Ecological classification of flow regimes in Ontario

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Abstract

The magnitude, frequency, duration, timing, and rate of change of river flows — or flow regime — influence the erosion, transport, and deposition of sediment, freshwater biodiversity, and both the life history characteristics and ecological traits of riverine biota. In Ontario, we lack a good ecological understanding of flow regime types. Our objective was to classify flow regimes using ecological theory, with the eventual goal of using classification to predict the ecology of streams, for example, community composition, ecological traits, and life history characteristics.

In this study, we examined 36 flow metrics calculated from 436 hydrometric stations from across Ontario. All metrics relate to the degree of harshness, including the harshness of winter. Harshness is a function of flood frequency, summer baseflow magnitude, the range in annual flow magnitudes, and mid-winter high flow event count, with the latter used to describe winter dormancy. Winter dormant rivers are defined as having less than one high flow event every 5 years from January through February. The geographic split between winter dormant and active occurs near North Bay or roughly 46° N latitude, corresponding to 1500 growing degree days above 5 °C (air temperature). South of this latitude, winter active rivers can have substantial flow increases any time of year, including winter. North of this boundary, rivers do not have notable flow increases during winter months.

We found that the open water season (May–November) high flow event count increased from north to south. Many southern Ontario streams had many high flow events (e.g., up to 30 high flow events during the open water season), whereas rivers in the north often had no more than two to four high flow events. Summer base flow yield was highest for groundwater-fed rivers and river networks with many lakes. Rivers without lakes and those on agricultural lands generally had the widest annual range in minimum to maximum flows. Using cluster analyses, we identified four fundamental flow regime types in Ontario: highly stable, stable, variable, and highly variable. Highly variable streams were associated with high levels of urbanization in southern Ontario. Before colonization, this flow type may not have existed so represents a novel flow regime type. In contrast, highly stable streams had high baseflow index or lake effect index values, minimal urbanization, and relatively high amounts of treed cover.

We predicted flow regime classes for more than 127,000 stream reaches in Ontario. Despite a low misclassification rate for the training data set, the number of highly stable stream reaches in Ontario was underpredicted. Our predictive model failed for these types of streams, likely because the hydrometric network is not representative of all streams in Ontario. That is, the model is trying to predict beyond the data used to train it. To remedy this, we manually reclassed all streams with a lake effect index ≥2 as highly stable. Although this approach might seem heavy handed, we feel the model predictions in many northern streams were misleading and less useful to end users. We hope that in future this classification can be used to make predictions about the ecology of streams (e.g., ecological traits, species distribution, life history characteristics).

Résumé

Classification écologique des régimes de débit en Ontario

L’ampleur, la fréquence, la durée, la période et le taux de changement des débits fluviaux (ou régime d’écoulement) influencent l’érosion, le transport et le dépôt des sédiments, la biodiversité des eaux douces, ainsi que les caractéristiques du cycle biologique et les traits écologiques du biote fluvial. En Ontario, nous n’avons pas une bonne compréhension écologique des types de régimes d’écoulement. Notre objectif était de classer les régimes d’écoulement selon la théorie écologique, dans le but éventuel d’utiliser la classification pour prédire l’écologie des cours d’eau, par exemple la composition de leurs communautés, les traits écologiques et les caractéristiques du cycle de vie.

Dans cette étude, nous avons examiné 36 paramètres de débit calculés à partir de 436 stations hydrométriques de l’ensemble de l’Ontario. Tous les paramètres sont liés au degré de rigueur, y compris la rigueur de l’hiver. La rigueur représente une fonction de la fréquence des crues, de l’importance du débit de base en été, de l’amplitude du débit annuel et du nombre d’épisodes de fort débit au milieu de l’hiver, ce dernier étant utilisé pour décrire l’état de dormance en hiver. Les rivières en état de dormance en hiver sont définies comme ayant moins d’un épisode de débit élevé tous les cinq ans, de janvier à février. La séparation géographique entre l’état de dormance en hiver et la dormance active se produit près de North Bay ou à environ 46 degrés de latitude nord, ce qui correspond à 1 500 degrés-jours de croissance au-dessus de 5 °C (température de l’air). Au sud de cette latitude, les rivières actives en hiver peuvent connaître des augmentations de débit substantielles à tout moment de l’année, y compris en hiver. Au nord de cette limite, les rivières ne connaissent pas d’augmentation notable de leur débit pendant les mois d’hiver.

Nous avons constaté que le nombre d’événements de forts débits pendant la saison des eaux libres (mai à novembre) augmentait du nord au sud. De nombreux cours d’eau du sud de l’Ontario ont connu de nombreux épisodes de débit élevé (p. ex., jusqu’à 30 épisodes de débit élevé pendant la saison des eaux libres), alors que les rivières du nord n’ont souvent pas connu plus de deux à quatre épisodes de débit élevé. Le débit de base en été était le plus élevé pour les rivières alimentées par les eaux souterraines et les réseaux fluviaux comportant de nombreux lacs. Les rivières dépourvues de lacs et celles situées sur des terres agricoles présentent généralement la plus grande amplitude annuelle entre les débits minimums et maximums. À l’aide d’analyses en grappes, nous avons identifié quatre types fondamentaux de régimes d’écoulement en Ontario : très stable, stable, variable et très variable. Des débits d’eau très variables ont été associés à des niveaux élevés d’urbanisation dans le sud de l’Ontario. Avant la colonisation, ce type de débit n’existait peut-être pas et représente donc un nouveau type de régime d’écoulement. En revanche, les cours d’eau très stables ont un indice de débit de base élevé ou un indice d’effet de lac élevé, une urbanisation minimale et une couverture arborée relativement importante.

Nous avons prédit les classes de régime d'écoulement pour plus de 127 000 passages de cours d'eau en Ontario. Malgré un faible taux d'erreur de classification pour l'ensemble des données de formation, le nombre de passages de cours d'eau très stables en Ontario a été sous-estimé. Notre modèle prédictif a échoué pour ces types de cours d'eau, probablement parce que le réseau hydrométrique n'est pas représentatif de tous les cours d'eau de l'Ontario. En d'autres termes, ce modèle tente de prédire des données au-delà de celles qui ont été utilisées pour sa formation. Pour remédier à cela, nous avons manuellement reclassé comme très stables, tous les cours d'eau ayant un indice d'effet de lac inférieur à deux. Bien que cette approche puisse sembler sévère, nous estimons que les prévisions du modèle dans de nombreux cours d'eau plus au nord étaient trompeuses et moins utiles pour les utilisateurs finaux. Nous espérons qu'à l'avenir cette classification pourra être utilisée pour faire des prédictions sur l'écologie des cours d'eau (p. ex., les traits écologiques, la distribution des espèces, les caractéristiques du cycle de vie).

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Contents

Introduction

Flow regimes influence the physical processes of streams, freshwater biodiversity, life history characteristics, and many ecological traits (Poff et al. 1997, Bunn and Arthington 2002, McManamay and Frimpong 2015). The natural flow regime paradigm implies that various patterns of disturbance, such as flooding and drought (i.e., the magnitude, frequency, duration, and timing of flow events), result in different degrees of physical control over biotic organization in streams (Poff 1992, Poff et al. 1997, Lake 2003; Figure 1). For instance, spring-fed streams have constant groundwater sourced base flow year-round where biotic interactions may govern community membership and abundance. In contrast, streams in dry regions can be temporary, unpredictable, and flashy where abiotic forces largely govern community characteristics, although biota can undergo strong, albeit brief, periods of predation and competition during droughts in isolated pools (Matthews 1998). Fishes inhabiting dryland rivers of Kansas have life history adaptations that promote population maintenance in otherwise harsh environments (Perkin et al. 2019). Many fishes in dryland rivers have adapted opportunistic life history strategies including early age at maturity, short life spans, low fecundity, and minimal parental care (Winemiller and Rose 1992, Olden and Kennard 2010). Periodic strategist species are optimized for predictable environments such as snow melt dominated regions where flow seasonality is strong (Figure 1). In these situations, fish species are typically large bodied with late maturation, high fecundity, and low juvenile survivorship (i.e., little if any parental care). At the other end of the gradient are equilibrium strategist species that thrive in stable flow regimes provided by large amounts of ground water or lake outlet flow (Figure 1). Equilibrium strategists are small- to medium-bodied fishes with moderate maturation age, low fecundity per spawning event, and high juvenile survivorship (i.e., provide parental care). These relationships apply to organisms other than fishes, including aquatic insects, mussels, and aquatic plants (Poff 1997).

For the past three decades, the classification of flow regimes has attracted much attention as a means to understand the complexities of riverine flow (e.g., Mosley 1981, Haines et al. 1988, Poff 1996, Snelder et al. 2009) and to examine the relationships between hydrology and biota (e.g., Jowett and Duncan 1990, Poff and Allan 1995, Kennard et al. 2007, Poff and Zimmerman 2010). Numerous flow metrics have been developed to characterize flows (Olden and Poff 2003) including various classification schemata (Haines et al. 1988, Olden et al. 2012). Often a large set of flow regime variables are included in the regime classification. We argue that under these circumstances it is difficult to understand how individual flow metrics contribute to the flow regime types. Further, data mining approaches that select a subset of metrics to be included in the classification might not select the most biologically relevant metric set. Though many authors aspire to take an ecological approach to flow classification, few have developed a framework as insightful, or highly cited, as Poff and Ward (1989).

Poff and Ward (1989) provided a framework that incorporates an understanding of the habitat template (Southwood 1977, Townsend and Hildrew 1994) for which stream flows shape ecological traits, life histories, and community composition. Colonizing fish species are filtered by flow regime type (Tonn 1990, Lytle and Poff 2004). Those that become established (i.e., fit the environment) may further evolve traits and life history characteristics over millennia that enable them to survive, exploit, and depend on disturbances such as the complexities of stream flow (Resh et al. 1988). Using 78 gauges across the United States, Poff and Ward (1989) characterized differences in flow regimes using flood frequency, seasonal predictability, flow intermittency, and overall flow variability to develop a

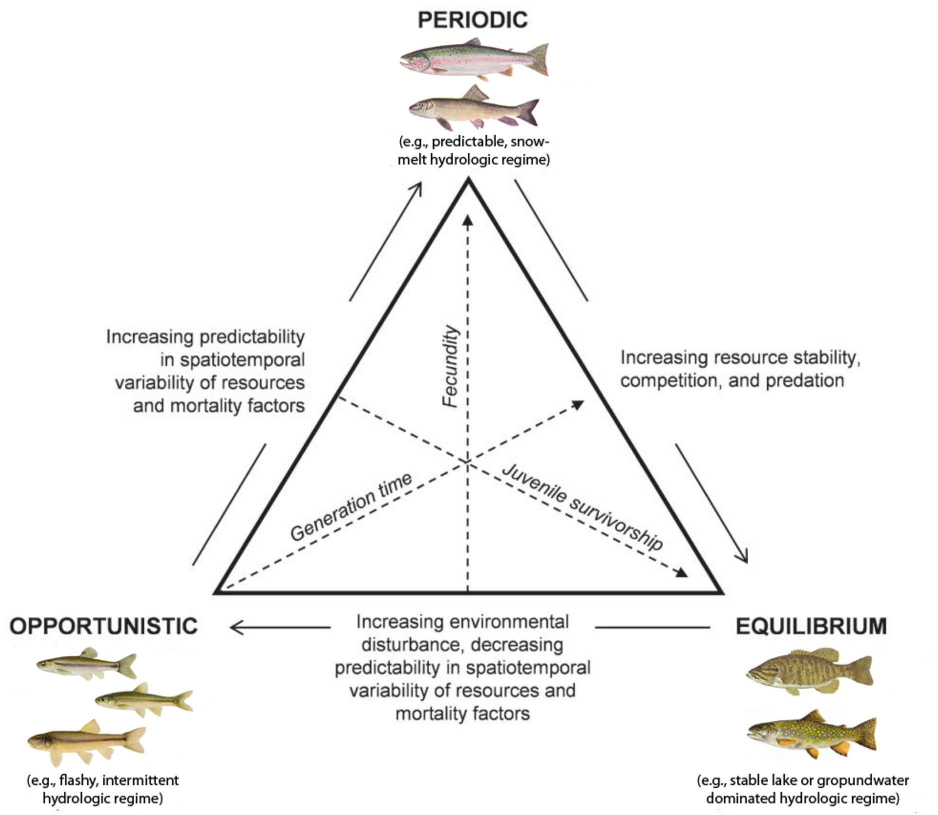


Figure 1. The life history triangle representing environmental gradients selecting for endpoint strategies that optimize demographic parameters: generation time, fecundity, and juvenile survivorship (modified from Winemiller 2005 and Olden and Kennard 2010).

gradient of environmental harshness across nine flow regime types. In their classification, some streams had relatively benign and constant environmental conditions, whereas others were very harsh due to a high degree of intermittency, flooding, and unpredictable timing of flow events. In other stream types, flows were often large enough to cause substrate disturbances, but if these large flows were predictable, biota could avoid or take advantage of such events. Classification of streams based on Poff and Ward's (1989) measures of flow regime can provide insights into the fundamental ecology of stream ecosystems.

