	Steep	Low	0.1
S30	Middle tributary	High	Medium	Low	2.9
S31	Middle tributary	High	Gentle	High	0.7

¹ Area less than 250 ha is displayed as 0%.

S32	Middle tributary	High	Steep	Low	0.2
S33	Middle tributary	Medium	Medium	High	0.2
S34	Middle tributary	Medium	Steep	High	0.0
S35	Middle tributary	High	Medium	High	0.2
S36	Middle tributary	High	Steep	High	0.0
S37	Mainstem	High	Steep	High	0.0
S38	Mainstem	High	Medium	High	0.2
S39	Mainstem	High	Steep	Low	0.0
S40	Mainstem	Medium	Steep	High	0.0
S41	Mainstem	High	Gentle	High	0.1
S42	Mainstem	Low	Steep	High	0.0
S43	Mainstem	High	Medium	Low	0.3
S44	Mainstem	Medium	Medium	High	0.0
S45	Mainstem	Medium	Steep	Low	0.0
S46	Mainstem	High	Gentle	Low	0.1
S47	Mainstem	Medium	Gentle	High	1.7
S48	Mainstem	Low	Medium	High	0.0
S49	Mainstem	Low	Steep	Low	0.2
S50	Mainstem	Low	Gentle	High	0.0
S51	Mainstem	Medium	Medium	Low	1.4
S52	Mainstem	Medium	Gentle	Low	0.2
S53	Mainstem	Low	Medium	Low	0.2
S54	Mainstem	Low	Gentle	Low	0.2

C. WETLANDS

Most of the wetland area in EDU 5 is swamp. The 6 largest wetland types comprise about 95% of the wetland area; 2 types are not represented in this EDU (Table 28).

Table 28. Summary data for wetlands in EDU5. Classes and class intervals are defined in Table 15.

ID	Type	Size	Connectivity	Percent area
W01	Marsh	Small	Unconnected	0.9
W02	Marsh	Small	Connected	3.6
W03	Marsh	Large	Unconnected	0.0
W04	Marsh	Large	Connected	3.8
W05	Swamp		Unconnected	9.5
W06	Swamp		Connected	66.0
W07	Fen		Unconnected	0.2
W08	Fen		Connected	7.1
W09	Bog		Unconnected	0.8
W10	Bog		Connected	2.4
W11	Muskeg		Unconnected	1.4
W12	Muskeg		Connected	4.4

D. INLAND LAKES

Lake Simcoe contributes almost two-thirds of the total lake area in EDU 5. The 10 largest lake types comprise 95% of the total lake area. Inland lakes not connected to a stream or river make up about 5% of the total lake area in this EDU (Table 29). All small lake types are represented; 16 medium and large lake types are not represented in EDU 5.

Table 29. Summary data for inland lakes in EDU5. Classes and class intervals are defined in Table 23.

ID	Size	Shape	Permeability	Connectivity	Percent area
L01	Large	Irregular	High	Unconnected	0.0
L02	Large	Irregular	High	Connected	65.6
L03	Large	Irregular	Medium	Unconnected	0.0
L04	Large	Round	High	Unconnected	0.0
L05	Large	Irregular	Low	Unconnected	0.0
L06	Large	Irregular	Medium	Connected	1.1
L07	Large	Round	High	Connected	0.0
L08	Large	Round	Medium	Unconnected	0.0
L09	Large	Irregular	Low	Connected	1.5
L10	Large	Round	Low	Unconnected	0.0
L11	Large	Round	Medium	Connected	0.0
L12	Large	Round	Low	Connected	0.0
L13	Medium	Round	Low	Connected	0.0
L14	Medium	Round	Medium	Connected	0.0
L15	Medium	Irregular	Low	Connected	3.4
L16	Medium	Round	Low	Unconnected	0.0
L17	Medium	Irregular	Medium	Connected	1.7
L18	Medium	Round	Medium	Unconnected	0.0
L19	Medium	Round	High	Connected	0.8
L20	Medium	Irregular	Low	Unconnected	1.0
L21	Medium	Irregular	Medium	Unconnected	0.0
L22	Medium	Irregular	High	Connected	2.3
L23	Medium	Round	High	Unconnected	0.0
L24	Medium	Irregular	High	Unconnected	0.0
L25	Small	Irregular	High	Unconnected	0.3
L26	Small	Irregular	High	Connected	1.5
L27	Small	Irregular	Medium	Unconnected	0.2
L28	Small	Round	High	Unconnected	0.4
L29	Small	Irregular	Low	Unconnected	2.2
L30	Small	Irregular	Medium	Connected	1.0
L31	Small	Round	High	Connected	0.8
L32	Small	Round	Medium	Unconnected	0.2
L33	Small	Irregular	Low	Connected	13.8
L34	Small	Round	Low	Unconnected	0.2
L35	Small	Round	Medium	Connected	0.4
L36	Small	Round	Low	Connected	1.5

