Landscape-based identification of human disturbance gradients and ecological integrity for Ontario's streams and rivers

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Abstract

No provincial standard is currently in place to define or report on rivers and streams. The Aquatic Ecosystem Classification allows us to define, describe, and make consistent predictions about flowing waters across the province. This consistent approach facilitates reporting and informs the decisions of policy makers and resource managers. In this report, we summarize the current state of the ecological integrity of Ontario's flowing waters based on the influence of human disturbance — something that has been well studied and frequently reported on in southern Ontario but not previously completed at provincial scale.

Our analysis represents the first stream network-based identification of human disturbance gradients and ecological integrity for Ontario's streams and rivers. Streams are a function of their upstream catchments and are stressed by land use activities, not only in the immediate area but also by stresses affecting upstream areas. We used upstream catchment land cover to determine the degree of human development for each stream reach in Ontario. This network approach is required for stream ecosystems, which function as directionally nested networks.

We summarized each stream reach by land cover attribute using Land Information Ontario's Provincial Land Cover Compilation v2. We present raw upstream catchment percentage values and then classify these values as natural, least disturbed, transitional, and stressed. We also summarize human disturbances in spatial units (e.g., jurisdictional boundaries, watersheds) using the reach data. We report on the health of streams based on several boundaries including Ministry of Natural Resources and Forestry (MNRF) districts, conservation authorities, and tertiary watersheds. Results are stratified by river size and by special interest categories (e.g., cold water streams).

Most streams (86% by length) in the Mixedwood Plains Ecozone of southern Ontario are stressed. Conversely, few streams (only 1.7% by length) are natural. Southern Ontario has the highest densities of people in the province and consequently large areas of developed land. It also has most of the agricultural lands due to suitable climate and soil conditions. About 85% of streams (by length) in this ecozone do not have treed riparian zones but the percentage of stressed streams in the ecozone was not affected by thermal class. In contrast, streams in Northern Ontario, which includes the Boreal Shield and Hudson Bay Lowlands, were mostly (≈99%) natural. This area is sparsely populated and has less agricultural activity, with urbanization spread over a much larger area.

These same methods can be used to assess changes in streams through time as reflected in updated land cover data. We propose that the influence of habitat fragmentation, forestry, and waterpower be assessed in future analyses, particularly in Northern Ontario where these stressors are more prevalent.

Résumé

Identification paysagère des gradients de perturbation anthropique et intégrité écologique des cours d'eau et rivières de l'Ontario

Aucune norme provinciale n'est actuellement en place pour définir le statut des rivières et les ruisseaux ou en faire rapport. La Classification des écosystèmes aquatiques nous permet de définir, de décrire les eaux qui coulent dans la province et de faire à leur sujet des prévisions

uniformes. Cette approche uniforme facilite la production de rapports et éclaire les décisions des décideurs et des gestionnaires des ressources. Dans ce rapport, nous résumons l'état actuel de l'intégrité écologique des eaux vives de l'Ontario en nous fondant sur l'influence des perturbations anthropiques, un aspect qui a été bien étudié et qui a souvent fait l'objet de rapports dans le Sud de l'Ontario, mais qui n'avait pas encore été étudié à l'échelle provinciale.

Notre analyse est la première identification des gradients de perturbation humaine axée sur les réseaux hydrographiques qui tient compte de l'intégrité écologique des cours d'eau et rivières de l'Ontario. Les cours d'eau sont fonction de leurs bassins versants en amont et subissent non seulement un stress imputable aux activités d'affectation des terres, notamment dans la région immédiate, mais aussi le stress exercé sur les régions en amont. Nous avons eu recours à la couverture terrestre des bassins versants en amont pour déterminer le degré d'aménagement humain pour chaque tronçon de cours d'eau en Ontario. Cette approche par réseau hydrographique est nécessaire pour les écosystèmes des cours d'eau, qui fonctionnent comme des réseaux imbriqués sur le plan directionnel.

Nous avons résumé chaque tronçon de cours d'eau selon les attributs de la couverture terrestre à l'aide de la version 2 de la Préparation cartographique de couverture terrestre. Nous exposons d'abord les valeurs brutes en pourcentage des bassins versants d'amont pour ensuite classifier ces valeurs en catégories : naturelles, moins perturbées, transitoires et stressées. Nous résumons également les perturbations humaines dans les unités spatiales (p. ex. limites administratives, bassins hydrographiques) à l'aide des données des tronçons. Nous rendons compte de la santé des cours d'eau d'après plusieurs limites, entre autres les districts du ministère des Richesses naturelles et des Forêts, les offices de protection de la nature et les bassins hydrographiques tertiaires. Les résultats sont stratifiés en fonction des dimensions des rivières et selon des catégories d'intérêt spécial (p. ex. cours d'eau froide).

La plupart des cours d'eau (86 % selon la longueur) dans l'écozone des plaines à forêts mixtes du Sud de l'Ontario sont stressés. À l'inverse, très peu de cours d'eau (1,7 % selon la longueur) sont naturels. On trouve dans le Sud de l'Ontario les plus fortes densités de population de la province et, par conséquent, de vastes régions de terres aménagées. C'est également là que se situent les meilleures terres agricoles en raison d'un climat et de conditions de sol favorables. Environ 85 % des cours d'eau (selon la longueur) de cette écozone sont dépourvus de zones riveraines boisées, mais le pourcentage de cours d'eau stressés n'a pas été affecté par la catégorie thermique. Cependant, les cours d'eau du Nord de l'Ontario, où se trouvent le Bouclier boréal et les basses terres de la Baie d'Hudson, étaient en presque totalité (≈99 %) naturels. Cette zone, peu densément peuplée, comporte moins d'activités agricoles et l'urbanisation est étalée sur une beaucoup plus grande superficie.

Ces mêmes méthodes peuvent servir à évaluer les changements des cours d'eau au fil du temps, tels que reflétés par les données à jour sur la couverture terrestre. Nous pensons que l'influence de la fragmentation des habitats, la foresterie et la force hydraulique devraient être la cible d'analyses futures, surtout dans le Nord de l'Ontario, où ces éléments de stress sont plus fréquents.

Contents

Introduction

Freshwater ecosystems are some of the most threatened in the world (Strayer and Dudgeon 2010). Fresh water occupies <1% of the Earth's surface yet supports 10% of all known species and 33% of vertebrate species. North America's freshwater habitats are being depleted of species as rapidly as tropical forests (Ricciardi and Rasmussen 1999). Flowing waters and their riparian areas support much of the aquatic biodiversity in Ontario (e.g., amphibians, reptiles, mussels, birds, and mammals) and relative to terrestrial areas contain a disproportionate number of species at risk. These attributes are particularly true for river sections flowing in flood plain valleys where diverse habitats, nutrient cycling, productivity of biota, and species interactions are concentrated (Hauer et al. 2016). Of the roughly 160 species of fish in Ontario, 84 have a higher affinity for flowing water than lakes while 42 others live primarily in streams and rivers; 16 species are non-native and 31 are species at risk.

Before European settlement, wetlands covered about 20,000 km^2 of southern Ontario but by 2002 only 5,600 km^2 remained — an overall decrease of about 14,000 km^2 or 72% of the pre-settlement wetlands (Ducks Unlimited 2010). Over a similar period, forested land has decreased from more than 80% of the land to less than 20% through conversion to agriculture and urban lands (Elliott 1998, Butt et al. 2005). The Conservation Authorities Act, 1946 was legislated by Ontario in response to concerns from agricultural, naturalist, and sports groups that many of the province's renewable natural resources were in an unhealthy state due to poor land, water, and forestry practices during the 1930s and 1940s. The combined effects of drought and deforestation led to extensive soil loss and flooding. Today, the landscape of the Mixedwood Plains Ecozone (Crins et al. 2009) of southern Ontario is composed of predominantly agricultural and urban lands. The urbanization of agricultural lands is one of the dominant patterns of land use change in developed countries (Moore and Palmer 2005), affecting hydrology, thermal habitat, and sediment regimes in streams and introducing pollutants.

Stream characteristics are a product of the lands they drain. This was exemplified in Noel Hynes' statement that "the valley rules the stream." Different landscapes produce different types of streams. For instance, an arctic stream in Polar Bear Provincial Park differs ecologically from a stream of similar size in the mixedwood plains of southern Ontario. More extreme examples include differences among desert, glacial, rainforest, and prairie streams. Similar to these natural differences, human-caused disturbances can influence stream characteristics including ecosystem processes and biological assemblages (Allan 2004, Wang et al. 2011).

The conversion of naturally vegetated land (e.g., forest and wetlands) to agricultural, industrial, and urban lands has increased the area of impervious surfaces (e.g., pavement) and decreased infiltration of precipitation, fundamentally changing the natural flow regime in many streams (Poff et al. 1997). Symptoms of the *urban stream syndrome* include a flashier hydrograph, elevated concentrations of nutrients and contaminants, altered channel morphology, and reduced biotic richness, with increased dominance of tolerant species (Walsh et al. 2005). More specifically, surface runoff from impervious areas increases the frequency and severity of flood events, increasing erosion and sediment loads and altering stream channel form and fish habitat (Klein 1979, Wang et al. 1997). Increases in impervious surfaces have also resulted in modified stream base flows (i.e., groundwater recharge), altered water temperature regimes and energy inputs, and increased nutrient and toxic substance loading (Wang et al. 2000, Stanfield and Kilgour 2006, Brisbois et al. 2008, McGrane 2016). These disturbances have led to major changes in stream water quality and quantity (Paul and Meyer 2001, Sponseller et al. 2001, Wang and Lyons 2003, McGrane 2016), biological assemblages (Weaver and Garman 1994, Wang et al. 2000, Wang and Lyons 2003, Wang et al. 2006, Weijters et al. 2009), and overall ecosystem health (Karr and Chu 1999, Meador and Goldstein 2003, Wang et al. 2003, Allan, 2004, Sciera et al. 2008).

Riparian zones are the interfaces between aquatic and terrestrial ecosystems that need to be considered in landscape planning and efforts to restore flowing waters (Naiman and Décamps 1997). Vegetated riparian areas provide shade, which directly influences energy pathways and moderates water temperature. Riparian areas also stabilize stream banks and filter sediment and nutrient in runoff (Swank et al. 1988, Gregory et al. 1991). This filtering is important for fish as it influences water clarity, food web structure, and habitat (Pusey and Arthington 2003).

Currently, no provincial standard is in place to define or report on rivers and streams. The Aquatic Ecosystem Classification allows us to define, describe, and make consistent predictions across the province. This consistent approach facilitates reporting and informs the decisions of policy makers and resource managers. In this report, we summarize the current state of the ecological integrity of Ontario's flowing waters based on the influence of human disturbance — something that has been well studied and frequently reported on in southern Ontario but not previously completed at provincial scale.

To monitor and report on the health and integrity of Ontario's streams and rivers, and to plan protected areas focused on watersheds with high ecological integrity, we needed to identify human disturbance gradients and assess the ecological integrity of Ontario's streams and rivers. To date, no province-wide stream network-based analysis of disturbance exists. Previous efforts (e.g., Chu et al. 2003) typically generated zonal statistics using watersheds, which does not accumulate upstream drainage characteristics and does not reflect how stressors move through stream networks. Other studies (e.g., Stanfield and Kilgour 2006, Stanfield et al. 2006) were focused on small areas of the province (e.g., Golden Horseshoe area). This network-based information is vital to our understanding of where stream ecosystems are stressed or least disturbed and still retain ecological integrity. As defined in the Provincial Parks and Conservation Reserves Act, (Statutes of Ontario 2006), ecological integrity is "a condition in which biotic and abiotic components of ecosystems and the composition and abundance of native species and communities are characteristic of their natural regions and rates of change and ecosystem processes are unimpeded." The core of ecological integrity is the naturalness of an area.

In this study, we summarized human disturbance and ecological integrity for each stream reach in Ontario based on its individual upstream catchment and riparian areas characteristics. We report the results based on Ministry of Natural Resources and Forestry (MNRF) districts, conservation authorities, and tertiary watershed (e.g., Upper and Lower Grand River) boundaries. We also summarize land cover statistics based on different stream thermal classes (unpublished data) and by stream size (Strahler order; Strahler 1952) for the Mixedwood Plains Ecozone of southern Ontario. In addition to upstream catchment areas, we summarize riparian conditions (e.g., treed land) as defined by a rasterized (30 m cell size) stream channel. The summary of riparian conditions was conducted for stream catchments smaller than 1000 km^2.