Jones et al. (2014) revisited Poff and Ward's (1989) flow classification framework for the continental United States and applied their methodology to classify and map 888 streamflow gauges across Canada into 10 classes. Jones et al. (2014) found regional grouping related to land physiography (e.g., Canadian Shield and ecozones). Larger river systems tended towards less harsh flow regimes and more flow regularity than small streams. They suggested that lakes, common across much of Canada, create a dampening effect related to lake surface area and lake location in the stream network. They noted that measures of lake size and position in the network need more attention before models can be developed to predict flow regime type based on landscape characteristics. Jones et al. (2014) found that the flow metric flood-free interval was potentially a misleading measure of reduced disturbance for high-latitude streams in Canada where ice formation and persistence result in extended flood-free periods, yet these can also be stressful times for biota (e.g., loss of space, low oxygen, starvation; Prowse 2001a,b).

In this study, we revisited the Canadian classification by Jones et al. (2014) but focused on the province of Ontario. To improve ecological understanding of flow regime types in Ontario, we examined 36 flow metrics calculated from 432 hydrometric stations. Some metrics were previously developed by Poff and Ward (1989) and some are new, and all relate to the degree of harshness and integrate the harshness of winter. We examined correlations amongst flow metrics with the goal of parsimony and simplicity. We then used cluster analyses to group hydrometric stations based on a final set of flow metrics. Lastly, we used random forests to predict flow classes for ungauged streams across Ontario. Our objective was to classify flow regimes using ecological theory, with the goal of using classification to better predict the ecology of streams, including community composition, ecological traits, and life history characteristics.

Methods

Flow data

All flow data came from the Water Survey of Canada (WSC; ECCC 2021). The WSC is the national authority responsible for collecting and disseminating water resource information in Canada. The WSC hydrometric network is designed to meet multiple resource management needs related to water quality, flooding hazards, and hydropower and irrigation potential. It was not designed to represent different flow regime types in Ontario. The density of stations is higher in densely populated areas of the province with smaller upstream catchment areas (UCA), while northern stations are usually associated with larger catchments (Figure 2). Stations were also categorized according to the percentages of the UCA draining the three terrestrial ecozones of Ontario. A station’s UCA is assigned to be predominantly (≥50% UCA) draining the Mixedwood Plains (MWP) terrestrial ecozone, the Ontario Shield, or the Hudson Bay Lowlands ecozones. For purposes of this study, the Ontario Shield and Hudson Bay Lowland ecozones were aggregated into a single category of non-Mixedwood Plains, where lakes and wetlands are prominent features on the landscape (Figure 2).

Daily flow data was obtained from the WSC (ECCC 2021) on May 12, 2021 (from Hydat_mdb_20210510 at https://collaboration.cmc.ec.gc.ca/cmc/hydrometrics/www/). For inclusion in the analyses, we required a minimum of 10 years of data between 1950 and 2020. Kennard et al. (2010) suggested at least 15 years of flow data, but that minimum was too restrictive for the limited number of stations available in Ontario. The trade-off is between the length of record and the number of stations available for analyses and their spatial coverage across Ontario. Stations had on average 40 years of data ranging from 10–71 years (Table 1). Seventy-three (17%) stations had less than 15 years of data. We used Matlab to inspect the time series data, calculate the flow metrics, assess correlations, and conduct cluster analyses. We also examined stations in terms of their spatial proximity to lake outlets and anthropogenic controls (e.g., hydropower facilities) using a geographic information system (GIS). From an initial list of 602 stations, 170 were removed because of data quality issues (e.g., missing data, erroneous values, less than 10 full years of data) and because some stations were influenced by regulation (e.g., hydropower, flood control). We used the Ontario Dam Inventory (OMNRF 2023) and Google Maps imagery to assess the influence of dams. This quality control process left 432 stations from across the province for further analysis (Figure 2). This final set of stations has an average drainage area of 2,268 km^2 ranging from 1–118,000 km^2 (Table 1).

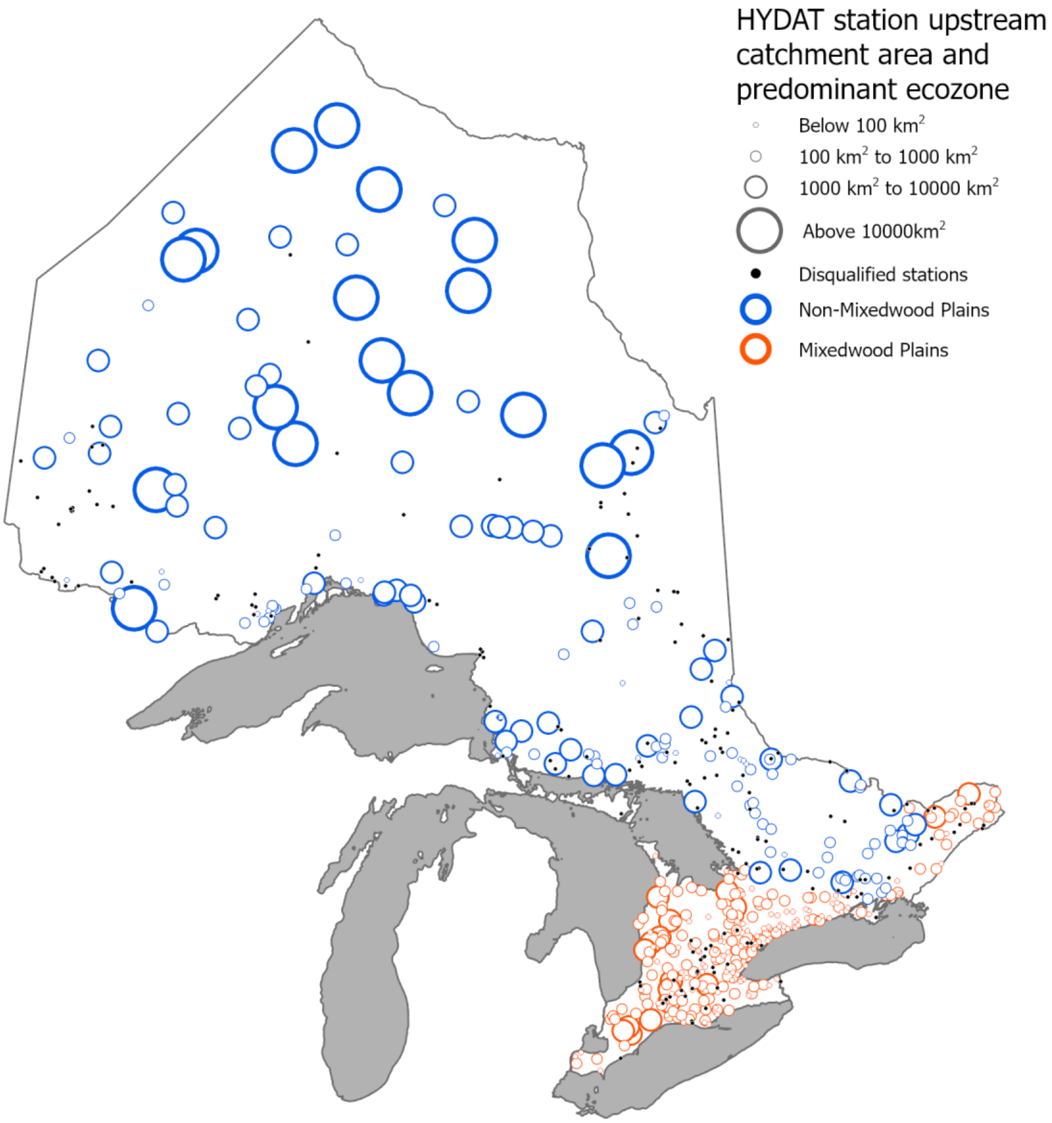


Figure 2. The geographic distribution of the 602 hydrometric stations considered for model input in a study of Ontario streams. Orange points are 269 stations with upstream catchment areas (UCA) that predominantly drain the Mixedwood Plains terrestrial ecozone. Blue points are 163 stations with UCAs predominantly draining the Ontario Shield or Hudson Bay Lowlands ecozones (i.e., non-Mixedwood Plains). The 170 black points are stations disqualified from the model input set because their hydrographs showed obvious signs of regulation or they did not have 10 or more complete years of record.

Table 1. Descriptive count data for the 432 stations in Ontario streams by years available (left) and drainage areas (right).

Full years of record	Station count
10–14	73
15–19	44
20–29	55
30–39	80
40–49	72
50–59	58
60–69	33
≥70	17

Drainage area (km^2)	Station count
<10	9
10–100	123
100–1,000	208
1,000–10,000	74
10,000–100,000	17
≥100,000	1

Flow metrics

We started with a list of 36 flow metrics that we hypothesized as describing flow regime variability and stability in the context of their effects on stream biota (Table A1.2). To be included in the classification, flow metrics needed to provide unique, non-redundant, information. The list of 36 metrics was reduced to 12 metrics by removing those deemed redundant and those for which calculations yielded division by zero errors (Table **2**2). One of these 12 metrics, winter high flow event count, was set aside for describing winter high flows event frequency (i.e., winter dormancy) independently, leaving 11 metrics for further evaluation. All subsequent clustering analyses were conducted using range-scaled metrics to ensure that each metric was scale-independent (Legendre and Legendre 1998) and subsequently converted back for reporting.

We used principal component analyses (PCA) and Spearman cross correlation to examine relationships among the remaining flow metrics to describe the major sources of variation. The goal was to reduce the list to a few metrics based on their hypothesized influence on flow stability and variability as well as their interpretability, orthogonality of their vectors in PCA component space, and acceptably low correlation with other metrics. The three metrics we chose were the average high flow event count during the open water season (May through November), the average annual range in yield (i.e., drainage area standardized mean annual range of flows), and the average annual mid-summer baseflow yield (i.e., drainage area standardized baseflow volume during July and August). Drainage area standardization removes the influence of drainage size on the latter two metrics, preventing cluster creation from being unduly informed by drainage area.