VIII. APPLICATIONS OF THE AQUATIC ECOSYSTEM CLASSIFICATION

Aquatic ecological classification systems can be used to map ecological potential, conduct ecological analyses, identify desired conditions, monitor the effects of management actions, and evaluate current and emerging trends in aquatic resource condition. This classification is useful to:

- Identify AEU boundaries that coincide with planning units. These planning units could be watershed based and may be as large as the Ontario Great Lakes drainage, or as small as an individual lake, wetland or stream segment.
- Assess the habitat suitability and ecological potential of the aquatic unit evaluated.
- Compare present ecosystem conditions in AEU's with past or future conditions given particular management prescriptions.
- Guide sampling design for research or species inventory and assessment.

The AEC can be used as the basis for:

- Aquatic gap analysis
- Watershed planning
- Water flow assessment
- Estimating surface water quality
- Approximating groundwater recharge and discharge areas

The AEC can guide:

- Aspects of the water taking permit process
- Flood hazard land identification
- Siting and evaluating water power projects

A useful aquatic ecosystem classification should encompass broad temporal and spatial scales, integrate structural and functional attributes of the system, convey information about cause and effect, be low in cost and promote consistent understanding among resource managers and researchers (Naiman et al. 1992). We synthesized information from Great Lakes coast, stream, wetland and inland lake classification and research studies into an ecological context for the Ontario Great Lakes watershed. Future refinements of the AEC might include greater emphasis on groundwater dynamics as an important influence on the natural flow regime of aquatic systems. The lake classification could be expanded to include depth and fetch as important determinants of species habitat.

A new process to delineate watersheds has been developed by the PGSC to delineate watersheds more accurately (Frank Kenney, personal communication). Future implementation of ALIS should incorporate the new delineation process. Future implementation should also retain all watershed boundaries to allow more robust and sophisticated spatial analyses than were possible in this iteration.

Identifying and describing relationships between AEC units and aquatic species distribution will add ecological meaning to the classification. Ground-truthing and characterizing errors in data inputs such as gradient estimates and outputs such as AEU boundaries will improve confidence in future AEC applications.

Aquatic fisheries science is currently undergoing a conceptual shift in understanding of fish-habitat linkages, assessment, and management (Minns and Wichert, submitted). In the present models, habitat is identified using relatively static indicators: e.g. depth, cover, substrate, and to a lesser extent velocity, which depend on geology, physiography and landscape – variables used in the Aquatic Ecosystem Classification. Because the spatial and temporal variability of water movements, – e.g. currents, waves, seiche effects, – has been difficult to measure and predict, especially at regional scales and larger, the more static features dominated investigation, analyses, and application. Emerging science links aquatic species life history traits and rate processes – hatching success, growth rate, survival – to dynamic habitat features that influence species more directly – temperature, light and water movements (currents, turbulence etc.). These dynamic habitat features are energy based and are driven by climate and hydrological processes and phenomena and draw more explicit links between physiology and habitat. As new remote sensing technologies are developed, spatial and temporal conditions of aquatic habitat can be characterized, and applied at larger geographic scales. The AEC can then be adapted to incorporate measures of phenomena that link dynamic habitat conditions with the factors that influence species reproductive success, distribution and abundance.