Our analysis differs from previous approaches. For instance, Chu et al. (2003) used tertiary watersheds as containers to generate zonal statistics for each watershed. They simply summarized land cover types and stressors in each watershed. The actual stream network is relevant because their approach does not consider the spatial arrangement of where the stressors occur in the stream network. Streams are a function of their upstream catchments. They are influenced by land use activities not only in the immediate area but by everything

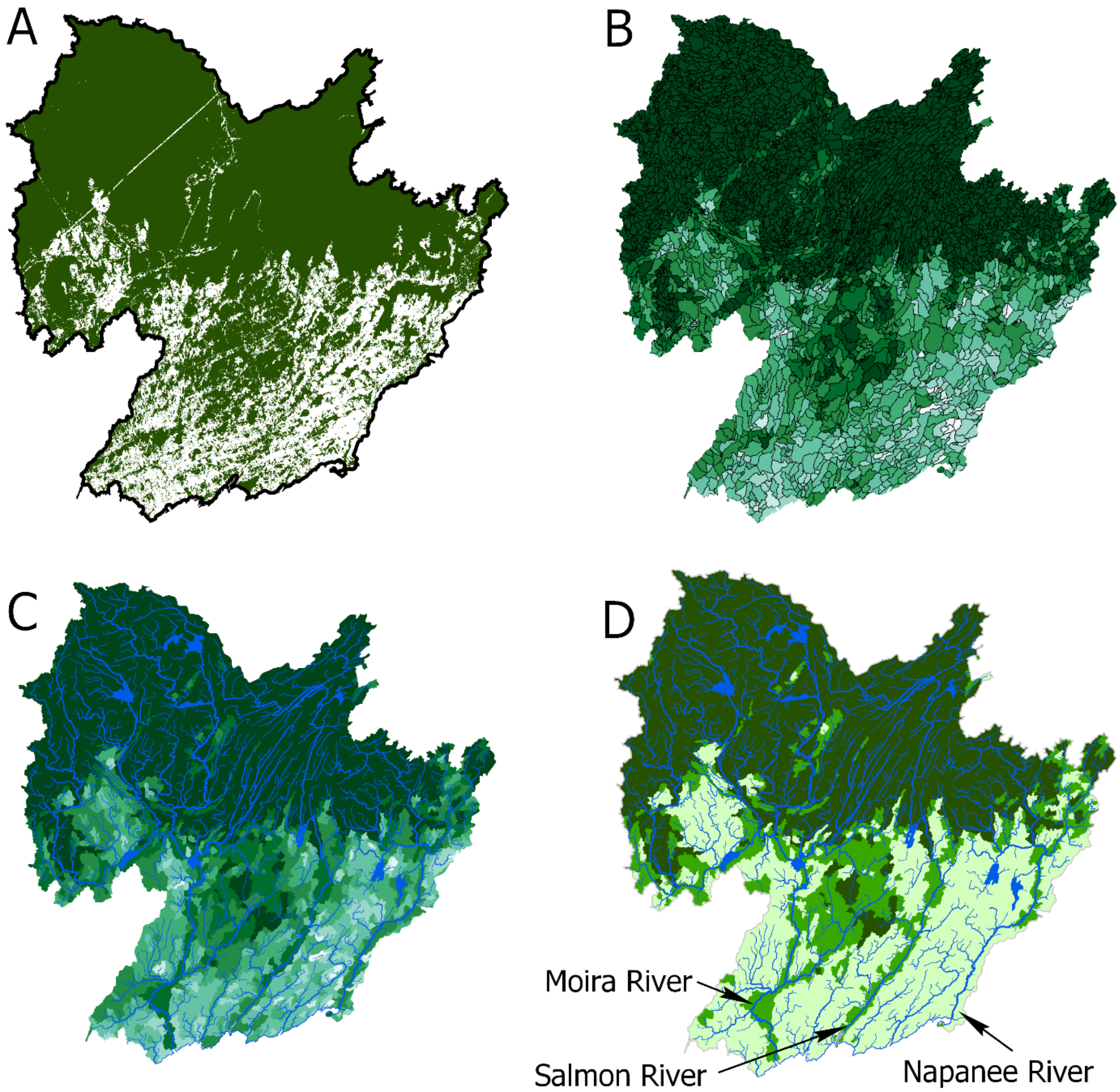


Figure 1. These maps illustrate how previous methods differ from our approach for quantifying stream naturalness within a jurisdictional boundary (e.g., part of the Quinte Conservation Authority). Previous methods simply quantify the percentage of natural land cover in the

catchment boundary without the need for knowledge of the stream network (A). A more accurate representation of stream naturalness requires the network structure and calculating the amount of natural land cover in each reach contributing area (B), which are then summed in each upstream catchment area (UCA) to allow us to calculate the percentage of natural stream reaches by length (C). The reaches are then classified based on their UCA per cent natural land cover (D). Dark, medium, and light green reach catchment area polygons indicate >90%, 75-90%, and <75% UCA natural landcover. The difference in results between the two approaches is significant. In the example above, the simple summary (A) of natural land cover indicates that 75% of the catchment is natural. Conversely, the network-based approach (D) indicates that only 57% of the stream length is natural.

flowing down the stream network (Figure 1). For example, we cannot expect a stream reach to be healthy if its headwaters are heavily urbanized even if the land use in the reach contributing area is natural (e.g., the Don River flowing through Lower Don Parklands in Toronto, Ontario). Conversely, a stream reach might be relatively healthy if its upstream catchment is natural but its reach contributing area is largely developed (e.g., the Humber River flowing through Etobicoke, Ontario). Another difference between our approach and that of others is that by using the stream network we could summarize the information by stream length. Overall, the network based analytical approach is more representative of actual conditions and uses a much finer scale, allowing a range of jurisdictional sizes to be used for the final summary. In addition, the jurisdictional summaries can show which areas (e.g., tertiary watersheds) have higher ecological integrity that is helpful to prioritize protection and restoration efforts. Our analysis at the stream reach scale allows users to determine where efforts are needed in each jurisdiction, which was not possible using previous non-stream network-based approaches.

Ecological thresholds

Ecological thresholds occur when a rapid ecosystem response occurs across a relatively small change in an environmental stressor (Groffman et al. 2006, Hilderbrand and Utz 2015). This assumes that changes are non-linear or that threshold responses to changes in stressors can be identified. Results from several studies indicate linear declines in species richness as imperviousness increases (Morley and Karr 2002, Moore and Palmer 2005). Results from other studies indicate that thresholds may be less common than believed (Karr and Chu 1999, Bledsoe and Watson 2001). Moore and Palmer (2005) found that macroinvertebrate richness was related negatively and linearly (no statistical threshold) to the amount of impervious surface cover. Another complication in determining ecological thresholds lies in choosing an adequately sensitive response variable, which could be a species (e.g., brook trout presence/absence or abundance), community composition (e.g., combined responses of many species), or ecosystem level (e.g., change of state).

A threshold response is more likely when using individual species. Several human-caused and natural drivers often influence a stream reach and these can confound understanding of the response to a stressor. For instance, urbanization leads to multiple changes including flashier flows, increases in toxins (salt, oils), and changes in water temperature — each may elicit their own or synergistic responses from biota. Allan (2004) suggested that urbanization is too complex to warrant a single threshold. Recent advancements in threshold analysis include the Threshold Indicator Taxa Analysis (TITAN) (Baker and King 2010). This approach uses indicator species scores to incorporate occurrence, abundance, and directionality of taxa responses. It highlights the importance of individual responses and thresholds that are often not seen in community analysis. For example, small losses of individual species that occur as stressor levels increase are more likely than entire benthic invertebrate community changes all at once. Some rare species or those with low abundances are often removed from community analyses, but not in TITAN because they could be the most sensitive taxa that disappear at low stress levels.

Findings from several studies and reviews include that fish communities change significantly when their catchments approach 10% impervious cover (Klein 1979, Wang et al. 2000, Paul and Meyer 2001, Allan 2004, Groffman et al. 2006, Stanfield and Kilgour 2006, Clapcott et al. 2011). More specifically, Stanfield et al. (2006) found that brook trout (*Salvelinus fontinalis*) and rainbow trout (*Oncorhynchus mykiss*) were sensitive to low per cent imperviousness cover, with populations absent at greater than 6.6% and 8.9%, respectively. These impervious values translate to about 33% urban or 65% agriculture. Using a similar data set, Stanfield and Kilgour (2006) noted that fish and benthos consisted of mainly warmwater or tolerant species at impervious values greater than 10% (i.e., about 50% urban). King et al. (2005) noted that as little as 21% developed land (low- and high-intensity residential and commercial land cover classes) in catchments can affect the composition of stream macroinvertebrates. King et al. (2005) also found that macroinvertebrates were more sensitive to increases in developed land if development was closer to the sampling station.

The influence of agricultural land cover is often more variable and has a smaller effect than urban areas (Allan 2004, Wasson et al. 2010). This may reflect the more variable nature (i.e., heterogeneity) of agriculture practices (e.g., intensive crops, fallow fields, and livestock grazing) and soils often captured in a single remotely sensed land cover type. Thorn et al. (2016) found that brook trout were absent in Lake Simcoe catchments when 40 to 50% of the forest cover had been removed — and mainly replaced by agriculture. Similarly, Death and Collier (2010) noted that, on average, stream catchments with 40 to 60% forest cover retain 80% of the mean biodiversity present in natural forest streams. Feld (2013) observed that ecological metrics changed markedly between 10 to 20% agriculture land use in mountain ecoregions and 40 to 45% in lowlands, regardless of the riparian width. However, at mountain streams with >10% agriculture, metrics differed between sites with <30% and >30% forest in the near-stream riparian area. This research highlights the positive role of riparian land use in catchment management and shows the need for ecoregion (or stream type) specific management.

Although uncertainty exists about the effectiveness of riparian areas in mitigating urbanization and agricultural land use, evidence suggests that they are important for the health of stream ecosystems (Trimble and Mendel 1995, Hickey and Doran 2004, McKergow et al. 2016). McKergow et al. (2016) noted that riparian zones and buffers for livestock exclusion (fencing with or without planting) increased nutrient processing, shaded small streams for temperature control, provided leaf and wood input to stream ecosystems, and enhanced fish and invertebrate habitat. In some studies (e.g., Stanfield and Kilgour 2006, Roy et al. 2007), catchment urbanization overwhelmed the potential mitigating effects of riparian forests on stream fishes.

Variability in determining thresholds also stems from the spatial design of studies (King et al. 2005, Grimstead et al. 2018). Setting thresholds based on catchment percentages is challenging because it does not account for where the urbanization is in the catchment. For example, how does the spatial arrangement of 30% urbanization on the network affect a stream. Is a random arrangement better than a concentration of urbanization in the headwaters or far downstream? Each of these scenarios will produce different ecological responses.

Collectively, this research suggests that the response of aquatic biota to human disturbance depends on 1) disturbance type and intensity, 2) stream type, 3) spatial proximity to the disturbance, 4) covariation among natural predictor variables (e.g., geology type) and land use stressors, 5) characteristics and size (width and length and slope) of the riparian area, 6) responses, which can be linear (gradual change) or non-linear (step or threshold), and 7) aspects of stream ecosystems (e.g., nutrients, hydrology, algae, benthic invertebrates, and fishes) that are influenced differently by the same disturbance.

Methods

For the spatial framework and attribution of streams, we used the Aquatic Ecosystem Classification data for Ontario streams (AEC; Jones and Schmidt 2017). The AEC was built using interconfluence stream reaches as the fundamental spatial units. Landscape data was summarized at three spatial scales for each stream reach in Ontario (Figure 2). Land cover data was summarized for each stream reach based on the upstream catchment characteristics and characteristics in the riparian area represented by a 30 metre buffer for stream catchments smaller than 1000 km^2. Information for reach contributing area was only used to generate catchment scale summaries.