Table 2. The subset list of 12 flow metrics examined in this study of Ontario streams including their descriptions, ecological relevance, and calculation methods. Q=discharge; CV=coefficient of variation. For a complete list of flow metrics, see Table A1.1.

Metric name	**Description**	**Ecological relevance**	**Calculation**
WINTER_HFECOUNT	Mean mid-winter event counts	High flow** events act as a disturbance during the mid-winter low flow period, with a higher event count indicating harsher conditions	Number of events occurring during January and February (winter dynamic vs. stable) per year averaged across the period of record
OPENWATER_HFECOUNT*	Mean open water season event counts	High flow events act as a disturbance during open water season, with a higher event count indicating harsher conditions	Number of events occurring May through November per year averaged across the period of record
COLWELL_C_HFECOUNT	Colwell constancy of monthly high flow event counts	Higher values are more ecologically benign	Colwell Constancy of the frequency of occurrence of monthly high flow event counts (1,2,3,4,5+ events) for the period of record. See Colwell (1974) for calculation method.
COLWELL_C_DAILYQ	Colwell constancy of daily flows	Higher values are more ecologically benign	Colwell Constancy of the frequency of occurrence of daily flow within period of record flow percentile bins (5, 10, 25, 50, 75, 90, 95). See Colwell (1974) and Poff (1989) for calculation method.
CV_MINMONTH_TIMING	Intra-annual dispersion of annual minima timing	The consistency of the timing of the annual minima, used to identify rivers for which the lowest annual flow can occur across multiple months	CV of the counts for each month during which the annual minimum occurs for each year of the period of record. This metric is an adaptation of the HIT metric which uses annual minima day of year instead of monthly modes.
CV_MAXMONTH_TIMING	Intra-annual dispersion of annual maxima timing	The average amount of flow that biota are subject to at the station	CV of the counts for each month during which the annual maximum occurs for each year of the period of record. This metric is an adaptation of the HIT metric which uses annual maxima day of year instead of monthly modes.
MEAN_ANNUALYIELD	Mean annual yield	The range in yield, with a larger range indicating harsher conditions	Mean of the annual yields divided by the drainage area.

Metric name	Description	Ecological relevance	Calculation
MEAN_CV_DAILYQ	Mean annual coefficient of variation of daily flows	A measure of day to day flow variability, with a higher value indicating harsher conditions	Mean of the annual CVs of flow (SD/mean) across the period of record.
RANGE_ANNUALYIELD*	Ratio of mean annual range of flows standardized by drainage area	A larger range means harsher conditions	(Mean maximum annual flow − mean minimum annual flow)/drainage area.
MINIMA_ANNUALYIELD	Mean minimum annual flow divided by drainage area	A measure of extreme low flow conditions standardized by drainage area, with a lower value indicating harsher conditions	The ratio of mean annual minimum over drainage area.
WINTER_BFYIELD	Mid-winter baseflow yield	A measure of drainage area standardized low flow stability during mid-winter, with a lower value indicating harsher conditions	Drainage area standardized baseflow volume during January and February. The total (i.e., sum) volume of baseflow (m^3) divided by drainage area (m^2).
SUMMER_BFYIELD*	Mid-summer baseflow yield	A measure of drainage area standardized low flow stability during mid-summer, with a lower value indicating harsher conditions	Drainage area standardized baseflow volume during July and August. The total (i.e., sum) volume of baseflow (m^3) divided by drainage area (m^2).

*=final subset of 3 metrics

**=High flow events are defined as flow peaks that are a multiple (e.g., 2x) larger than their adjacent flow troughs on the hydrograph. Events not matching this criterion and peaks below the period of record 20th flow percentile are excluded.

Flow regime classification

Determining the most suitable number of flow regime classes was explored using K-means clustering and dendrograms with distance measures. Most hydrologic metrics are continuously distributed across a gradient without noticeable groupings or breakpoints. This type of data distribution makes creating distinct, clearly defined clusters difficult. It is an unavoidable yet common problem when using continuous data for clustering and makes choosing the optimal number of clusters a challenge. Using too few clusters will result in high within cluster variability, whereas too many clusters will result in insufficient differences amongst clusters. Researchers must find the best balance between these scenarios. We capped the number of clusters tested at eight because it would be illogical to have more flow regime classes for Ontario than the 10 classes found by Jones and Schmidt (2014) across all of Canada which represents a much broader range in climate and elevation.

Lastly, we briefly examined how landscape variables differ among flow regime types. The landscape data was drawn from the Aquatic Ecosystem Classification for Ontario (AEC; Jones and Schmidt 2022). Lake effect index (LEI) is a relative measure of lake influence on streamflow stability (Allerton, unpublished). It is based on a network model to quantify the stabilizing effect of lake outlet contributions on stream flow regime, accounting for lake size and position in the drainage network upstream of a given stream reach. The network approach takes advantage of the existing hydrologic network structure of the AEC, using stream reaches as basic units to propagate information through the network in the direction of streamflow. An LEI value was computed for every reach. Reaches with no upstream lakes were assigned an LEI value of zero. Lake outlet reaches were assigned an LEI value dependent on the lake area to lake catchment area ratio, which is representative of lake size relative to stream size and is related to a lake's efficiency in transferring water downstream and, hence, its capacity to dampen flow fluctuations (Spence 2006). LEI values for individual stream reaches range from 0 to 10 across the province. Values higher than 1 are considered heavily influenced by upstream lakes.

Lake area to lake catchment area values of 1:500 and 1:100 were used as approximate lower and upper thresholds, respectively, beyond which changes in lake storage are hypothesized to have negligible effect on downstream flow. Below the lower threshold, lake outlet reaches received an LEI of zero, reflecting insufficient storage to dampen flow fluctuations. Above the upper threshold, an LEI of 1 was assigned, as lake storage is expected to produce a maximum stabilizing effect at a given stream size. Between these thresholds, LEI values between 0 and 1 were assigned in proportion with the lake area to catchment area ratio. Lake effect declines with distance downstream due to dilution from overland flow and tributary confluences. Dilution over the course of a reach is approximated by the reach contributing area to UCA ratio. Dilution values of reaches downstream of lakes were sequentially subtracted from reach LEI values, such that LEI values gradually decline to a minimum of zero. A series of lakes can result in LEI values higher than one, as the index value associated with the effect of each lake is added to index value of its inflow reach, reflecting the cumulative nature of upstream inputs on flow regime. Below a confluence, LEI was computed as the UCA-weighted average of the index values of the combining tributaries.

Flow regime prediction for ungauged streams

We used classification and regression random forests to predict flow classes for ungauged stream reaches across Ontario. Random forests is an ensemble learning method for classification that involves constructing a multitude of decision trees at training time. For classification purposes, the random forest output is the class selected by most trees. We used the bagging method and sampled randomly with replacement. For bagging, each tree is independently constructed using a bootstrap sample of the data set. Our sample size was 100, with a minimum of 100 trees. In model development, we used several variables pulled from the AEC (Jones and Schmidt 2022) including percent cover of upstream lakes (lake area/land area), base flow index (Neff et al. 2005), UCA (km^2), mainstem slope, inverse distance of treed and agriculture land cover (OMNR 2014), mean precipitation (OMNR 2000) during the open water season at the UCA scale, and inverse distance of wetland and urban land cover. The inverse distance weighting (IDW) was calculated, using a similar method as that described by Peterson et al. (2011), with an DW power of -0.5. IDW measures are calculated by applying an inverse distance function to patches of a given land cover category in a catchment. Patches closer to the point of interest of a drainage (e.g., gauge) are weighted more heavily than patches farther upstream (Peterson et al. 2011).

For training the model, we removed stream reaches (n= 86) with an urbanized IDW value higher than 10 as these streams were highly variable and impacted, i.e., all gauges in the highly variable class. Urbanization alters landscape-scale processes influencing streams (Allan 2004), particularly the balance of ground to surface water contributions to stream flow. This screening left 346 stream reaches for analyses and three remaining flow regime classes. Very few small drainages have long-term gauge data. We excluded stream reaches <10 km^2 (n=7) for flow class prediction because they are often associated with specific interests (e.g., Turkey Lakes, Chalk River) and data is insufficient. Also streams less than 5 km^2 in Ontario are likely temporary with flows only existing during spring and after severe rainfall events (Buttle et al. 2012). Their flow regime characteristics are unique and require additional classification, but the data are lacking.

Results

Flow metrics

Spearman cross correlations among flow metrics were generally low (Table 3). Colwell's constancy (C) for high flow event count was correlated with open water high flow event count. Annual range yield was correlated to Colwell's C for high flow event count and coefficient of variation in daily flow. Average coefficient of variation in daily flow magnitudes was correlated to summer base flow yield. None of the three selected flow metrics were strongly correlated (Table 3).

Using 11 flow metrics, Axis 1 of the PCA accounted for 47% of the total variance, and Axis 2 accounted for 19% (Figure 3). The winter high flow event count metric was not included because it was applied separately to classify stations. Using this PCA plot, the Spearman correlation table (Table **3**3), and professional judgement, with the goal of understanding ecological harshness of flow regime, we selected a parsimonious list of three flow metrics (Figure 4).

Table 3. Spearman cross correlations for 11 flow metrics used in this study of Ontario streams. The highlighted variables denote the final set of 3 clustering metrics. Winter high flow event count was excluded because it is used separately to classify stations by winter dormancy. For variable descriptions, refer to Table 2.

Flow metric	OPENWATER_HFECOUNT	COLWELL_C_HFECOUNT	COLWELL_C_DAILYQ	CV_MINMONTH_TIMING	CV_MAXMONTH_TIMING	MEAN_ANNUALYIELD	MEAN_CV_DAILYQ	RANGE_ANNUALYIELD	MINIMA_ANNUALYIELD	WINTER_BFYIELD	SUMMER_BFYIELD
OPENWATER_HFECOUNT											
COLWELL_C_HFECOUNT	**-0.78**										
COLWELL_C_DAILYQ	0.09	0.18									
CV_MINMONTH_TIMING	-0.26	0.18	-0.21								
CV_MAXMONTH_TIMING	-0.57	0.63	-0.09	0.16							
MEAN_ANNUALYIELD	0.08	-0.12	-0.04	0.06	0.14						
MEAN_CV_DAILYQ	0.41	-0.63	0.38	-0.16	-0.28	0.00					
RANGE_ANNUALYIELD	0.53	**-0.74**	0.33	-0.14	-0.37	0.43	**0.82**				
MINIMA_ANNUALYIELD	0.00	0.12	-0.17	-0.07	-0.06	0.15	-0.68	-0.38			
WINTER_BFYIELD	-0.21	0.13	-0.19	0.14	0.10	0.58	-0.52	-0.16	0.55		
SUMMER_BFYIELD	-0.23	0.53	-0.20	0.09	0.13	-0.01	**-0.78**	-0.59	**0.77**	0.28	