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X. REFERENCES

- Aadland, L.P. 1993. Stream habitat types: their fish assemblages and relationship to flow. *North American Journal of Fisheries Management* 13:790-806.
- Abell, R.A., D.M. Olson, E. Dinerstein and, P.T. Hurley. 2000. *Freshwater ecoregions of North America: a conservation assessment*. Island Press, Washington, D.C.
- Angermeier, P.L., and I.J. Schlosser. 1995. Conserving aquatic biodiversity: beyond species and populations. *American Fisheries Society Symposium* 17:402-414.
- Bailey, R.G. 1995. *Description of the ecoregions of the United States*. Second edition. Washington, D.C.: U.S. Forest Service, Miscellaneous Publication No. 1391.
- Bendel, B.E., and D.K. McNicol. 1987. Cyprinid assemblages, and the physical and chemical characteristics of small northern Ontario lakes. *Environmental Biology of Fishes* 19:229-234.
- Boström, U., and S.G. Nilsson. 1983. Latitudinal gradients and local variations in species richness and structure of bird communities on raised peat-bogs in Sweden. *Ornis Scandinavica* 14:213-226.
- Burke, V.J., and J.W. Gibbons. 1993. Terrestrial buffer zones and wetland conservation: a case study of freshwater turtles in a Carolina Bay. *Conservation Biology* 9:1365-1369.
- Burrough. P.A. 1986. *Principles of geographical information systems for land resources assessment*. Clarendon Press, Oxford.
- Busch, W.-D.N., and P.G. Sly. 1992. *The development of an aquatic habitat classification system for lakes*. CRC Press, Inc. Boca, Raton, USA.
- Cowardin, L.M., V. Carter, F.C. Golet, and E.T. LaRoe. 1979. *Classification of wetlands and deepwater habitats of the United States*. Washington, D.C. U.S. Fish and Wildlife Service, Office of Biological Services, FWS/OBS-79/31.
- Cross, T.K., and M.C. McInerney. 1995. Influences of watershed parameters on fish populations in selected Minnesota Lakes of the central hardwood forest region. *Minnesota Department of Natural Resources Investigational Report* 441, 1995.
- Cudmore-Vokey, B., and E.J. Crossman. 2000. Checklists of the fish fauna of the Laurentian Great Lakes and their connecting channels. *Canadian Manuscript report of Fisheries and Aquatic Sciences* 2250:v+39p.
- Detenbeck, N.E., C.M. Elonen, D.L. Taylor, L.E. Anderson, T.M. Jicha, and S.L. Batterman. 2003. Effects of hydrogeomorphic region, catchment storage and mature forest on baseflow and snowmelt stream water quality in second-order Lake Superior Basin tributaries. *Freshwater Biology* 48:912-927.
- Eadie, J. McA., and A. Keast. 1984. Resource heterogeneity and fish species diversity in lakes. *Canadian Journal of Zoology* 62:1689-1695.
- Environment Canada, Ontario Ministry of Natural Resources, and Ontario Ministry of Environment. 1998. *A framework for guiding habitat rehabilitation in Great Lakes Areas of Concern*. Canada-Ontario Remedial Action Plan Steering Committee.
- Frissell, C.A., W.J. Liss, C.E. Warren, and M.D. Hurley. 1986. A hierarchical framework for stream habitat classification: viewing streams in a watershed context. *Environmental Management* 10:199-214.