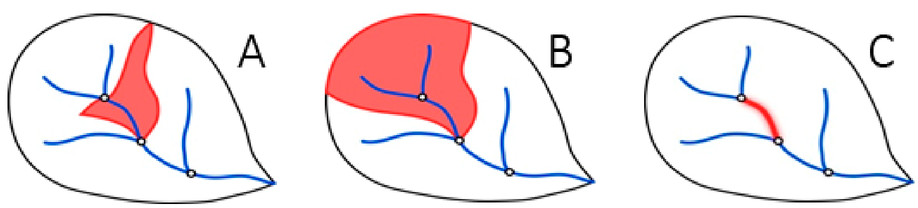


Figure 2. The three scales applied to group stream reaches: a) reach contributing area, b) upstream catchment, and c) reach channel (30 m raster) in Ontario's Aquatic Ecosystem Classification and applied in this study.

The steps in the process are listed below and are described in greater detail in Jones and Schmidt (2017).

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

We used the Provincial Land Cover Compilation v2 (PLCCv2) found in Land Information Ontario. The Ontario Land Cover Compilation (OLCC) is a rationalized land cover product for the province, combining three land cover databases (Far North Land Cover v1.4, Southern Ontario Land Resource Information System (SOLRIS) v1.2, and the Provincial Land Cover 2000 edition).

Source land cover databases in Provincial Land Cover Compilation v2

1. The Provincial Land Cover Database (PLC2000; 2000 edition) consists of 27 broad land cover types and was produced in 2004 from an unsupervised classification of about 55 Landsat-7 Enhanced Thematic Mapper satellite images acquired between 1999 and 2002. The PLC2000 was produced as 4 overlapping rasters, one for each UTM zone in the province, with a pixel resolution of 25 metres.

2. Southern Ontario Land Resource Information System (SOLRIS) Version 1.2 (SOLRISv1.2) consists of 25 land cover classes that follow the Ministry of Natural Resources' Ecological Land Classification (ELC) for southern Ontario (Crins et al. 2009). This database was produced in 2008 from an object oriented classification of 11 Landsat-7 ETM satellite images acquired between 1999 and 2002. SOLRIS was produced as 2 overlapping rasters, one for each UTM zone in southern Ontario, with a pixel resolution of 15 metres.

3. Far North Land Cover Version 1.4 (FNLCv1.4) consists of 26 land cover types and was updated in 2014 from an object oriented classification of Landsat-5 TM satellite images acquired between 2005 and 2011. The FNLC was produced as 3 overlapping rasters, one for each UTM zone in northern Ontario, with a pixel resolution of 30 metres.

Several land cover classes were grouped to represent disturbed lands and natural lands (Table 1). We used the term developed lands to describe the land class Community/Infrastructure that includes clearings for human settlement and economic activity, major transportation routes, and built-up areas. Agriculture includes open grassland with sparse shrubs in rural land, areas of row crops and fallow fields and all agricultural features (e.g., field and forage crops, pasture, and rural properties) as well as urban brown fields, and openings in forests (PLCCv2).

We used disturbance threshold values that are conservative and supported in the literature (see Ecological Thresholds above). Catchments were considered stressed when developed land cover in a catchment was >25% or agriculture was >50%. This approach acknowledges that developed lands have double the influence of agriculture. Combinations of developed and agricultural lands were also considered stressed; for example, 1% developed and 48% agriculture or 24% developed and 2% agriculture. Computationally all the combinations were best determined by the formula:

Stress Index = (2% UCA developed land cover) + %UCA agricultural land cover*

where UCA is upstream catchment area. Catchments were considered stressed when the index was ≥49. Streams that were not considered stressed are either transitional (<75% natural), least disturbed (75-90% natural), and natural (>90% natural such as forest and wetland) based on the land cover in the catchment (Table 2).

The area of developed and natural land in each catchment was calculated by summing their corresponding land cover types and then calculating their upstream catchment percentages by stream length. The riparian treed data was calculated by first summing its corresponding land cover types and then determining the percentage of channel length covered by trees.

Table 1. Land cover classes in Provincial Land Cover Compilation v2 (PLCCv2) and their groupings into a stress index based on developed and natural lands. (The omission of Land Unit ID 9 is intentional as it is not included in the PLCCv2 data set.)

Unit ID	Unit name	Developed	Agricultural	Natural	Treed riparian
1	Clear open water	-	-	✓	-
2	Turbid water	-	-	✓	-
3	Shoreline	-	-	✓	-
4	Mudflats	-	-	✓	-
5	Marsh	-	-	✓	-
6	Swamp	-	-	✓	-
7	Fen	-	-	✓	-
8	Bog	-	-	✓	-
10	Heath	-	-	✓	-
11	Sparse treed	-	-	✓	-
12	Treed upland	-	-	✓	✓
13	Deciduous treed	-	-	✓	✓
14	Mixed treed	-	-	✓	✓
15	Coniferous treed	-	-	✓	✓
16	Plantation – treed cultivated	-	-	✓	✓
17	Hedge rows	-	-	✓	✓
18	Forest disturbance*	-	-	✓	-
19	Open cliff and talus	-	-	✓	-
20	Alvar	-	-	✓	-
21	Sand barren and dune	-	-	✓	-
22	Open tallgrass prairie	-	-	✓	-
23	Tallgrass savannah	-	-	✓	-
24	Tallgrass woodland	-	-	✓	✓
25	Mine tailings/extraction**	✓	-	-	-
26	Bedrock	-	-	✓	-
27	Community/infrastructure	✓	-	-	-
28	Agriculture and rural land use	-	✓	-	-

* Includes natural and human-caused disturbances over the past 20 years

**Includes beach deposits, sand river islands, aggregate quarries and sand dunes, mines, and mine tailings

Table 2. In this study streams were categorized using a combination of whether the stream is stressed (stress index) and how much natural land cover is in each upstream catchment for each reach (percentage natural land cover).

Data layers	Stressed	Transitional	Least disturbed	Natural
Stress index	49–200	0–49	0–49	0–49
Percentage natural land cover	<75	<75	75–90	>90

The jurisdictional analysis was used to evaluate the percentage of stressed and natural stream length of total stream length in a jurisdiction. We also calculated the length in kilometres and percentages of stressed, transitional, least disturbed, and natural streams by stream order and thermal class in the mixedwood plains. Further, treed riparian stream length to total stream length in stream orders and temperature classes were calculated. Aside from being a reach channel scale measure, the treed riparian cover differs because it was not categorized using thresholds before calculating the percentages.

Results and discussion

The results are illustrated in three groupings:

- provincial scale maps for each of the inputs including natural, agriculture, and developed lands (overview; maps 1-3)
- the information in the first three maps classified using the threshold values including the three categories of transitional (<75% natural), least disturbed (75–90% natural), and natural (>90% natural), and which stream reaches are considered stressed (overview using thresholds; maps 4-9)
- jurisdictional summaries (maps 10-14)

Summary tables show the percentage of stressed and natural streams by stream order and thermal classification and percentage of riparian areas covered by natural treed vegetation.

Overview

Most maps show patterns of natural and stressed streams that reflect the distribution of people in Ontario. Most of Ontario's population is in southern Ontario where little natural land cover remains and agriculture has replaced much of the natural landscape (Map 2). Over time, urbanized areas have grown and replaced some of the agricultural landscape (Map 3).

Overview using thresholds

The Boreal Shield and Hudson Bay Lowlands (maps 4 and 5) have little development and most of these streams are considered least disturbed or natural. Most streams in southern Ontario are stressed due to farming or developed land (maps 6 and 7). Combined views of the three land cover categories for Ontario (Map 8) and the Mixedwood Plains Ecozone (Map 9) show our three natural status categories (transitional, least disturbed, and natural) and the developed and agricultural areas. Depending on future growth and land management policies, transitional areas could move towards less disturbed or stressed.

Jurisdictional summaries

Streams in conservation authority catchments are most stressed in southwestern Ontario and around Lake Simcoe. Authorities in the north and in eastern Ontario have a lower proportion of stressed streams (Map 10). Stream stress increases from north to south. MNRF districts in the north (Boreal Shield and Hudson Bay Lowlands ecozones) have a smaller proportion of stressed stream length than the Mixedwood Plains Ecozone (Map 11). This pattern is also reflected in tertiary watersheds across Ontario (Map 12). Not surprisingly, the proportion of natural stream length is the reciprocal or opposite of the patterns of stressed streams (maps 13–15).

The jurisdictional summaries clearly show which areas are more stressed or natural, information that could be used to help prioritize protection and restoration efforts. Our analysis at the stream reach scale allows resource managers to determine where efforts are needed in each jurisdiction, something that was not possible using previous stressors summary that were not stream network based.

Higher order streams (e.g., 4 and 5 based on the Strahler order) generally have a higher proportion of stressed streams than small, low order, streams (e.g., 1-3; Table 3). It is easier to find a small catchment that is relatively natural. Larger natural streams are hard to find in southern Ontario, except for the lower Otonabee, Rideau, and Severn rivers, which still have large areas of land in a natural state. This pattern by stream order is mirrored in the other

Table 3. Stressed, transitional, least disturbed, natural, and treed riparian stream length of streams in the Mixedwood Plains Ecozone by Strahler order. The percentages (in parentheses) represent the respective proportions of streams in each Strahler order. Catchments were considered stressed when the stress index, combining developed or agricultural cover, was ≥49. Streams were considered transitional when <75%, least disturbed when 75-90%, and natural when >90% of the catchment was natural land cover (e.g., forest and wetland).

Strahler order	Order (km)	Stressed (km)	Transitional (km)	Least disturbed (km)	Natural (km)	Riparian treed (km)
1	29,882	25,440 (85)	2,603 (9)	1,099 (3.7)	740 (2.5)	4,311 (14)
2	15,091	12,937 (86)	1,468 (10)	473 (3.1)	213 (1.4)	2,468 (16)
3	8,171	7,102 (87)	871 (11)	168 (2.1)	30 (0.4)	1,453 (18)
4	3,834	3,564 (93)	218 (6)	52 (1.4)	0	731 (19)
5	1,466	1,412 (96)	45 (3)	10 (0.7)	0	170 (12)
6	828	690 (83)	138 (17)	0	0	1 (0.1)
7	17	0	17 (100)	0	0	-
Total	59,289	51,145 (86)	8,143 (9.0)	1,801 (3.0)	984 (1.7)	9134 (15)

categories; for example, natural streams representing stream orders 4-7 do not occur. The average proportion of treed riparian length was approximately 16% across orders 1-5, while sixth order streams had only 0.1%. Seventh order streams were excluded as they are above the 1,000 km^2 threshold for this analysis; these wider stream systems are not well represented by the 30 m raster of the stream channel.