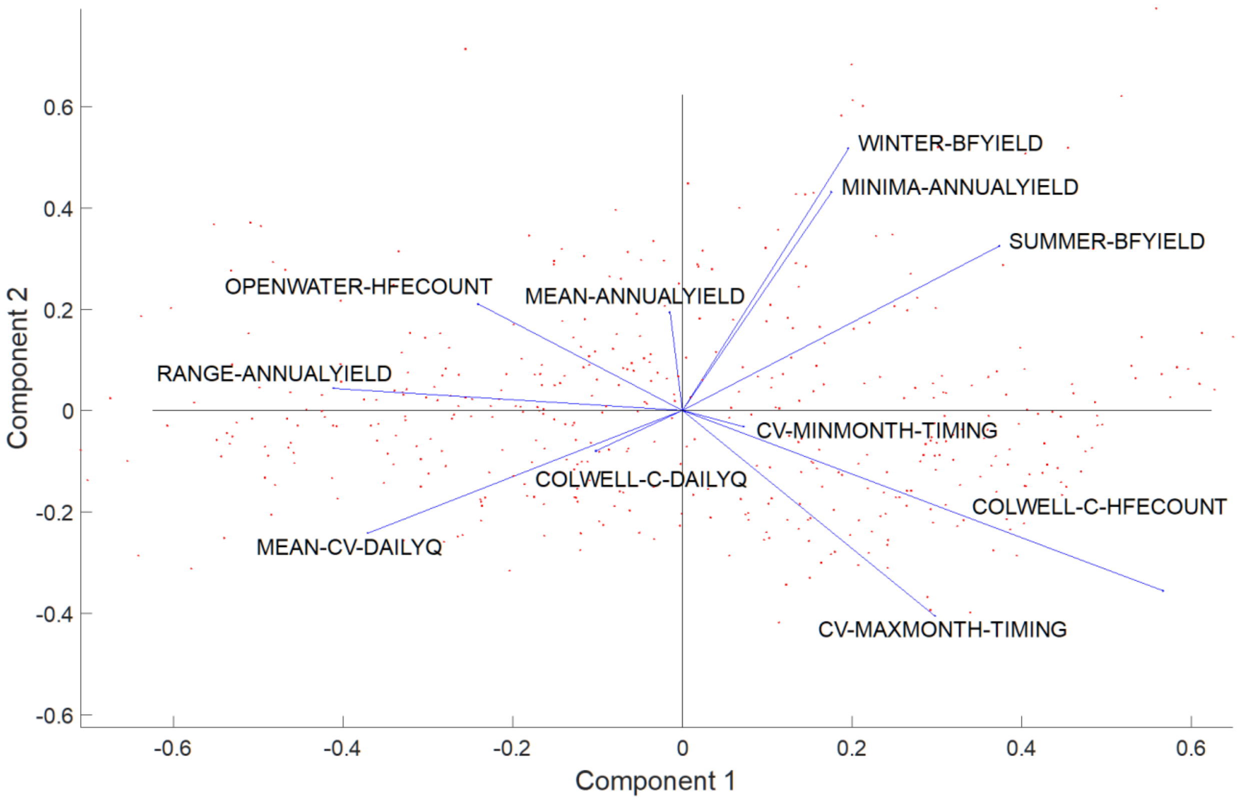


Figure 3. Principle component analysis components 1 and 2 of the 11 candidate flow metrics in this study of Ontario streams. Red dots are the individual hydrometric stations. The variance explained by component 1 and 2 is 47% and 19%, respectively. For variable descriptions, refer to Table 2.

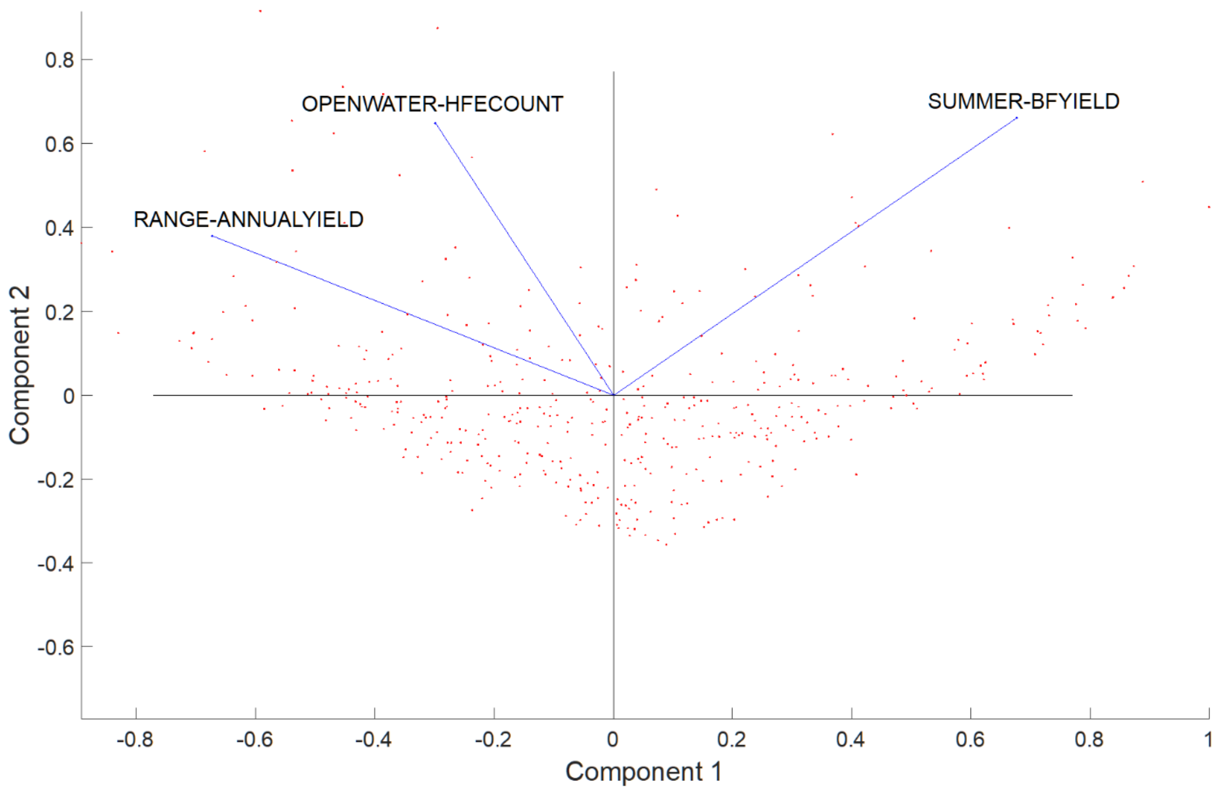


Figure 4. PCA components 1 and 2 of the 3 clustering flow metrics in this study of Ontario streams. Red dots are the individual hydrometric stations. The variance explained by component 1 and 2 is 68% and 22%, respectively. For variable descriptions, refer to Table 2.

May through November high flow event count captures disruptive high flow frequency during the open water growing season (Figure 5), July and August base flow yield characterizes summer low flow stability (Figure 6), and drainage area standardized range in annual flows captures the annual variability between high and low flows (Figure 7). A fourth flow metric, winter high flow event count, was used separately to overlay on the classification to understand winter dormant vs. active rivers (Figure 8). Dormant stations had less than 1 mid-winter event (January and February) for every 5 years of record. The split between winter dormant and active occurs near North Bay or roughly 46°N latitude and includes the higher elevation Algonquin dome. More correctly, this split is related to about 1500 growing degree days above 5 °C air temperatures. South of this line, flows can increase substantially at any time of year. Above this line, rivers do not have notable flow increases during winter months. During these mid-winter months, rivers in the north typically have the lowest flows of the year. In contrast, the lowest flows for southern rivers usually occur during summer. The 1500 growing degree days threshold also coincides with the division of Ontario Shield Ecozone’s productivity regions 3 and 4 as defined by the AEC (Jones and Schmidt 2022).

Winter dormant streams show very few if any high flow events during winter reflecting little surface flow in these drainages. Winter flows in these streams are also very low relative to summer flow magnitudes. In contrast, winter active streams can have multiple winter high flow events (median=1.7, maximum=4.5, and minimum=0.2 events per winter) and annual low flows occur during

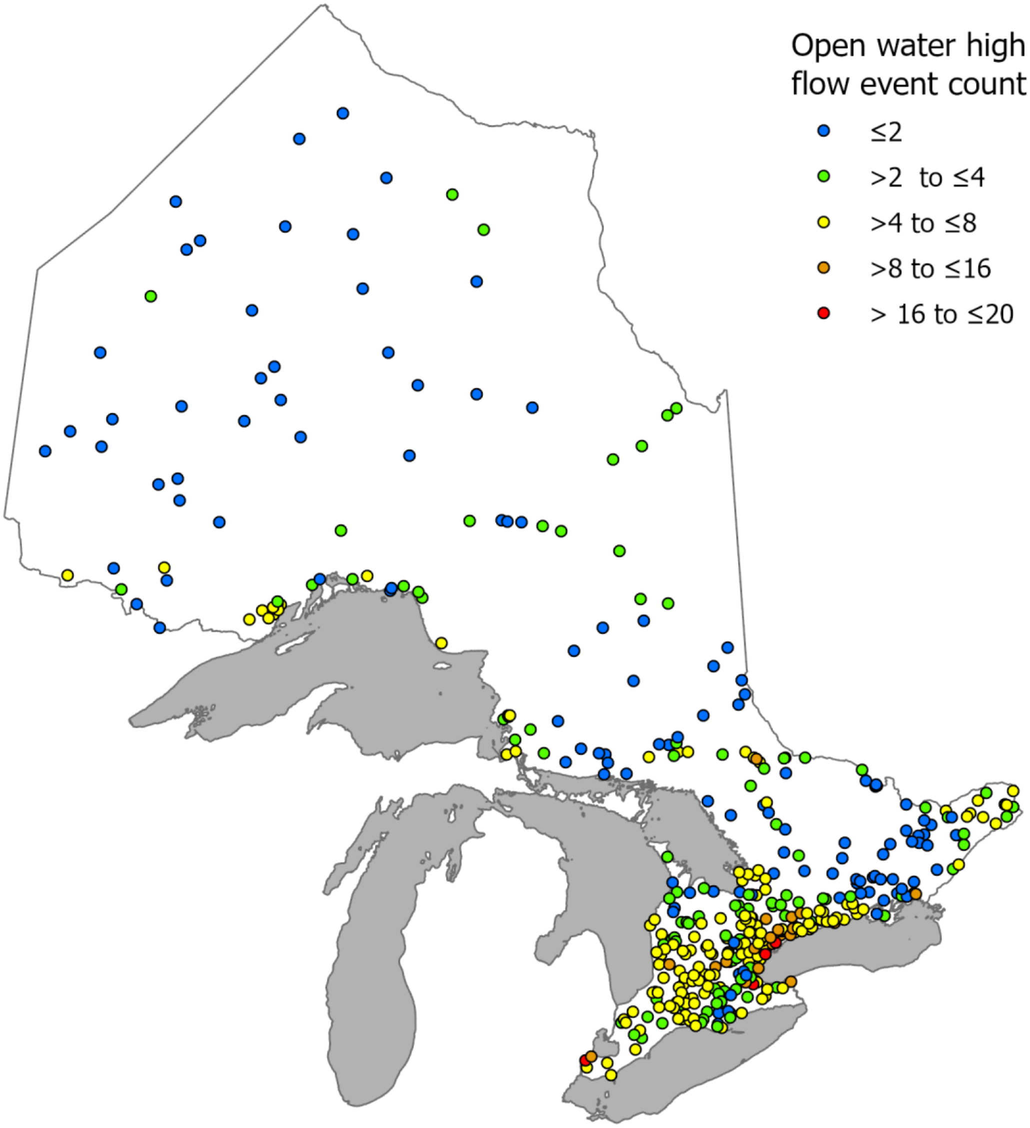


Figure 5. Map of average annual open water (May to November) high flow event counts in Ontario.

summer months. Highly variable flows show little seasonality relative to other flow regime types. Highly stable, winter dormant streams occur primarily in northern Ontario.