- Goodier, J.L. 1981. Native lake trout (*Salvelinus namaycush*) stocks in the Canadian waters of Lake Superior prior to 1955. *Canadian Journal of Fisheries and Aquatic Sciences* 38:1724-1737.
- Gopal, B. 1990. Pages 91-242 in B.C. Patten, editor. *Wetlands and continental water bodies*. Volume 1. SPB Academic Publishing. The Hague, Netherlands.
- Gordon, N. D., T.A. McMahon, and B.L. Finlayson. 1992. *Stream hydrology: an introduction for ecologists*. Chichester, UK: John Wiley & Sons.
- Hallam, J.C. 1959. Habitat and associated fauna of four species of fish in Ontario streams. *Journal of the Fisheries Research Board of Canada* 16: 147-173.
- Harris, A.G., S.C. McMurray, P.W.C. Uhlig, J.K. Jeglum, R.F. Foster, and G.D. Racey. 1996. *Field Guide to the wetland ecosystem classification for northwestern Ontario*. Ontario Ministry of Natural Resources, Northwest Science and Technology. Thunder Bay. Ontario Field Guide FG-01. 74 pp. + Appendices.
- Harris, H.J., D.R. Talhelm, J.J. Magnuson, and A.M. Forbes. 1982. *Green Bay in the future – a rehabilitative prospectus*. Technical Report No. 38. Great Lakes Fishery Commission, Ann Arbor, Michigan.
- Hawkins, C.P., J.L. Kershner, P.A. Bisson, M.D. Bryant, L.M. Decker, S.V. Gregory, D.A. McCullough, C.K. Overton, G.H. Reeves, R.J. Steedman, and M.K. Young. 1993. A hierarchical approach to classifying stream habitat features. *Fisheries* 18:3-11.
- Higgins, J., M. Lammert, M. Bryer, M. DePhilip and, D. Grossman. 1998. *Freshwater conservation in the Great Lakes basin: development and application of an aquatic community classification framework*. Report to the George Gund Foundation, Grant Number 95-65. The Nature Conservancy, Great Lakes Program, Chicago, IL.
- Hills, G.A. 1952. *The classification and evolution of site for forestry*. Ontario Department of Lands and Forest. Toronto, Ontario, Research Report No. 24, 41 pp.
- Hills, G.A. 1958. *Soil-forest relationships in the site regions of Ontario*. Pages 190-212 in *Proceedings of the First North American Forest Soils Conference*, Michigan State University, East Lansing, Michigan.
- Hinch, S.G., N.C. Collins, and H.H. Harvey. 1991. Relative abundance of littoral zone fishes: biotic interactions, abiotic factors, and postglacial colonization. *Ecology* 72:1314-1324
- Holling, C.S. 1985. Resilience of ecosystems: local surprise and global change. Pages 228-269 in T.F. Malone and J.G. Roederer, editors. *Proceedings of ICSU 20th General Assembly*. Cambridge University Press, London.
- Hubbs, C.L., and K.F. Lagler. 1983. *Fishes of the Great Lakes Region*. University of Michigan Press, Ann Arbor, Michigan.
- Hudson, P.L., R.W. Griffiths, and T.J. Wheaton. 1992. Review of habitat classification schemes appropriate to streams, rivers, and connecting channels in the Great Lakes Drainage basin. Pages 73-107 in W.-D.N. Busch and P.G. Sly, editors. *The development of an aquatic habitat classification system for lakes*. CRC Press, Inc. Boca, Raton, USA.
- IJC. 2000. *Protection of the water of the Great Lakes: final report to the governments of Canada and the United States*. International Joint Commission, Windsor, Ontario.

- Jackson, D.A., P.R. Peres-Neto, and J.D. Olden. 2001. What controls who is where in freshwater fish communities – the roles of biotic, abiotic, and spatial factors. *Canadian Journal of Fisheries and Aquatic Sciences* 58:157-170.
- Johnson, M.G., J.H. Leach, C.K. Minns, and C.H. Olver. 1977. Limnological characteristics of Ontario lakes in relation to associations of Walleye (*Stizostedion vitreum vitreum*), Northern pike (*Esox lucius*), Lake trout (*Salvelinus namaycush*), and Smallmouth bass (*Micropterus dolomieu*). *Journal of the Fisheries Research Board of Canada* 34:1592-1601.
- Kuyvenhoven, R. 2001. Lake Huron Landscape Based Aquatic Inventory: Automation for Characterizing and Classifying Valley Segments. Ontario Ministry of Natural Resources, Peterborough, Ontario.
- Lee, H.T., D. Leadbeater, P. Uhlig, and K. Ursic. 2001. Ecological Land Classification for Southern Ontario: Training Manual. Ontario Ministry of Natural Resources, Science and Information Division, Science and Information Branch, Southcentral Science and Information Section, SCSIS Training Manual TM-01.
- Lee, H.T., W.D. Bakaowsky, J. Riley, J. Bowles, M. Puddister, P. Uhlig, and S. McMurray. 1998. Ecological Land Classification for Southern Ontario: First Approximation and its Application. Ontario Ministry of Natural Resources, Southcentral Science Section, Science Development and Transfer Branch. SCS Field Guide FG-02.
- MacRae, P.S.D., and D.A. Jackson. 2001. The influence of smallmouth bass (*Micropterus dolomieu*) predation and habitat complexity on the structure of littoral zone fish assemblages. *Canadian Journal of Fisheries and Aquatic Sciences* 58:342-351.
- Magnuson, J.J. 1990. Fish and fisheries ecology. *Ecological Applications* 1:13-26.
- Magnuson, J.J., W.M. Tonn, A. Banerjee, J. Toivonen, O. Sanchez, and M. Rask. 1998. Isolation vs. extinction in the assembly of fishes in small northern lakes. *Ecology* 79:2941-2956.
- Mandrak, N.E. 1995. Biogeographic patterns of fish species richness in Ontario lakes in relation to historical and environmental factors. *Canadian Journal of Fisheries and Aquatic Sciences* 52:1462-1474.
- Mandrak, N.E. 1998. An assessment of the suitability of using a terrestrial ecoregion classification to protect aquatic biodiversity in Ontario. Trent University, Peterborough, Ontario.
- Mandrak, N.E. 1999. An aquatic ecoregion classification for Ontario. Department of Biological Sciences, Youngstown State University, Youngstown, Ohio.
- Marshall, T.R., and P.A. Ryan. 1987. Abundance patterns and community attributes of fishes relative to environmental gradients. *Canadian Journal of Fisheries and Aquatic Sciences* 44 (Supplement 2):198-215.
- Maxwell, J.R., C.J. Edwards, M.E. Jensen, S.J. Paustian, H. Parrot, and D.M. Hill. 1995. A hierarchical framework of aquatic ecological units in North America (Near Arctic zone). North Central Forest Experiment Station, Forest Service – U.S. Department of Agriculture, St. Paul, Minnesota.
- Mayden, R.L., editor. 1992. Systematics, historical ecology, and North American freshwater fishes. Stanford, CA: Stanford University Press. 969 pp.