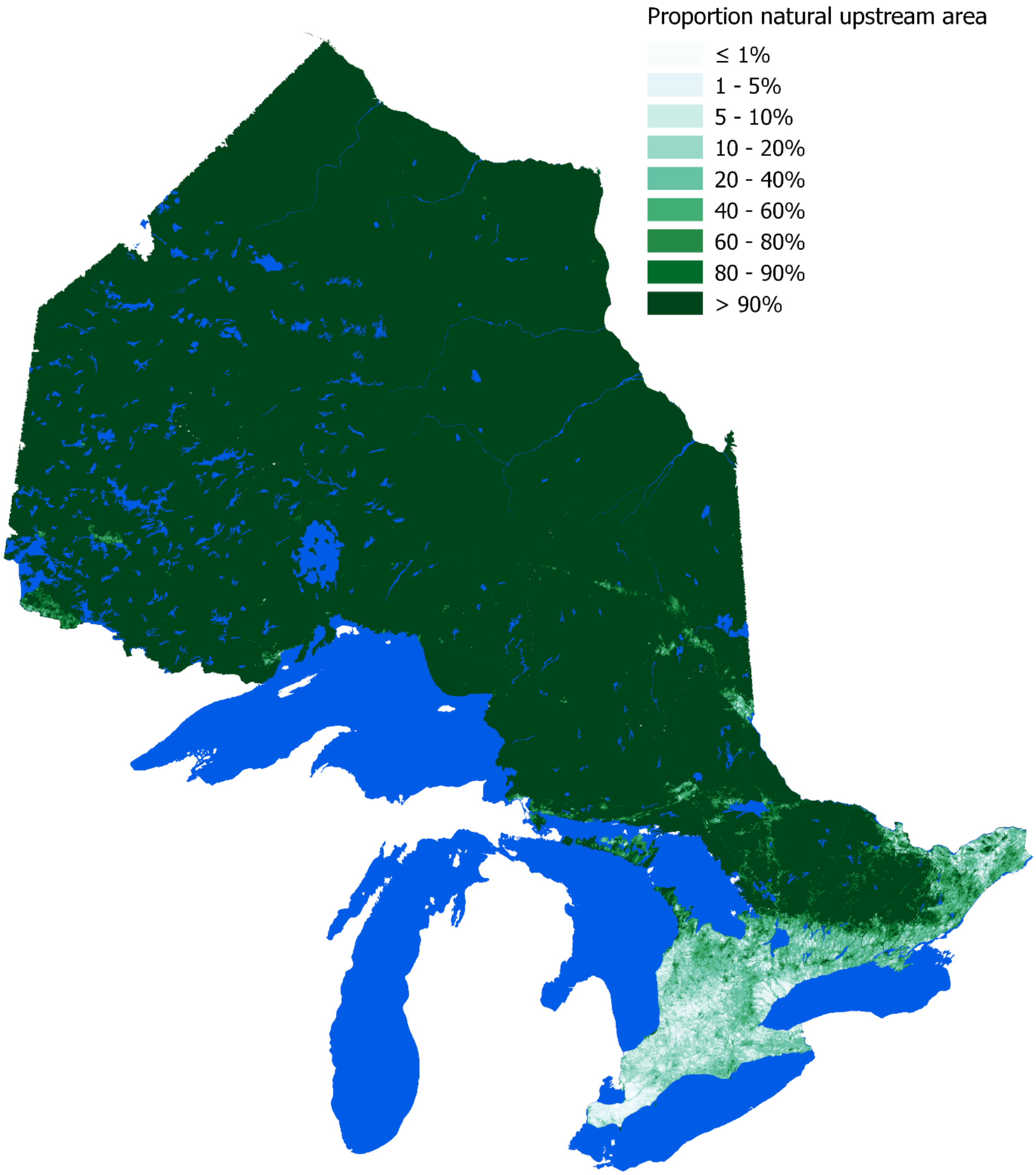
Streams classified as coldwater in the mixedwood plains had a smaller proportion of stressed stream length (79%) than the other thermal classes, but the differences were small (Table 4). Cool-warm streams had the most stream length categorized as stressed (93%). Interestingly, a similar pattern of stress emerged among thermal classes (increasing stress as streams get warmer) as was seen among stream orders (increasing stress as streams get larger), which may reflect that small streams are often cold. Coldwater streams had approximately double the proportion of treed riparian zones compared with other thermal classes.

This analysis represents the first stream network-based identification of human disturbance gradients and ecological integrity for Ontario's streams and rivers. This analysis is repeatable and as landscape data is updated could be used to assess trends through time. In addition, older landscape data could be analyzed using this approach to assess historical trends; however, land cover classes would need to be harmonized.

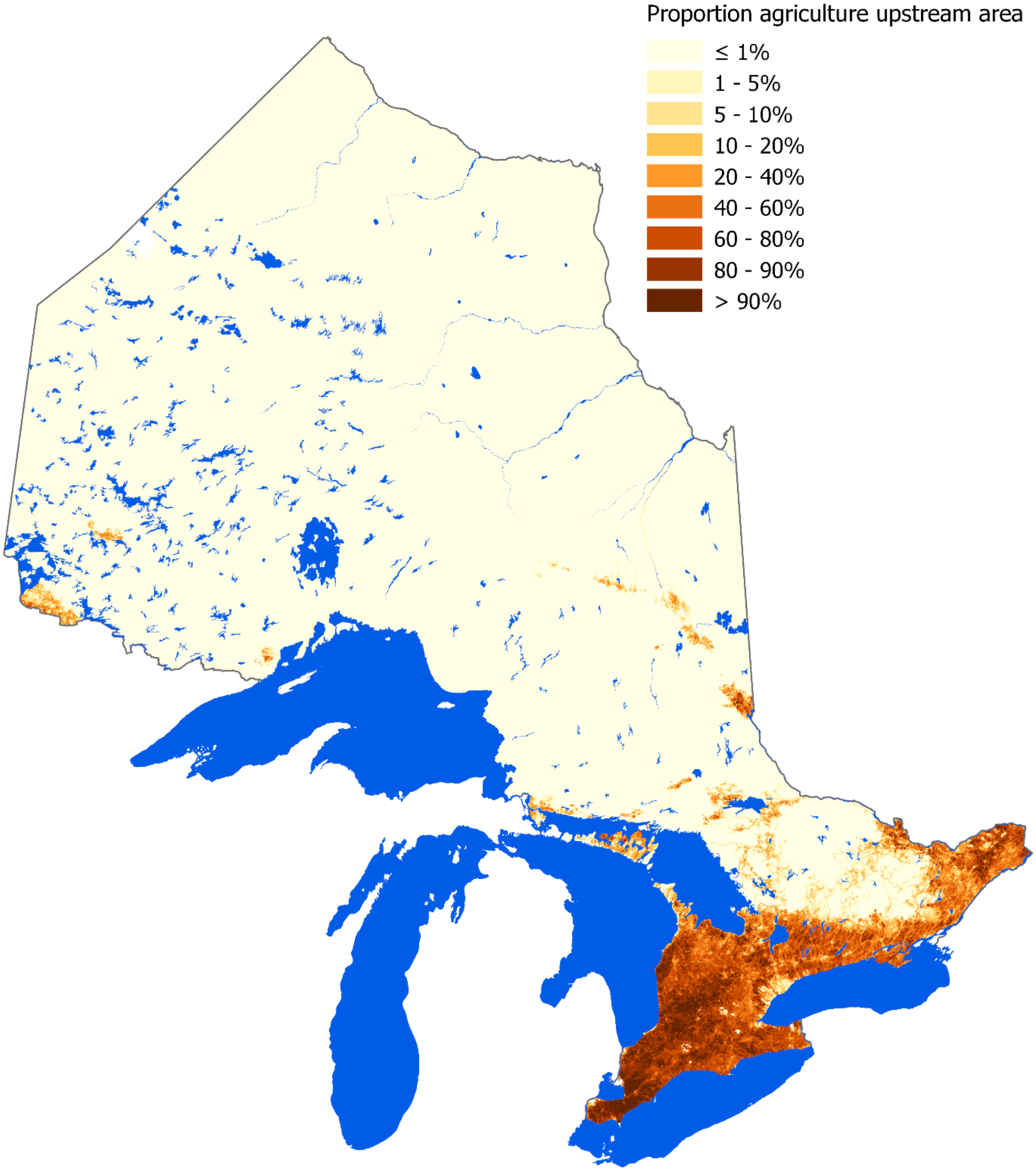
We used upstream catchment land cover to determine the characteristics (integrity) for each stream reach. This network approach is required for streams, which are directionally nested. Streams are a function of their upstream land use activities not only in the immediate reach contributing area but from everything flowing from upstream. Our analysis shows that streams of the Mixedwood Plains ecozone of southern Ontario are stressed.

Table 4. Stressed, transitional, least disturbed, natural, and treed riparian stream length (in kilometres) by thermal class in the Mixedwood Plains (MWP) Ecozone of southern Ontario. The percentages (in parentheses) represent the respective proportions in each Strahler order. Catchments were considered stressed when the stress index, combining developed or agricultural cover, was ≥49. Streams were considered transitional when <75%, least disturbed when 75-90%, and natural when >90% of the catchment was natural land cover (e.g., forest and wetland).

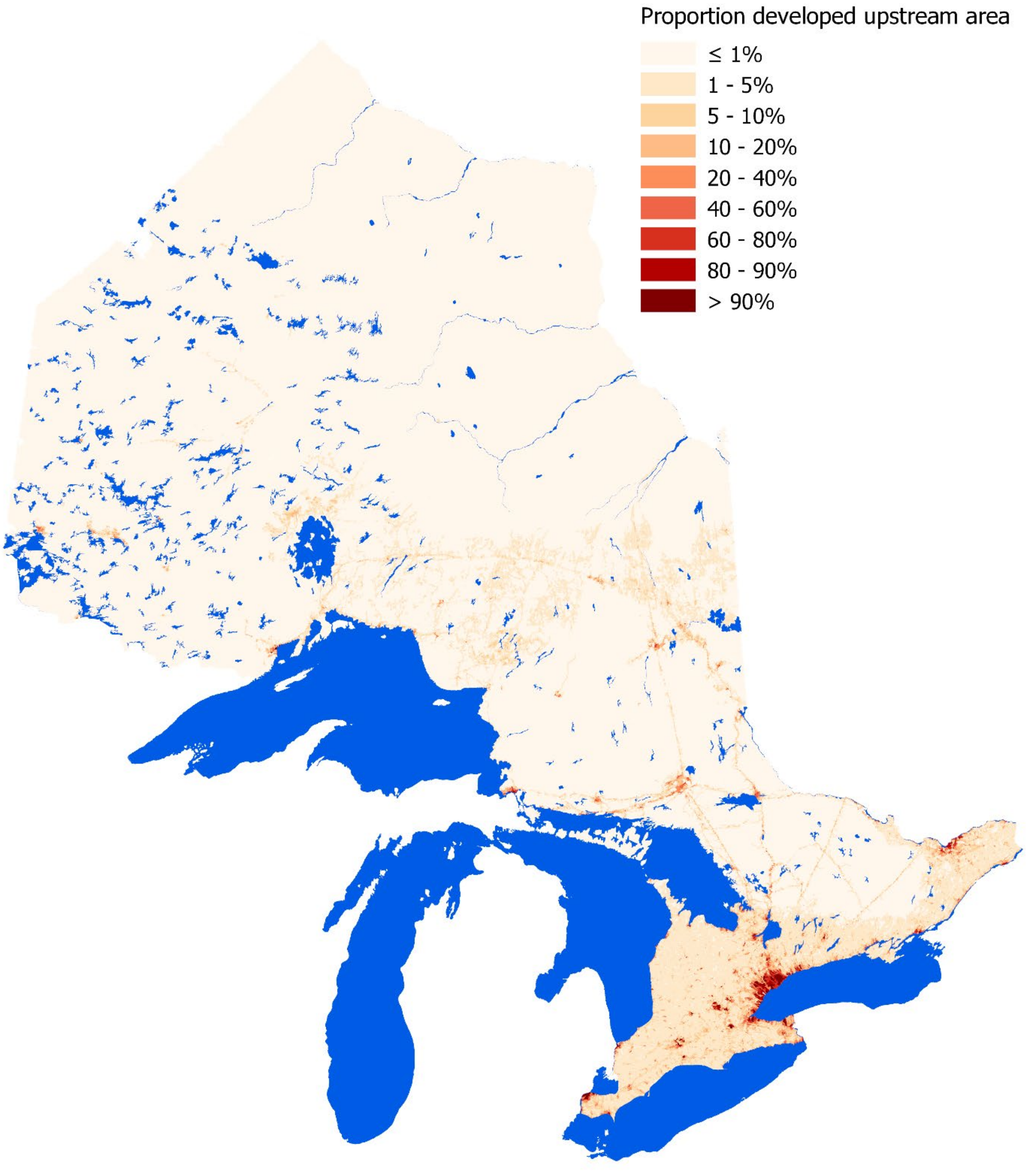
Thermal class	Class (km)	Stressed (km)	Transitional (km)	Least disturbed (km)	Natural (km)	Riparian treed (km)
Cold	4,400	3,466 (79)	611 (14)	188 (4.3)	135 (3.1)	1,359 (31)
Cold-cool	13,806	11,612 (84)	1,339 (10)	514 (3.7)	341 (2.5)	2,327 (17)
Cool	25,427	21,934 (86)	2,465 (10)	773 (3.0)	255 (1.0)	3,215 (13)
Cool-warm	11,721	10,838 (93)	568 (5)	192 (1.6)	123 (1.0)	1,684 (14)
Warm	3,785	3,292 (87)	362 (10)	100 (2.6)	31 (0.8)	456 (12)
Total	59,139	51,142 (86)	5,345 (9)	1,801 (3.0)	984 (1.7)	9041 (15)