The open water high flow event count increased from north to the south. Some rivers in southern Ontario can have as many as 30 high flow events during the open water season, whereas rivers in the north often have no more than two to four high flow events. Summer base flow yield was highest for groundwater-fed rivers and river networks with many lakes or where lakes were upstream of hydrometric stations (Table 4). Rivers on agricultural lands (i.e., high clay content soils) generally had low base flow yield. Rivers without lakes and those on agricultural lands tended to have the widest range in minimum to maximum flows. Distinct differences were evident in the landscape characteristics of flow regime types (Table 4). Highly stable streams had high baseflow index or LEI values, small amounts of urbanization, and relatively high amounts of treed cover. Highly variable flow regimes had high amounts of urbanization and low base flow index (BFI) and LEI contributions to flow (Table 4). A gradient in landscape characteristics spanned flow regime types from highly stable to highly variable.

Table 4. Flow metrics and landscape summaries for the four flow regime classes for Ontario streams in this study. Values are class means with corresponding standard deviations in parentheses. HFE=high flow event; IDW=inverse distance weighting; BFI=base flow index.

Metric	**Highly stable**	**Stable**	**Variable**	**Highly variable**
Number of stations	66	218	134	14
Drainage area (km^2)	8,847	1,178 (4,498)	258 (460)	65 (55)
Openwater HFE count	2.3 (2.0)	3.3 (2.2)	5.4 (1.9)	18.4 (3.6)
Range annual yield (m^{3}s^{-1}km^2)	0.05 (0.04)	0.11 (0.04)	0.24 (0.06)	0.24 (0.06)
Summer base flow yield (mm)	42.6 (9.7)	16.1 (7.4)	6.59 (5.0)	16.5 (9.9)
IDW treed	37 (17)	36 (26)	18 (25)	5 (4)
IDW agriculture	18 (27)	34 (29)	60 (29)	19 (16)
IDW urban	2 (5)	6 (10)	9 (14)	73 (18)
IDW wetland	18 (18.0)	12 (14)	9 (8)	2 (2)
BFI	0.53 (0.08)	0.51 (0.08)	0.39 (0.11)	0.31 (0.08)
Lake effect index (LEI)*	1.98 (1.71)	0.84 (1.04)	0.14 (0.48)	0.001 (0.005)

*Lake effect index is similar to the percentage of lakes (storage capacity) in a catchment but more accurately describes the size and location of lakes in stream networks. IDW was calculated using methods similar to those described by Peterson and Pearse (2017).

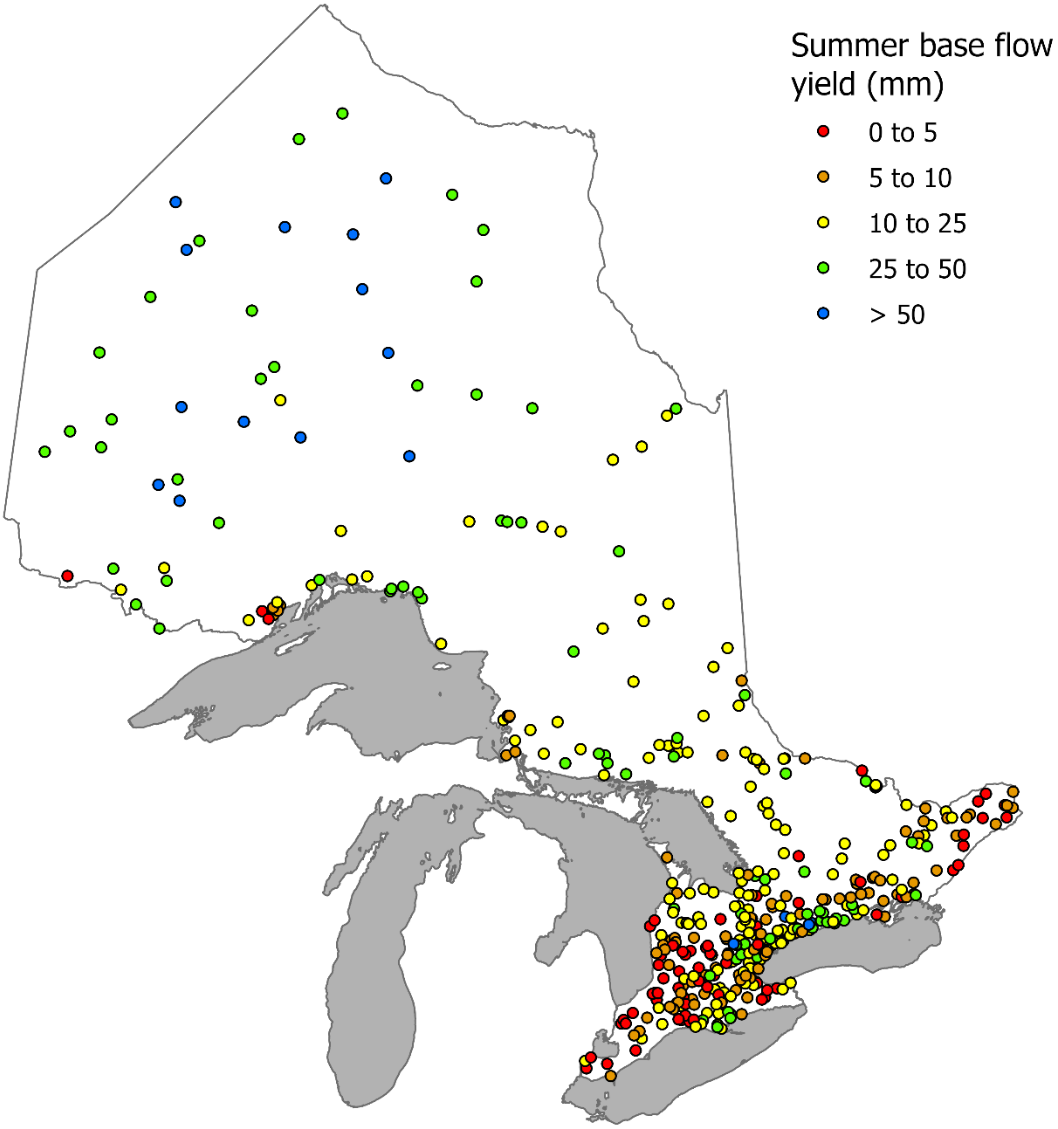


Figure 6. Map of average annual summer (July and August) base flow volume (m^3) in Ontario scaled by drainage area (m^2) to arrive at base flow yield (mm).

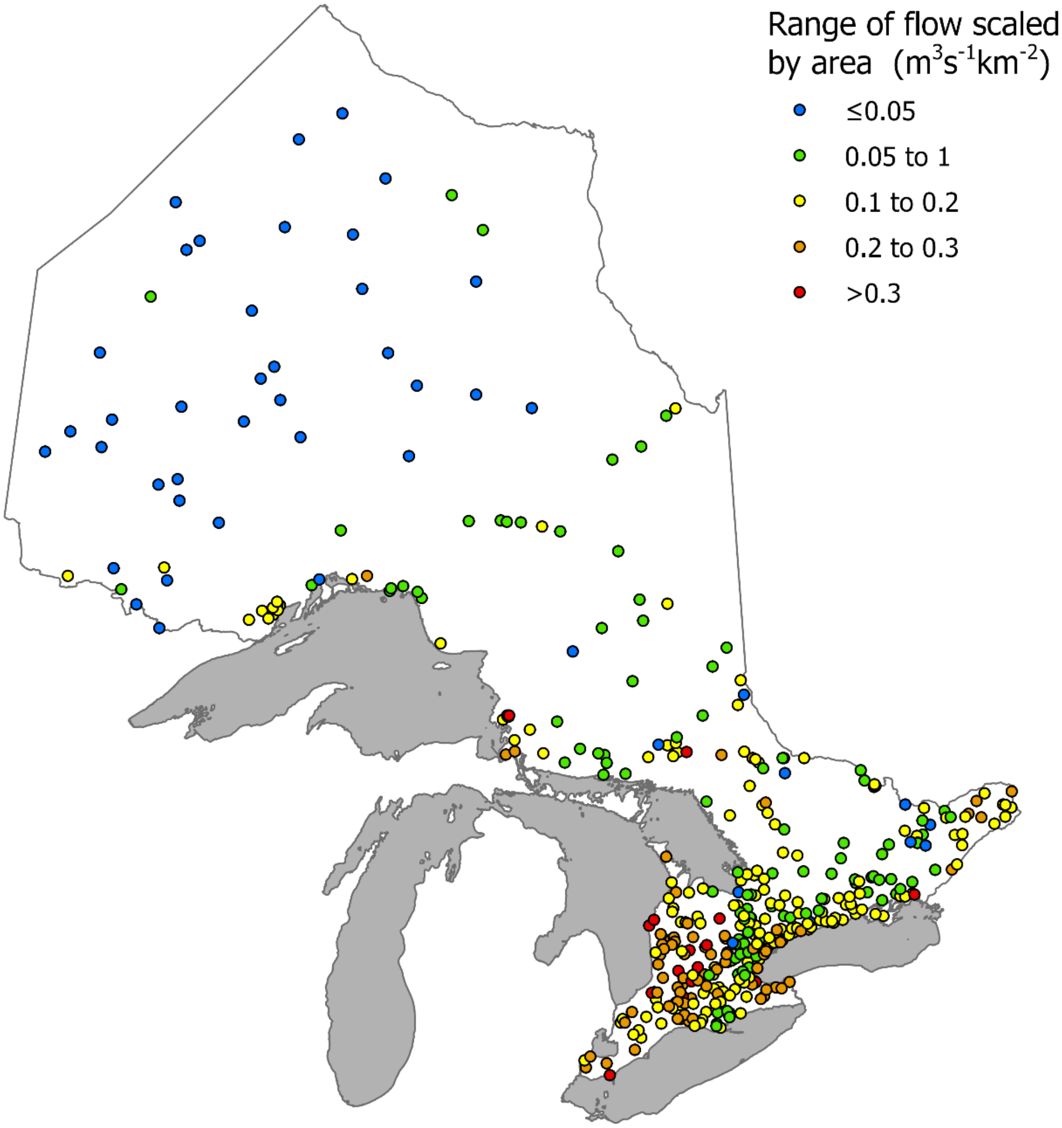


Figure 7. Map of average annual range in annual flows ($m^3 \cdot s^{-1}$) in Ontario scaled by drainage area (km^2) to provide annual range of flow per square kilometre ($m^3 \cdot s^{-1}$ per km^{-2}).