- Minns, C.K. 1989. Factors affecting species richness in Ontario lakes. *Transactions of the American Fisheries Society* 118:533-545.
- Minns, C.K. 1995. Allometry and home range size in lake and river fishes. *Canadian Journal of Fisheries and Aquatic Sciences* 52:1499-1508.
- Minns, C.K., and G.A. Wichert. A framework for defining fish habitat domains in freshwaters using Lake Ontario and its drainage as a case study. *Journal of Great Lakes Research*. Under review.
- Naiman, R.J., D.G. Lonarich, T.J. Beechie, and S.C. Ralph. 1992. General principles of classification and the assessment of conservation potential. Pages 93-123 in P.J. Boon, P. Calow, and G.E. Petts, editors. *River conservation and management*. John Wiley & Sons. New York.
- National Working Group. 1988. *Wetland of Canada. Ecological Land Classification Series No. 24. Sustainable Development Branch. Environment Canada, Ottawa, Ontario. Polyscience Publications, Inc., Montreal, Quebec. 452 pp.*
- OMNR. 1994. *Ontario Wetland Evaluation System: Southern Manual, 3rd Edition. Ontario Ministry of Natural Resources, Peterborough, Ontario. 113 pp. + Apendices.*
- OMNR. 1997. *Nature's Best, Ontario's Parks and Protected Areas: A Framework and Action Plan. Ontario Ministry of Natural Resources, Lands and Natural Heritage Branch, The Natural Heritage Section. Peterborough, Ontario.*
- OMNR. 1999. *Ontario's Living Legacy Landuse Strategy. Ontario Ministry of Natural Resources, Peterborough, Ontario.*
- Osborne, L.L., and M.J. Wiley. 1992. Influence of tributary spatial position on the structure of warmwater fish communities. *Canadian Journal of Fisheries and Aquatic Sciences* 49: 671-681.
- Pennak, R.W. 1971. Toward a classification of lotic habitats. *Hydrobiologia* 38:321-334.
- PLUARG (Pollution from Land Use Activities Reference Group). 1980. *Pollution in the Great Lakes Basin from Land Use Activities. International Joint Commission, Ottawa Ontario and Washington, D.C.*
- Poff, N.L., and J.V. Ward. 1989. Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patterns. *Canadian Journal of Fisheries and Aquatic Sciences* 46:1805-1818.
- Portt, C.B., S.W. King, and H.B.N Hynes. 1989. A review and evaluation of stream habitat classification systems with recommendations for the development of a system for use in southern Ontario. C. Portt and Associates. Guelph, Ontario.
- Quinlan, R., A.M. Paterson, R.I. Hall, P.J. Dillon, A.N. Wilkinson, B.F. Cumming, and M.V. Douglas. 2003. A landscape approach to examining spatial patterns of limnological variables and long-term environmental change in a southern Canadian lake district. *Freshwater Biology* 48:1676-1697.
- Regier, H.A. 1992. Ecosystem integrity in the Great Lakes Basin: an historical sketch of ideas and actions. *Journal of Aquatic Ecosystem Health* 1: 25-37.
- Regier, H.A., and J.J. Kay. 1996. An heuristic model of transformations of the aquatic ecosystems of the Great Lakes-St. Lawrence River basin. *Journal of Aquatic Ecosystem Health* 5:3-21.
- Regier, H.A., R.L. Welcomme, R.J. Steedman, and H.F. Henderson. 1989. *Rehabilitation of degraded river ecosystems. Pages 86-97 in D.P. Dodge, editor.*