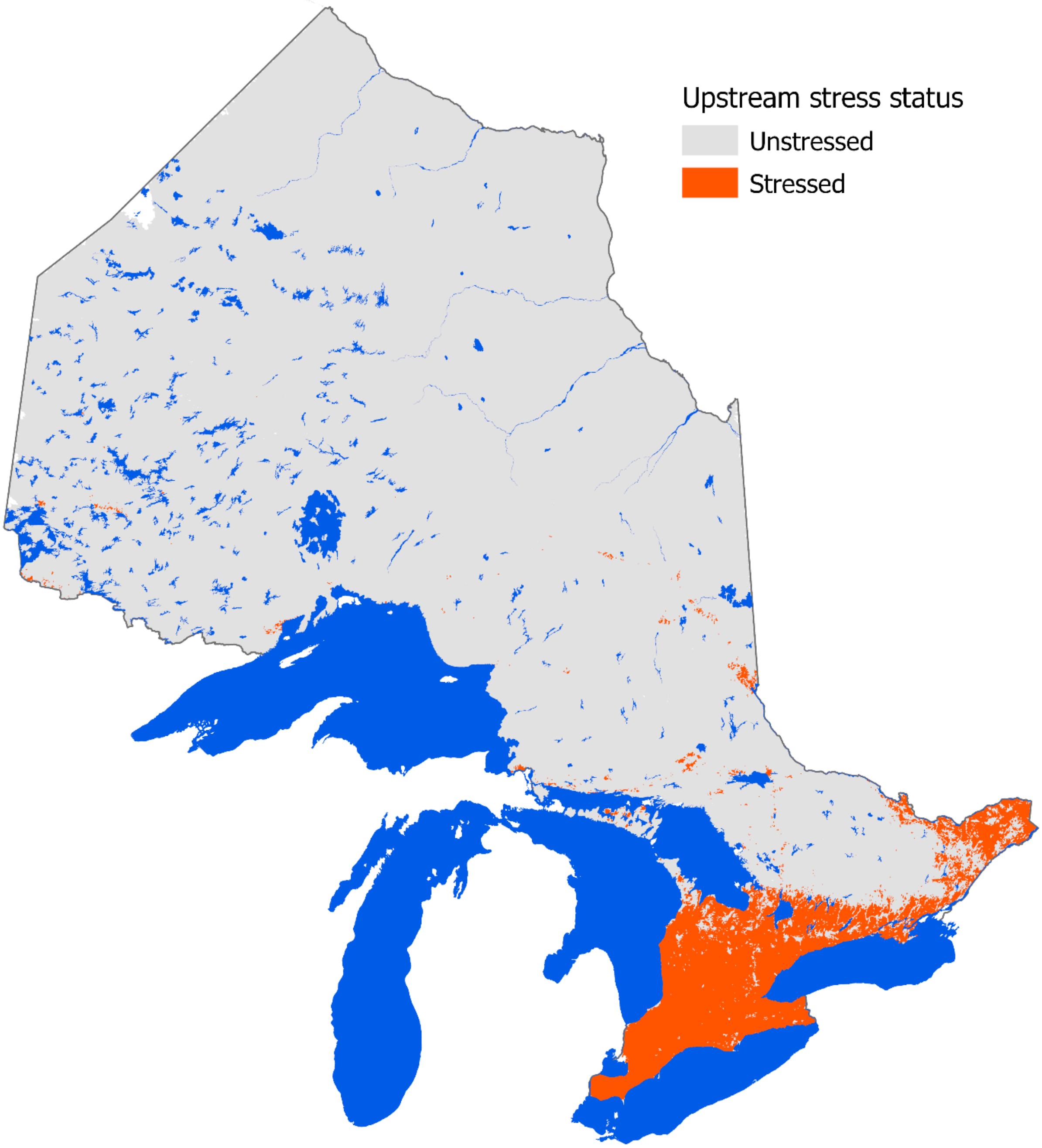
Map 1. Percentages of upstream catchment area with natural land cover in Ontario.



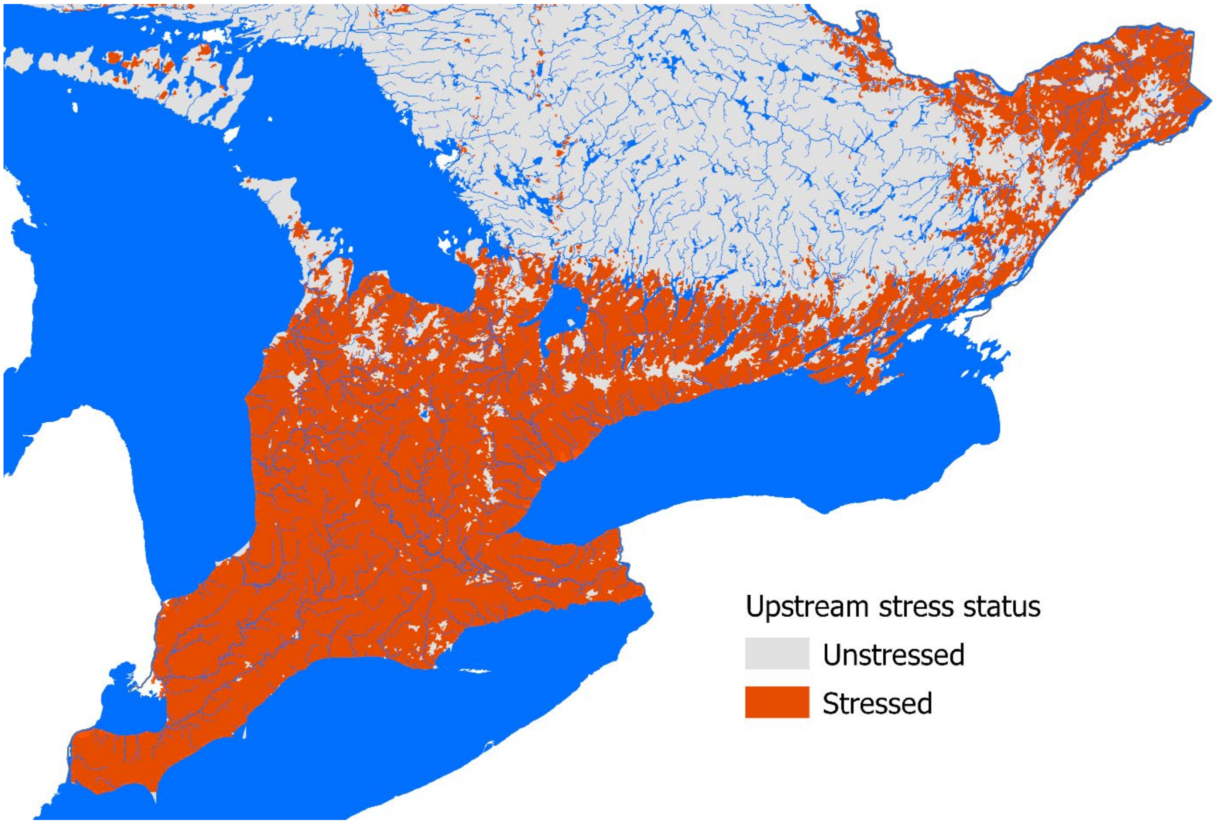
Map 2. Percentages of upstream catchment area with agricultural land cover in Ontario.



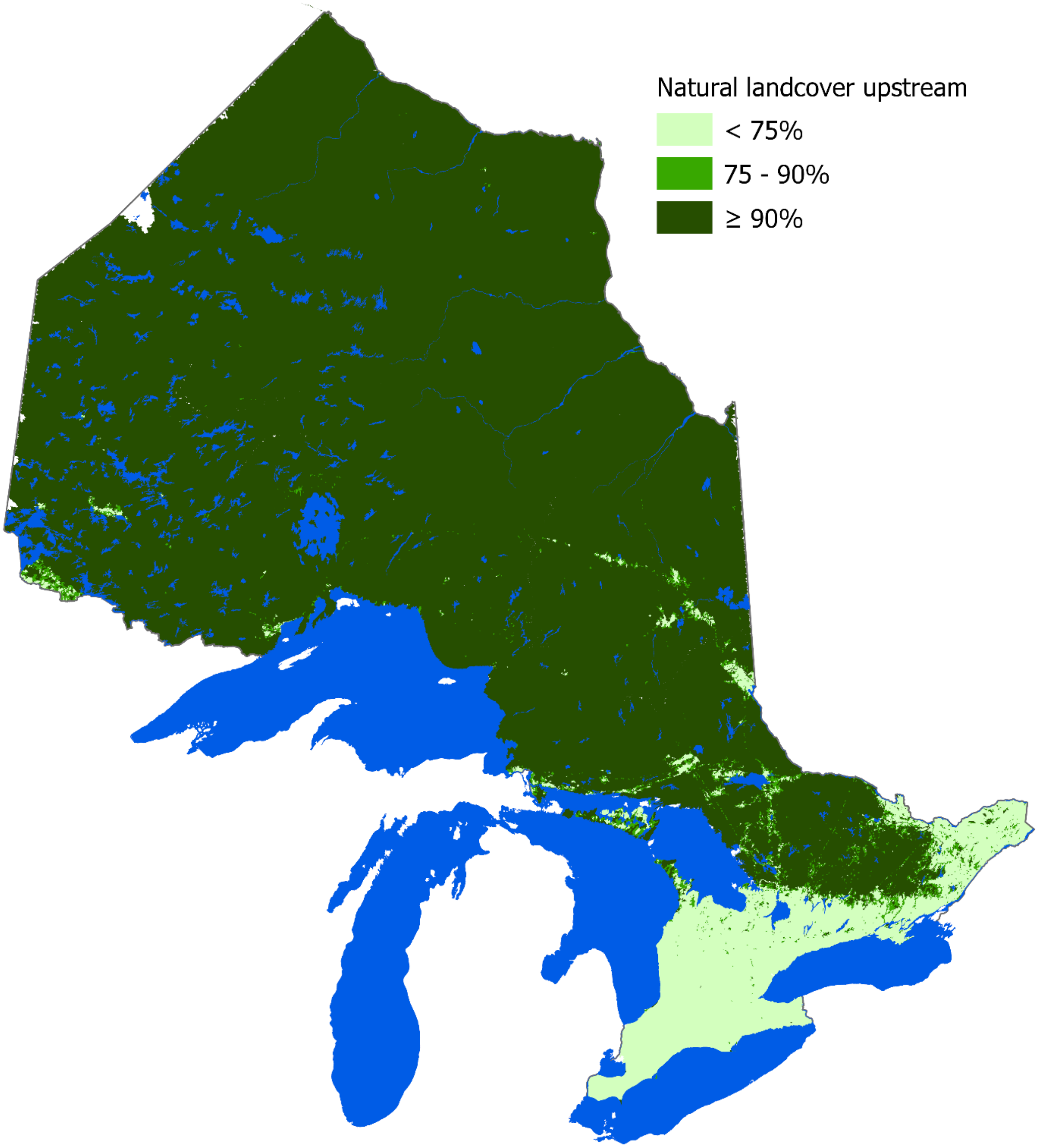
Map 3. Percentages of upstream catchment area with developed land cover in Ontario.