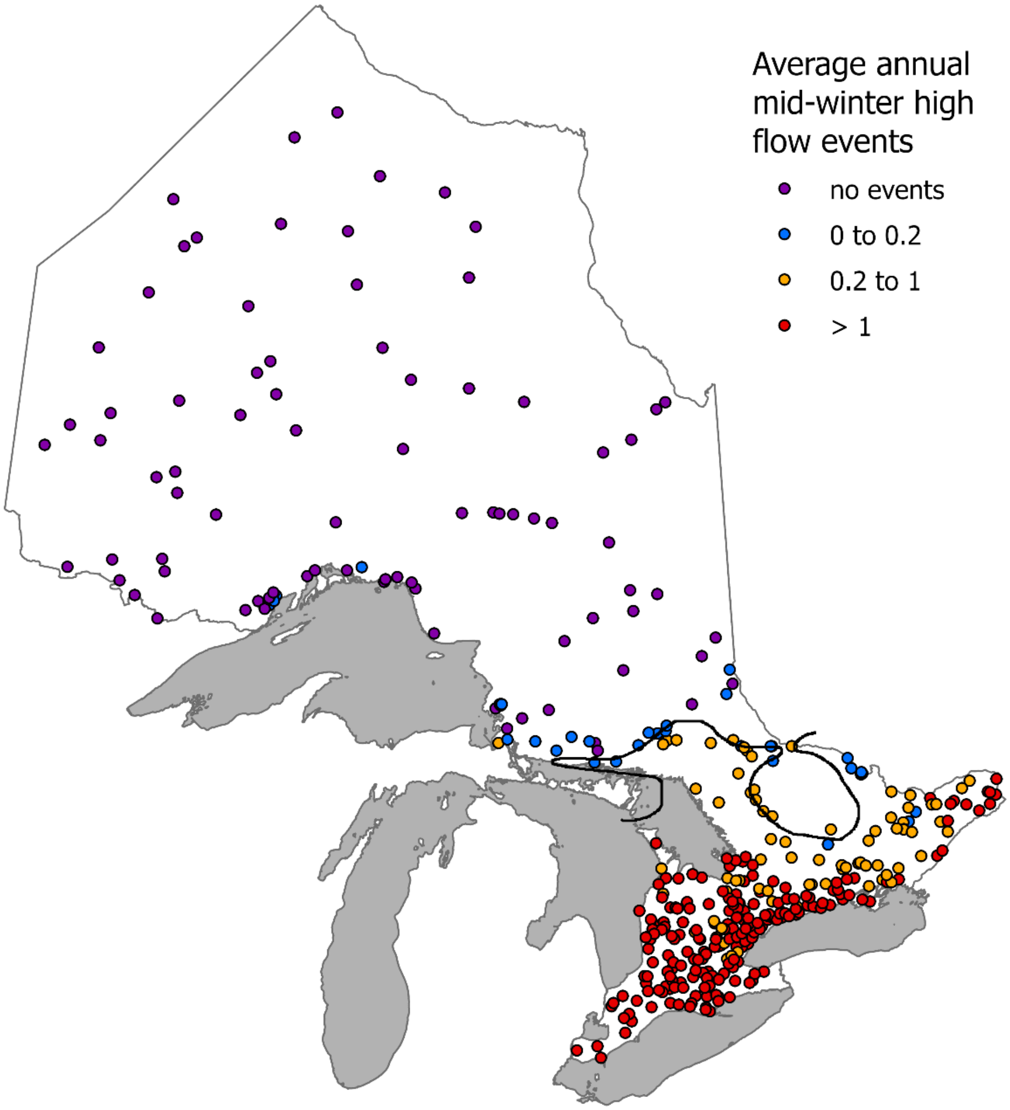
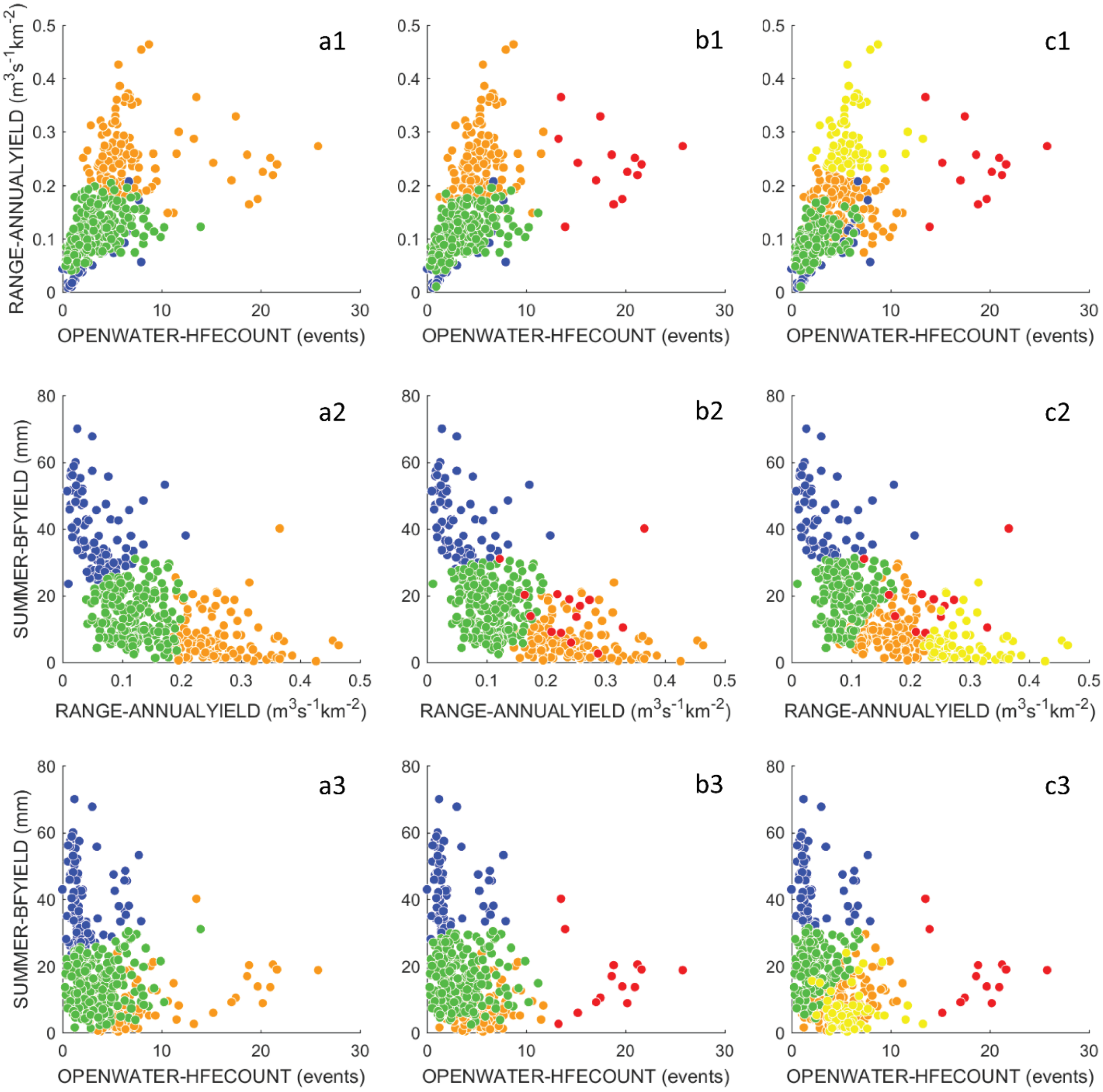


Figure 8. Map of average annual high flow event count in Ontario for mid-winter (January and February) representing the degree of winter dormancy of a stream (i.e., number of high flow events occurring during the coldest part of the year). Winter dormant rivers have ≤0.2 events per year (i.e., ≤1 event every 5 years). Purple stations have no high flow events during winter. Blue stations are rivers that rarely have a high flow event in winter. Orange and red stations have >0.2 events per year. Some of the most southern stations may have multiple high flow events each winter. Whether a river is winter dormant or active relates well to 1500 growing degree days in average air temperature (i.e., north of the black line).

Flow regime classification

The three flow metrics were plotted in relation to each other with increasing number of flow classes in three dimensions (Figure 9). The least amount of overlap among flow classes occurred when four flow regime classes were used (b1, b2, and b3).



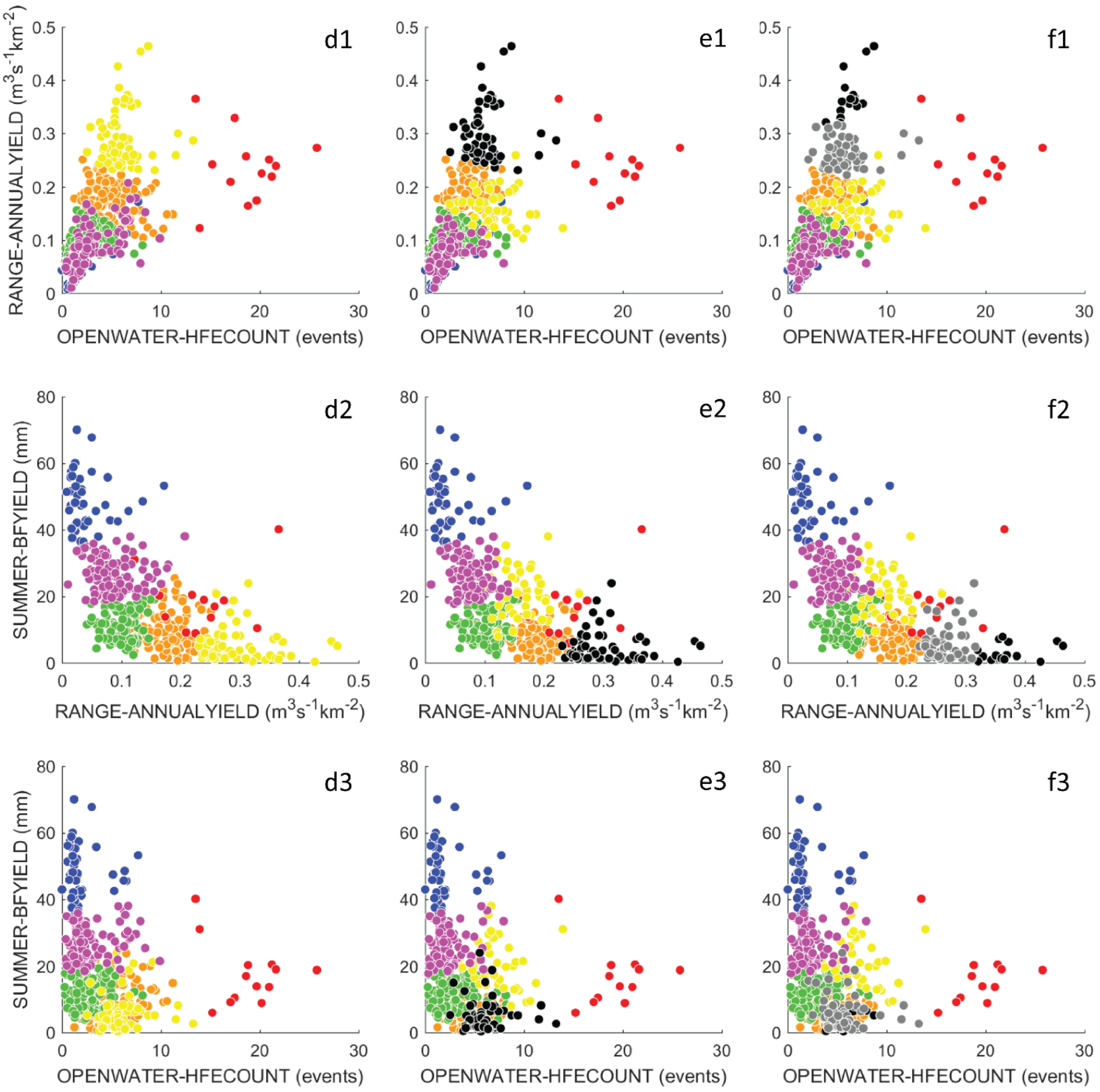
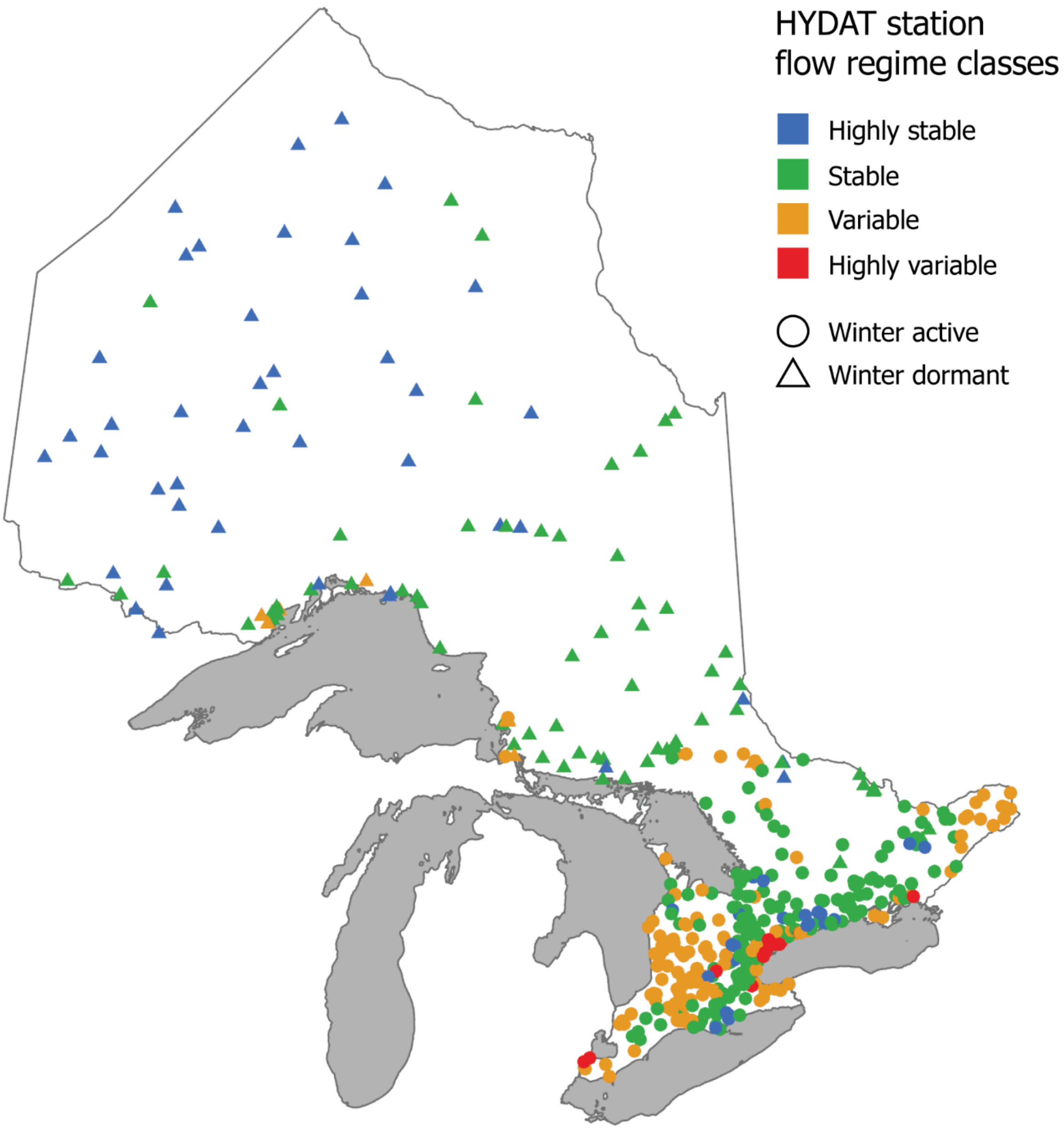