- Proceedings of the International Large River Symposium. Canadian Special Publication of Fisheries and Aquatic Sciences 106.
- Ricker, W.E. 1934. An ecological classification of certain Ontario streams. Publication of the Ontario Fisheries Research Laboratory 49: 1-114.
- Rosgen, D.L. 1994. A classification of natural rivers. *Catena* 22:169-199.
- Ryder, R.A. 1964. Chemical characteristics of Ontario lakes as related to glacial history. *Transactions of the American Fisheries Society* 93: 260-268.
- Ryder, R.A. 1965. A method of estimating the potential fish production of north-temperate lakes. *Transactions of the American Fisheries Society* 94: 214-218.
- Schlosser, I.J. 1991. Stream fish ecology: a landscape perspective. *BioScience* 41:704-712.
- Schupp, D.H. 1992. An ecological classification of Minnesota lakes with associated fish communities. St. Paul, Minnesota. Minnesota Department of Natural Resources, Investigational Report 417.
- Seelbach, P.W., M.J. Wiley, J.C. Kotanchik, and M.E. Baker. 1997. A landscape-based ecological classification system for river valley segments in lower Michigan (MI-VSEC Version 1.0). Michigan Department of Natural Resources, Fisheries Division Research Report No. 2036
- Sly, P.G. Thee effects of land use and cultural development on theLake Ontario ecosystem since 1750. *Hydrobiologia* 213:1-75.
- Sly, P.G., and W.-D.N. Busch. 1992. A system for aquatic habitat classification of lakes. Pages 16-26 in W.-D.N. Busch and P.G. Sly, editors. *The development of an aquatic habitat classification system for lakes*. CRC Press, Inc. Boca, Raton, USA.
- Stanfield, L., and B. Kilgour. 2001. Protocols for delineating, characterizing, and classifying valley segments. Region of Ottawa Carleton and Ontario Ministry of Natural Resources. Glenora, Ontario.
- Stanfield, L., and R. Kuyvenhoven. 2002 Protocol for application used in the aquatic landscape inventory software application for delineating, characterizing and classifying valley segments within the Great Lakes basin. Ontario Ministry of Natural Resources, Glenora, Ontario.
- Stephenson, T.D. 1990. Fish reproductive utilization of coastal marshes of lake Ontario near Toronto. *Journal of Great Lakes Research* 16:71-81.
- The Nature Conservancy. 2001. Aquatic ecoregional planning in the U.S. portion of the Great Lakes watershed (CD-ROM) Chicago, Illinois: The Nature Conservancy, Great Lakes Program.
- Tonn, W.M. 1990. Climate change and fish communities: a conceptual framework. *Transactions of the American Fisheries Society* 119:337-352.
- Tonn, W.M., and J.J. Magnuson. 1982. Patterns in the species composition and richness of fish assemblages in northern Wisconsin lakes. *Ecology* 63:1149-1166.
- Tyson, J.T., D.H. Davies, and S.D. Mackey. 2001. Influence of riverine inflows o western Lake Erie: implications for fisheries management. Proceedings of the 12th Biennial Coastal Zone Conference. Cleveland, Ohio, 2001.
- Underhill, J.C. 1986. The fish fauna of the Laurentian Great Lakes, the St. Lawrence Lowlands, Newfoundland, and Labrador. Pages 105-136 in C.H. Hocutt and E.O. Wiley, editors. *The zoogeography of North American freshwater fishes*. John Wiley & Sons, Inc., New York.

- Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E. Cushing. 1980. The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences* 37:130-137.
- Whillans, T.H. 1988. Wetlands and fisheries in central Ontario lakes. Pages 407-413 in M.J. Bardecki and N. Patterson, editors. *Wetlands: inertia or momentum*. Federation of Ontario Naturalists, Toronto, Ontario.
- Wichert, G.A. 2004. Implementing an Aquatic Landscape Inventory System (ALIS) in the Great Lakes aquatic biodiversity conservation blueprint. Prepared for the Nature Conservancy of Canada, Toronto, Ontario.
- Wichert, G.A., and D.J. Rapport. 1998. Fish community structure as a measure of degradation and rehabilitation of riparian systems in an agricultural drainage basin. *Environmental Management*. 22:425-443.
- Wichert, G.A., and H.A. Regier. 1998. Four decades of sustained use, of degradation and of rehabilitation in various streams of Toronto. Pages 189-214 in L.C. de Waal, A.R.G. Large and P.M. Wade, editors. *Rehabilitation of Rivers: Principles and Implementation*. John Wiley & Sons, Chichester, U. K. xii + 331 pp.
- Wickware, G.M., and C.D.A. Rubec. 1989. Ecoregions of Ontario. *Ecological Land Classification Series, No. 26 Sustainable Development Branch, Environment Canada, Ottawa, Ontario*. 37 p.
- Willis, T.V., and J.J. Maguson. 2000. Patterns in fish species composition across the interface between streams and lakes. *Canadian Journal of Fisheries and Aquatic Sciences* 57:1042-1052.
- Wright, J.F., D. Moss, P.D. Armitage, and M.T. Furse. 1984. A preliminary classification of running-water sites in Great Britain based on macro-invertebrate species and the prediction of community type using environmental data. *Freshwater Biology* 14:221-256.
- Zorn, T.G., and P.W. Seelbach. 1995. The relationship between habitat availability and the short-term carrying capacity of a stream reach for Smallmouth bass. *North American Journal of Fisheries Management* 15: 773-783.

XI. APPENDIX A. Comparison of ALIS and ORSECT.

Table A1. Comparison of ORSECT and ALIS features as of September 2001.

Criteria	Program	
	ORSECT	ALIS
Function	Automated routines to extract digital spatial information	Automated routines to extract digital spatial information
Geographic focus	Developed in north, intended for use throughout Ontario	Implemented first in Lake Huron basin, Ontario side, and then applied throughout the Ontario Great Lakes watershed
Delineation model building process	Literature review of parameters and variables prior to incorporation	Selection of parameters and variables based on empirical observations and expert judgement
Selection of classification criteria	Classification criteria based on review of literature	emphasis on data collection and organization
Validation	Ground-truth through field surveys; characterize errors associated with node and segment identification, and geo-referencing	Ensure GIS software renders accurate representation of underlying digital data
Timeline	ORSECT development for small pilot area by September 2001. Field testing of pilot area in 2002. ORSECT development for extensive geographic application to commence after September 2002.	ALIS development for Lake Huron streams complete by the end of November 2001. Processing of Great Lakes watersheds to commence immediately following ALIS development.
Documentation	No development rationale, work plan or schedule available for review.	Conceptual framework and development plans (Stanfield and Kilgour 2001) and a workplan (Kuyvenhoven 2001)

XII. APPENDIX B: ALIS attributes

List of ALIS attributes

Water flow

- drainage area (ha)
- stream order (Strahler)
- link (number of upstream first order tributaries)
- area estimates for each of 28 land cover classes (ha)
- area estimates for each of 32 geologic classes (ha)
- area of lakes and wetlands within the catchment (ha)
- distance upstream and downstream to nearest lake (m)
- distance upstream and downstream to nearest wetland (m)
- distance upstream and downstream to nearest barrier
- number of dams in catchment
- climate, mean annual precipitation (mm), and maximum mean monthly air temperature (degrees C)
- gradient (%)

Great Lakes coast

Land-water ecotone:

- geomorphic shoreline features (descriptive classes, see Table 7 this document)

Coastal area, with no defined water flow:

- area estimates for each of 32 geologic classes (ha)

Wetland

- size (ha)
- shoreline complexity (no units)
- connectivity (connected or unconnected to water flow)
- mean maximum monthly air temperature (degrees C)

Inland lake

- size (ha)
- shoreline complexity (no units)
- connectivity (connected or unconnected to water flow)
- geological context (no units, geological permeability values range from 1 to 3 on a continuous scale; (see Table 23, this document)
- mean maximum monthly air temperature (degrees C)