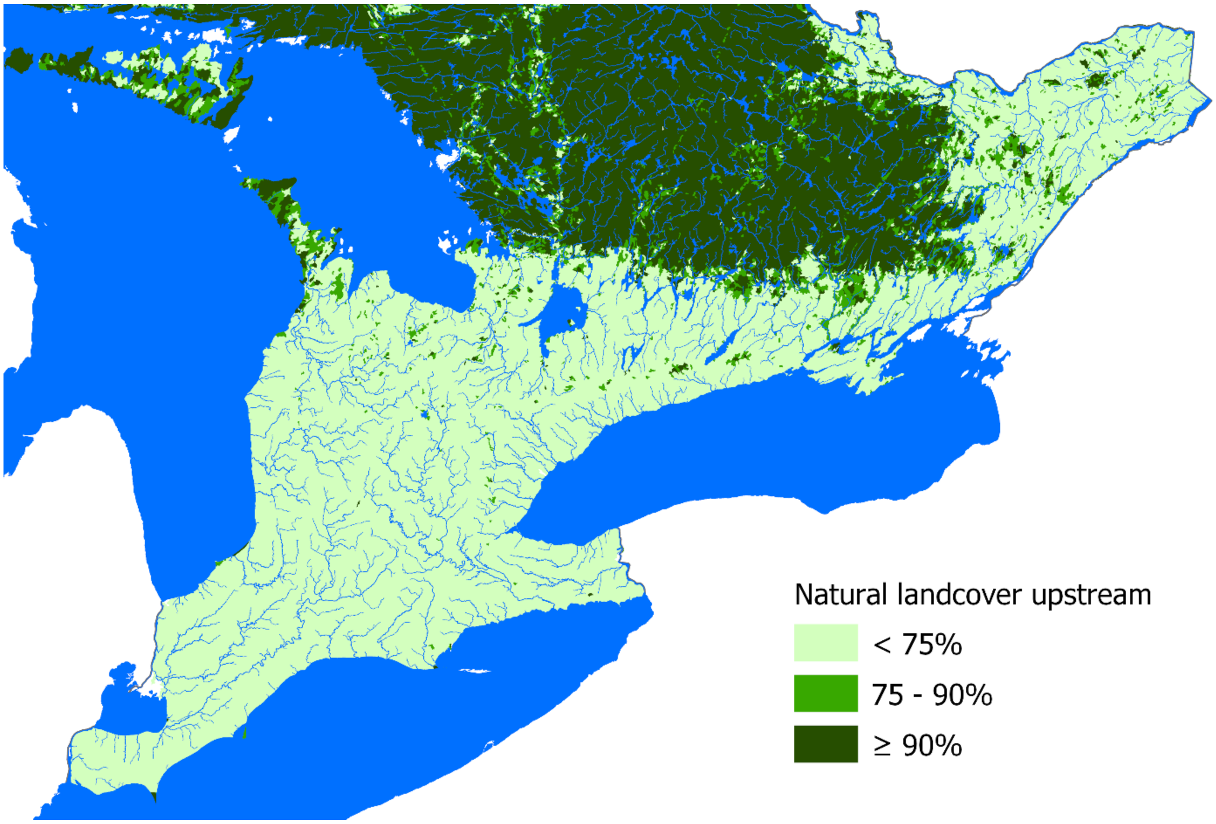
Map 4. Stress index for Ontario's rivers and streams. The stress index combines developed and agricultural lands in Ontario in the upstream catchment area. Streams are considered stressed when the stress index exceeds 49, derived using the following formula: *Stress Index = (2 x UCA %Developed) + UCA %Agriculture),* where UCA is the upper catchment area.



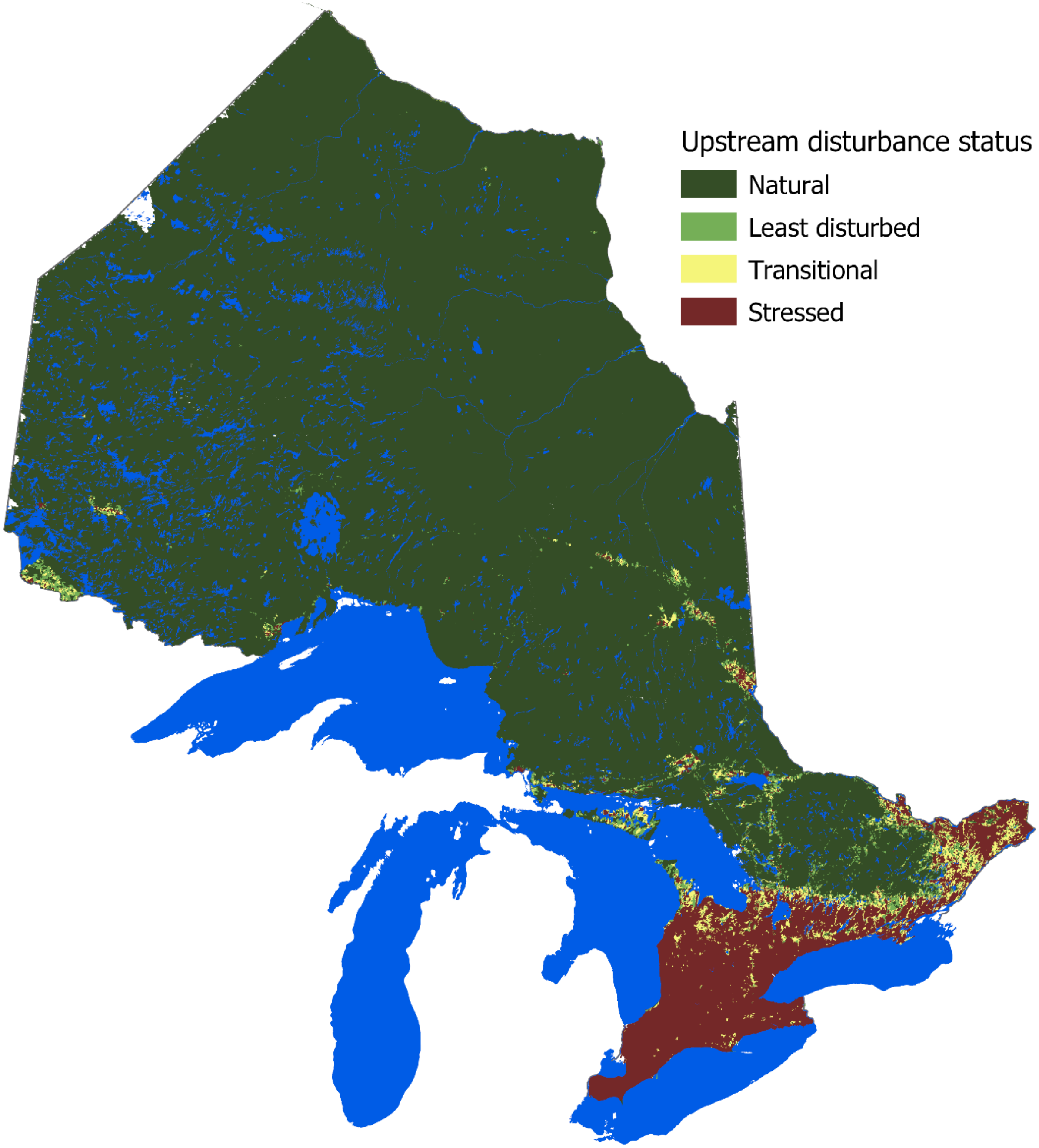
Map 5. Stress index for southern Ontario based on combinations of developed and agricultural lands in the upstream catchment area.



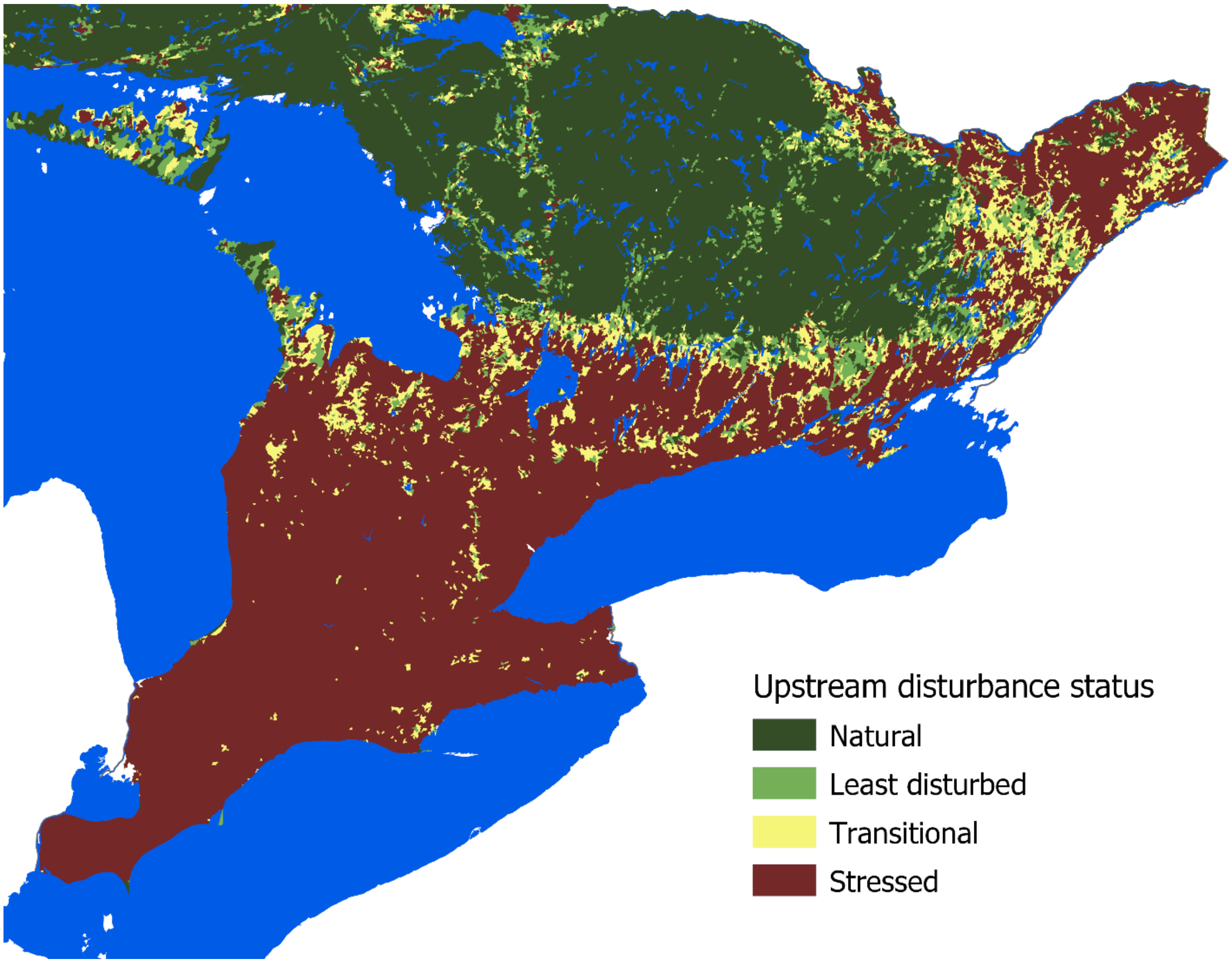
Map 6. Natural land cover types for Ontario streams: disturbed (light green, <75% natural), least disturbed (medium green, 75-90% natural), and natural (dark green, ≥90% natural).



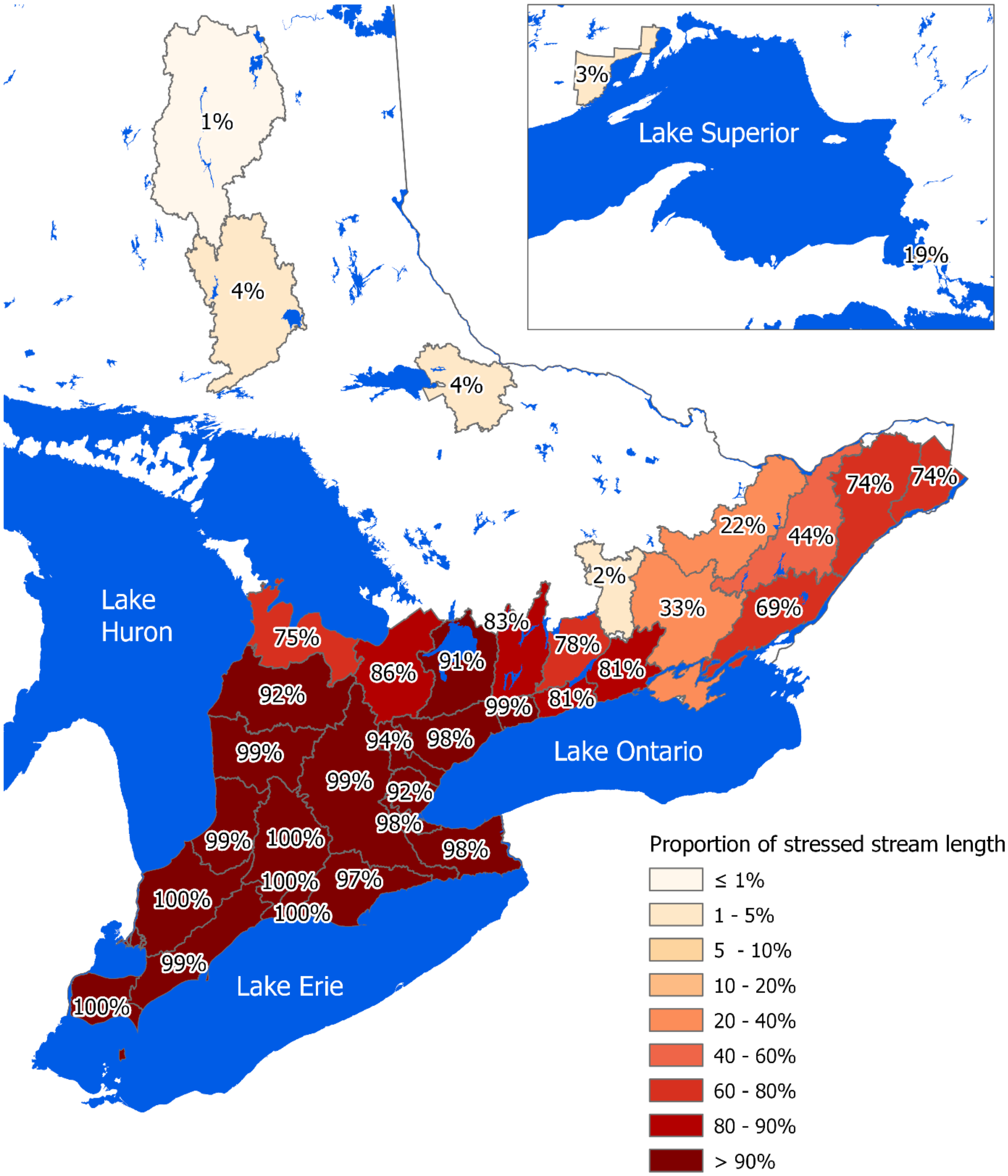
Map 7. Natural land cover types for southern Ontario streams: disturbed (light green, <75% natural), least disturbed (medium green, 75-90% natural), and natural (dark green, ≥90% natural).