Figure 9. K-means clusters showing from 3 to 8 class cluster solutions (columns a-f) using the flow metrics: range annual yield, summer base flow yield, and open water high flow event count for streams in Ontario. The plots are arranged in columns representing the different numbers of class clusters solutions (e.g., 3 class clusters in a1, a2, and a3), while the rows within each column show the three dimensional scatter plots from different two dimensional perspectives. The point colours denote the different clusters that were found.

Of the four types, three are found in northern Ontario's winter dormant streams, whereas all four are found in winter active streams of southern Ontario (Figure 10 and Figure 11). Strong regionality of flow regime type was related to landcover types. Highly stable streams were associated with high groundwater contributions (base flow index) or numerous lakes on the upstream network. Stable streams were associated with coarse textured surficial geologies (e.g., sand plains, moraines). Variable streams were widespread in southern Ontario. In the north, variable streams were associated with agricultural lands (e.g., Nipissing basin) and those with few lakes in the upstream network. Highly variable streams were found in urbanized areas (e.g., Toronto, Kingston, Hamilton, Windsor). Cluster centroids for each flow regime were used to select representative hydrometric stations to illustrate the differences in flow regimes for their respective periods of record (Figure 12).



Fig**ure 10**. Map of Ontario showing four flow regime classes based on three flow metrics: open water high flow event count, summer base flow yield, and range in annual flow. Also shown is whether the river is winter active or dormant. A river is considered winter dormant if it has less than 1 high flow event for every 5 years of record on average.

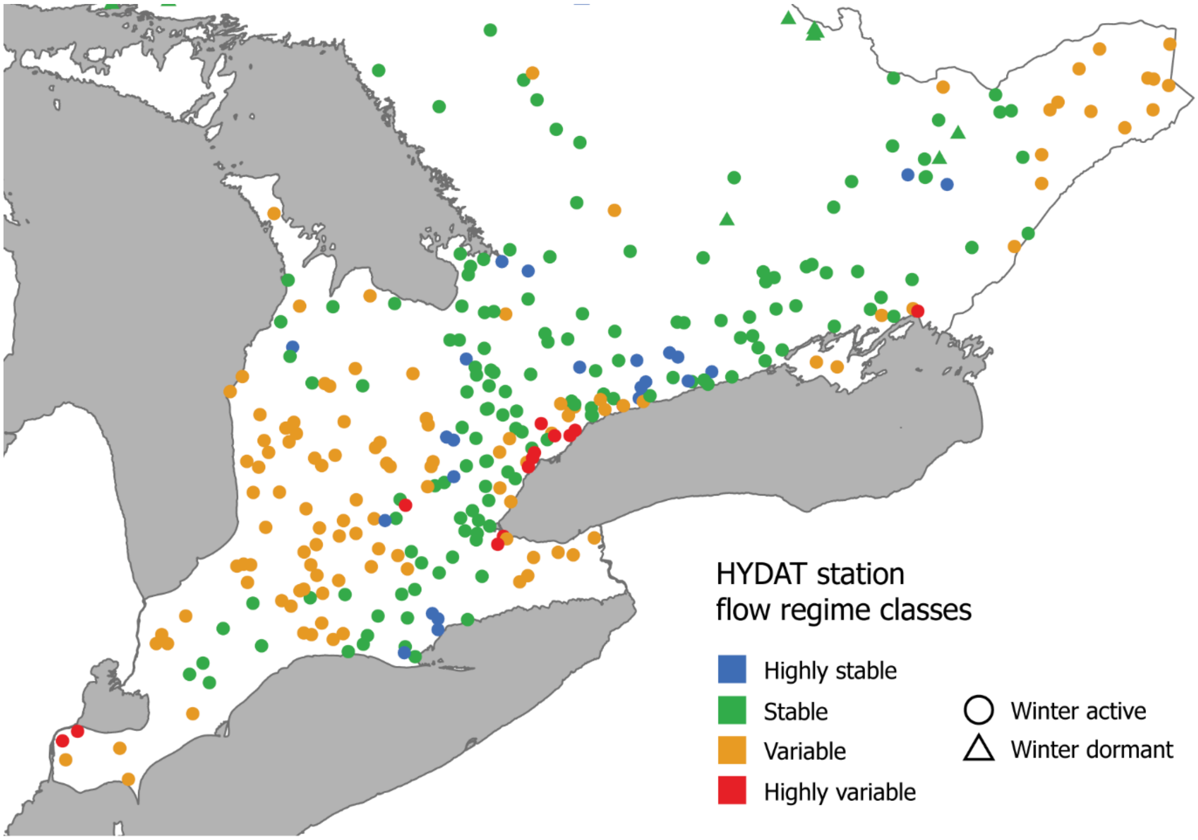
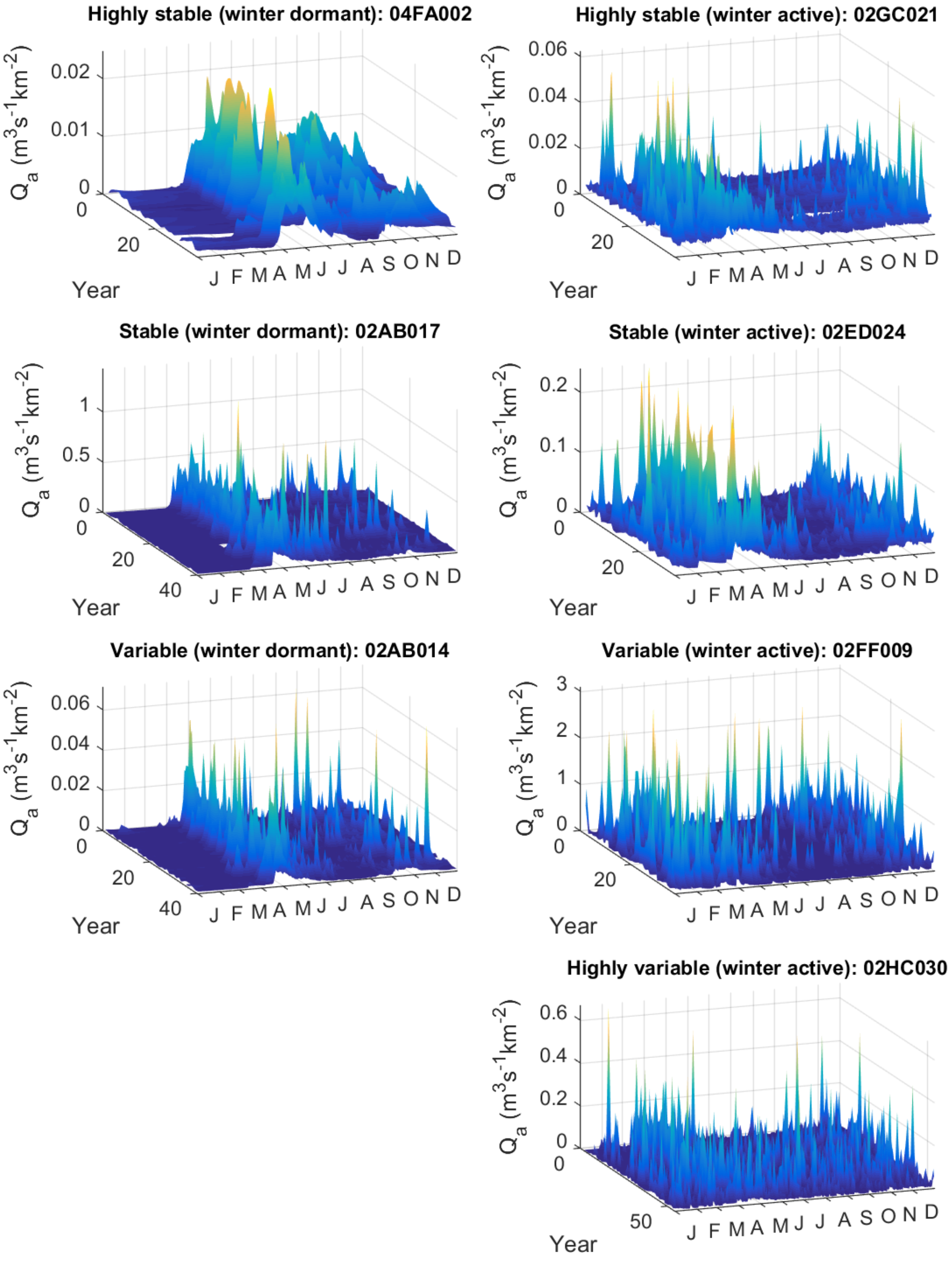


Figure 11. Map of southern and central Ontario showing four flow regime classes based on three flow metrics: open water high flow event count, summer base flow yield, and range in annual flow. Flow metrics were calculated for the period of record and averaged across years. Also shown is whether the river is winter active or dormant. A river is considered winter dormant if it has less than 1 high flow event for every 5 years of record on average.