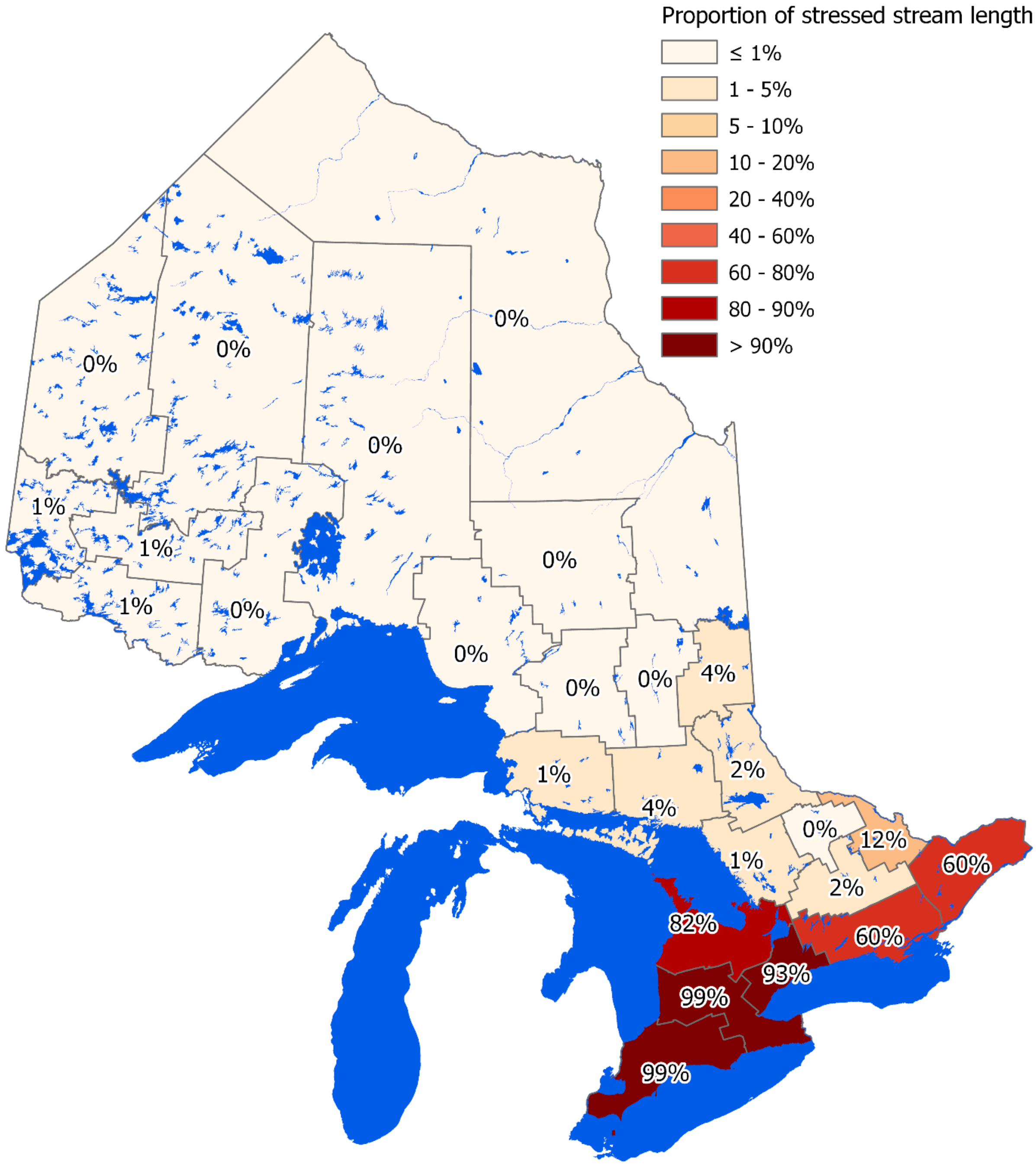
Map 8. Land cover categories for Ontario streams: stressed (red), transitional (yellow, <75% natural), least disturbed (light green, 75-90% natural), and natural (dark green, >90% natural).



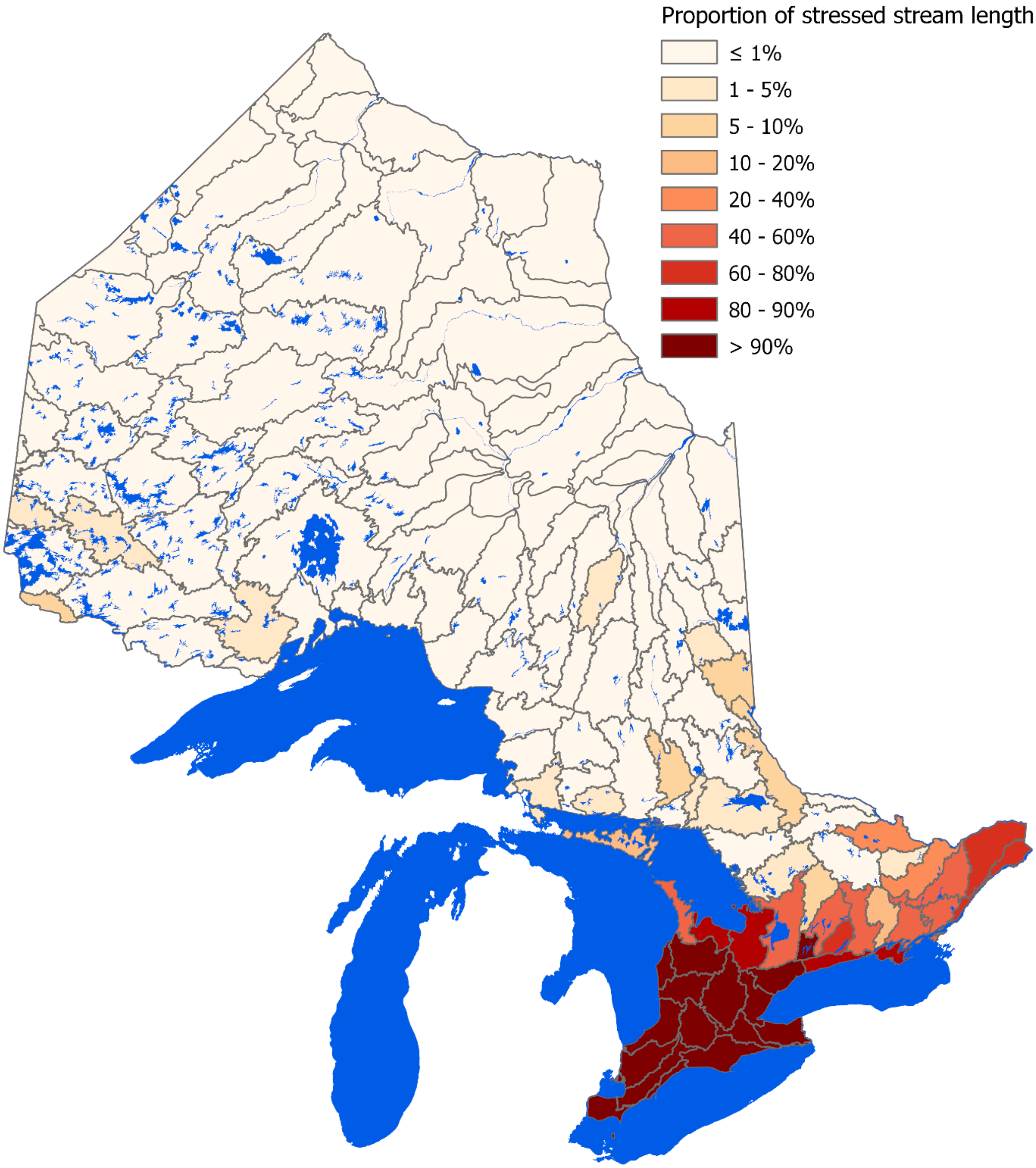
Map 9. Land cover categories for southern Ontario streams: stressed (red), transitional (yellow, <75% natural), least disturbed (light green, 75-90% natural), and natural (dark green, >90% natural).



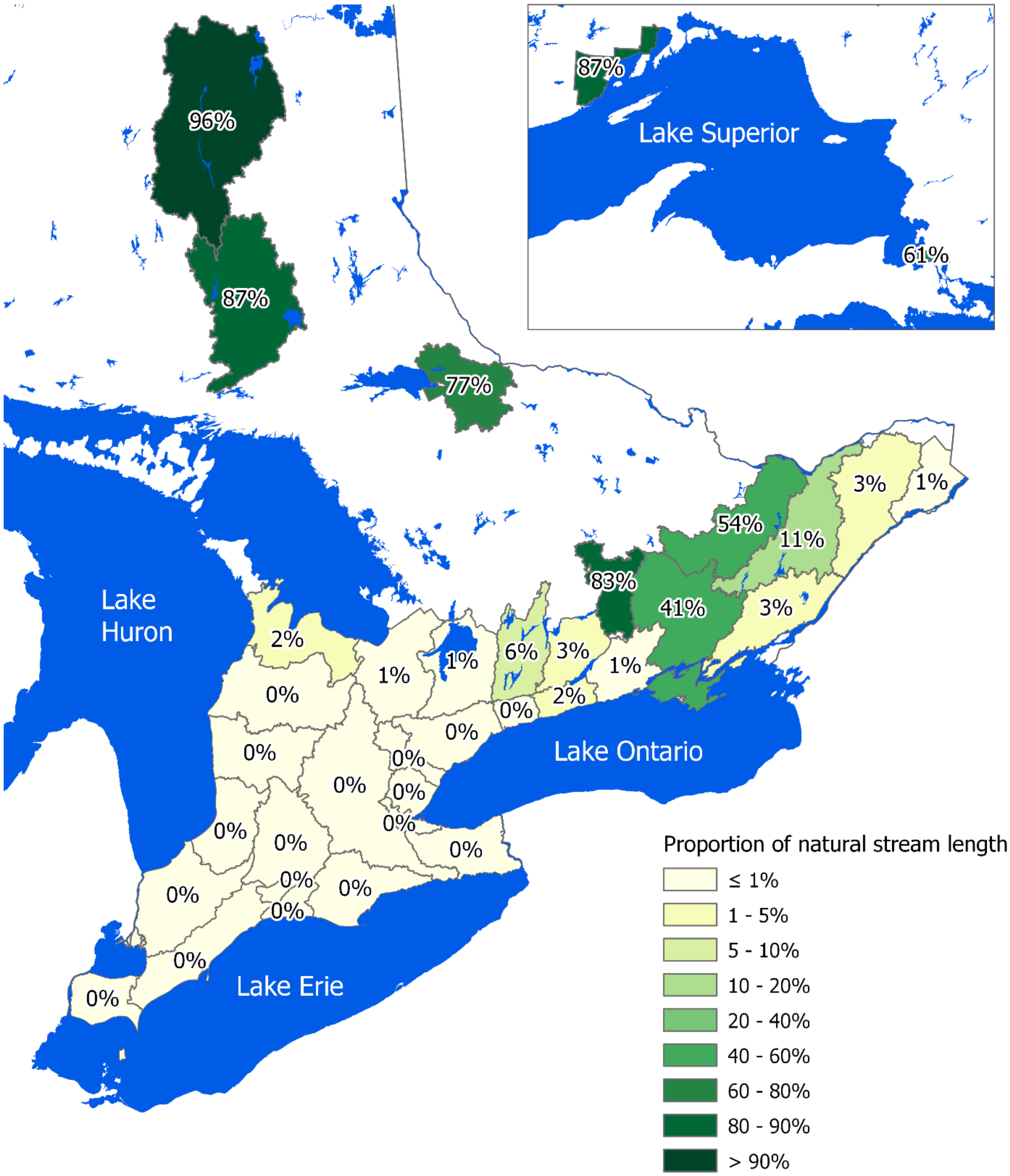
Map 10. Proportion of stressed stream length in Ontario by conservation authority.



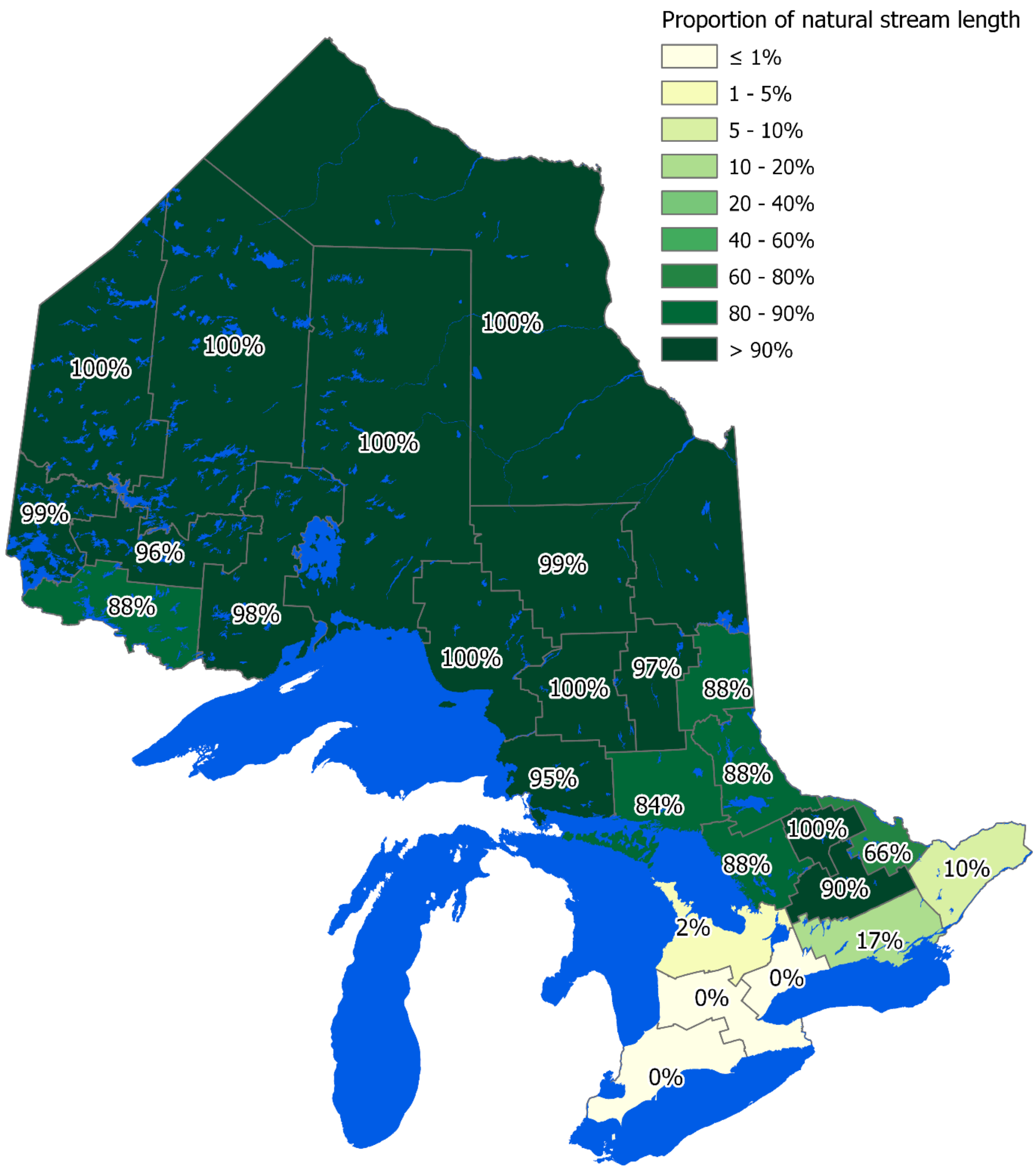
Map 11. Proportion of stressed stream length in Ontario by Ministry of Natural Resources and Forestry district boundaries.



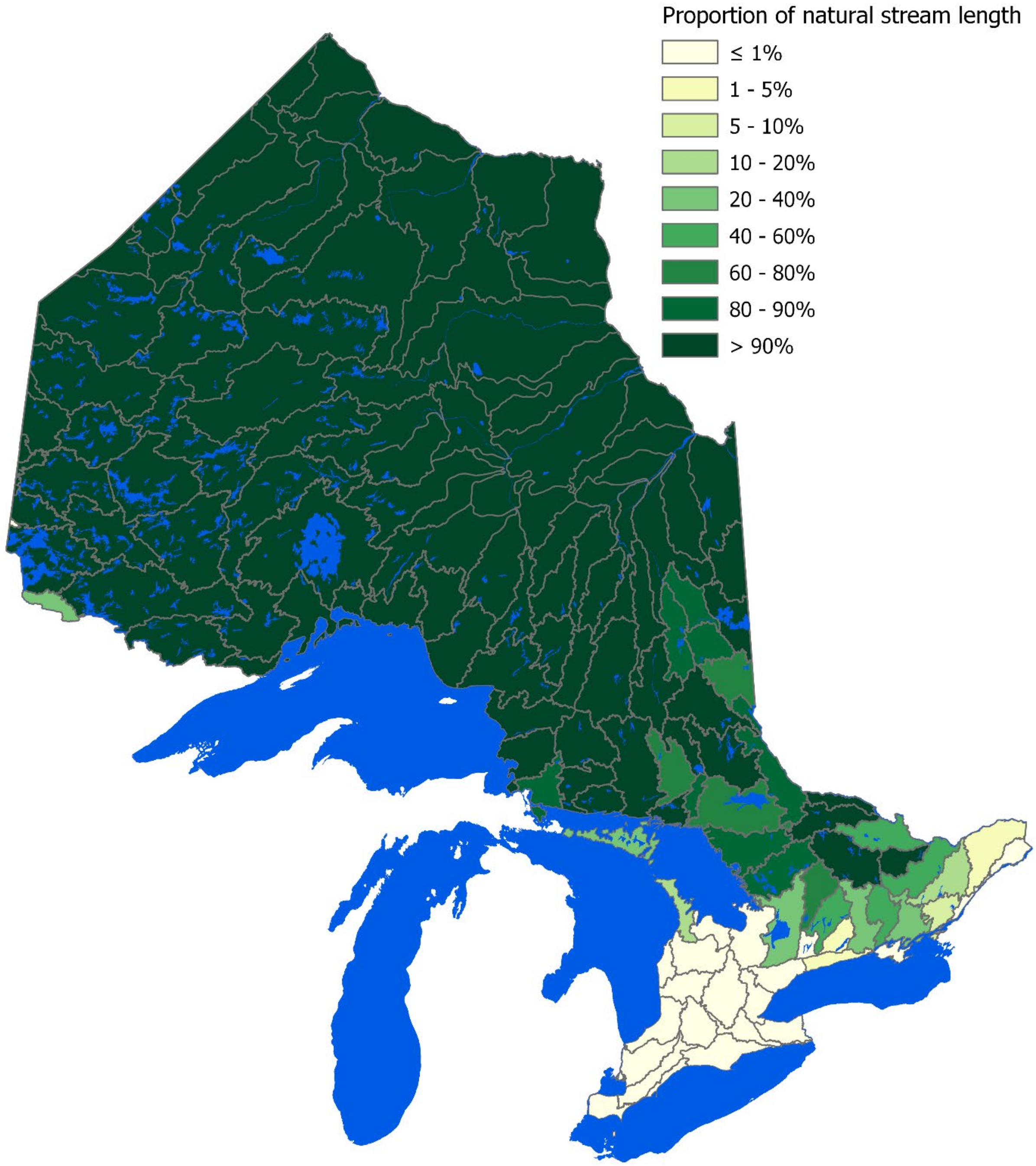
Map 12. Proportion of stressed stream length in Ontario by tertiary watershed.



Map 13. Proportion of natural stream length in Ontario by conservation authority.



Map 14. Proportion of natural stream length in Ontario by Ministry of Natural Resources and Forestry district boundaries.



Map 15. Proportion of natural stream length in Ontario by tertiary watershed.

Limitations and future assessments

Factors not considered in this analysis that may limit stream health include habitat fragmentation (e.g., improperly fit culverts, dams), hydropower, tile drainage, sewage treatment facilities, road density, phosphorus and nitrogen loading, forestry activities, and the presence of invasive species. We also did not include population census and business pattern data that contain information about the densities of crop farms, forestry operations, petroleum manufacturers, waste and remediation facilities, and discharge sites (industrial chimneys and laundry facilities). These data are summarized by census subdivisions, a scale that differs from our analysis, which was based on stream reaches. Many of these additional factors are correlated. For example, urbanization is correlated with road density, use of road salt, sewage treatment plants, and population densities. We purposely kept our analysis high level to avoid potential redundancy.

We recognize the importance of connectivity in stream networks for the migration of fishes, ecosystem productivity, and resiliency; however, the available information about barriers requires too many assumptions about barrier permeability to be useful. Not all barriers are absolute. The permeability of a barrier depends on factors such as the fish species and its size, water temperature and flow volume, and barrier height. We also do not have a reliable, comprehensive database of the location and condition of small dams in the province, particularly on private land. According to Januchowski-Hartley et al. (2013), a culvert is more likely to be a barrier if the stream channel slope is high and the upstream drainage area is large enough to create a velocity barrier given the flow magnitude. Clearly, more work is needed to adequately represent barriers and their potential effects on stream ecosystem integrity.

In addition to fragmentation effects, dams influence stream hydrology, physical habitat, temperatures, and biogeochemical processes (Ward and Stanford 1979). Northern Ontario has more developed and potential locations for waterpower development. The effects of hydropower are well understood in general but specifics for individual facilities are difficult to estimate across the landscape without a more detailed understanding of the environmental context. Lewis et al. (2004) suggested that the zone of influence extends downstream to a point on the river where the catchment area is five times larger than the catchment area draining to a waterpower site — essentially one part regulated flow to four parts natural flow. This attenuation is assumed sufficient to mask the changes in physical and chemical regimes.

Similarly, the potential effects of forestry operations, including tree harvesting and road construction, depend on the environmental context. Best management practices and guidelines are designed to limit potential effects. Also, potential impacts are time dependent because there is regrowth after harvest. The potential effects of forestry, waterpower, and fragmentation are difficult to discern without a greater understanding that cannot be gleaned from remotely sensed landscape data. Future research should attempt to address the potential effects of these activities given the uncertainties and make reasonable assumptions where possible. This will be a challenge but is important for developing aquatic biodiversity protected areas in Ontario’s north, where intact ecological integrity is required for representation.

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