Highly stable (winter dormant): 04FA002

Highly stable (winter active): 02GC021

Stable (winter dormant): 02AB017

Stable (winter active): 02ED024

Variable (winter dormant): 02AB014

Variable (winter active): 02FF009

Highly variable (winter active): 02HC030

Figure 12. Examples of each flow regime type using hydrometric stations close to the centroid of each flow cluster. X-axes units are month of the year. Y-axes units are mean daily flows standardized by drainage area (Q_a; cubic metres per second per square kilometre). Z-axis units are the data year of record for the station. Station codes were from the Water Survey of Canada (ECCC 2021). The highly variable winter dormant class does not exist.

Flow regime prediction for ungauged streams

Variables in the model in order of importance were percent cover of upstream lakes, base flow index, UCA, mainstem slope, inverse distance of treed and agriculture land cover, mean precipitation during the open water season at the UCA scale, and inverse distance of wetland and urban land cover. Using this model, we predicted flow regime classes for 127,627 stream reaches across Ontario (Figure 13).

The out of bag error — the mean prediction error on each training sample — was 0.217. On average, 78% of flow gauges are predicted correctly (Table **5** 5). For example, 29 of 35 (82.9%) gauges belonging to the highly stable class were correctly classified, with six misclassified as stable flow regimes. The highest misclassification errors (24.4%) are for stable streams, likely because they share characteristics of both highly stable and variable flow regimes.

Table 5. From-to confusion matrix showing percentage of hydrological stations in a study of Ontario streams in a primary membership class that are confused to some degree with another class.

Flow regime	Highly stable	Stable	Variable	Total	% correct	% incorrect
Highly stable	29	6	0	35	82.9	17.1
Stable	28	158	23	209	75.6	24.4
Variable	1	15	77	93	82.8	17.2
Total	58	179	100	337	78.3	21.7

Regionality is evident in flow classes (Figure 13). Areas of high groundwater infiltration are apparent, such as the Oak Ridges Moraine and a band stretching from the Norfolk Sand Plains to Nottawasaga River, consisting of moraines and coarse glacial till. These areas have some highly stable and many stable streams. Because we did not predict flow regimes for drainage smaller than 10 km^2, many more small groundwater-dominated streams are likely draining these coarse textured glacial features than are shown on the map (Figure 13). A few highly stable streams are also associated with the Trent Severn and Rideau waterways because these drainages have many lakes and are heavily regulated. Outside these areas, much of the Mixedwood Plains has variable streams, particularly the clay plains areas of Niagara, Exeter, and Cornwall. The urbanized streams (mostly in southern Ontario), many of which are highly variable were excluded from modelling because their inclusion greatly reduced model predictive power. Stable streams dominate much of northern Ontario, likely reflecting the lake and wetland dominated landscape of the Ontario Shield and Hudson Bay Lowlands ecozones. In northern Ontario, highly stable streams are associated with the high storage capacity of lakes and chains of lakes on the shield. Variable streams are common among the clay plains in northeastern Ontario (e.g., Kesagami Provincial Park, Timmins, Kirkland). Some differences in landscape characteristics were evident among the three classes for predictions, particularly for LEI and BFI (Table 6).

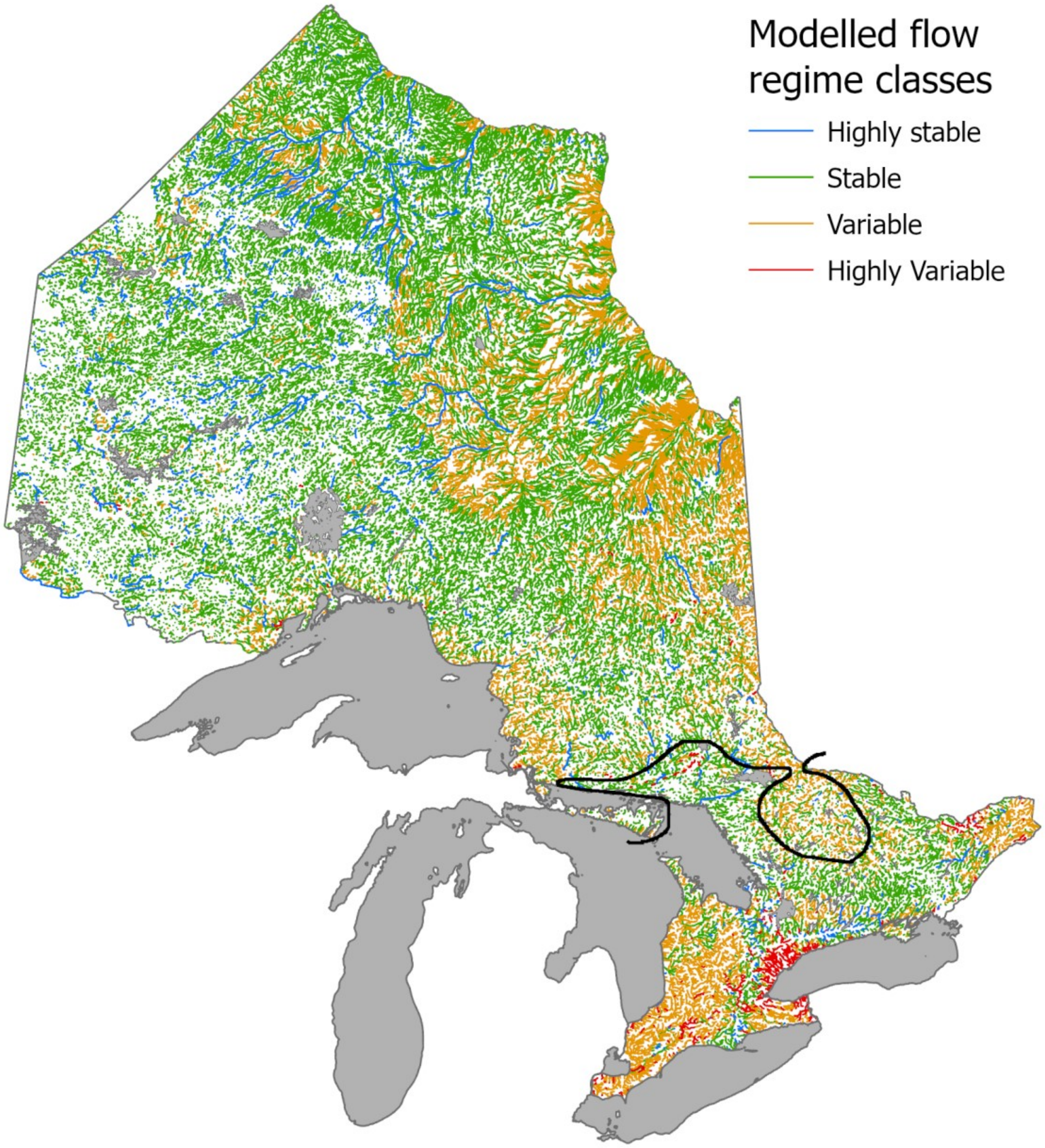


Figure 13. The modelled flow regime classes of Ontario. Highly variable streams are typically urbanized streams that have an inverse distance weighted urbanized value of higher than 10. Highly stable streams are under-represented in regions with many lakes (e.g., Algonquin Provincial Park, Algoma, northwestern Ontario). The black line from Sault Ste. Marie to Mattawa, including the Algonquin dome, represents the division line between winter dormant and active streams. This line corresponds to average growing degree days air temperature of about 1500 as defined by Aquatic Ecosystem Classification productivity region boundaries (Jones and Schmidt 2022).

Table 6. Summaries for landscape variables for the three predicted flow regime classes for streams in Ontario. Values are means (standard deviations) and minimum-maximum. Precipitation is the sum of precipitation (in mm) from May to November. UCA=upper catchment area; IDW=inverse distance weighting; BFI=base flow index; LEI=lake effect index.

Attribute	**Variable**	**Stable**	**Highly stable**
Count	22568	105061	9397
UCA (km^2)	68 (218) 10–6405	1126 (6423) 10–106809	6169 (14931) 10–106119
IDW wetland	22 (27.8) 0–99	38 (33.8) 0–99	25 (21.9) 0–93
IDW treed	38 (33.4) 0–99	31 (27.3) 0–96	37 (22.7) 0–94
IDW agriculture	38 (33.4) 0–99	31 (27.3) 0–96	37 (22.7) 0–94
IDW urban	2.2 (7.3) 0–97	0.6 (2.5) 0–95	0.6 (2.1) 0–47
Mainstem slope	0.004 (0.0039) 0–0.045	0.002 (0.0021) 0–0.039	0.002 (0.0035) 0–0.039
Precipitation	578 (59.2) 359–780	505 (70.9) 352–754	516 (59.5) 360–714
BFI	0.37 (0.134) 0.15–0.73	0.51 (0.083) 0.15–0.73	0.56 (0.086) 0.38–0.73
LEI	0.52 (0.78) 0–4.85	1.37 (1.25) 0–10.60	2.61 (1.43) 0–7.15

Discussion

We classified flow regimes across Ontario using a small number of flow regime metrics that, when combined, reflect the degree of environmental harshness of flows. This harshness is defined by open water season flood frequency, mid-summer base flow yield, and annual flow variability. We then developed a predictive model using classification and regression random forests and used this model to predict flow regime classes for each stream reach in Ontario excluding drainages less than 10 km^2 and those that have a value of more than 10 for the IDW urbanization variable. This process follows some of the first steps in the ecological limits of hydrologic alteration (ELOHA) framework for developing regional environmental flow standards (Poff et al. 2010). Some key differences between our approach and the steps outlined in ELOHA include using a relatively small set of flow metrics and removing climate influence where possible.

Unlike previous studies that use many flow regime metrics to classify flow (e.g., Growns and Marsh 2000, Thoms and Parson 2003), we deliberately used a simple set of flow metrics that relate to the ecology of rivers along a gradient of benign to harsh flow regimes. We chose this approach because we wanted to create a classification that was readily interpretable. Hundreds of flow regime metrics have been categorized into magnitude, frequency, duration, timing, and rate of change (Olden and Poff 2003). Seasonality is also considered in relation to timing of events, which is directly related to climate. The large number of metrics also stems from arbitrary time periods used in summary statistics (e.g., 12 monthly statistics for the same metric). Only a small subset of these metrics is hypothesized to be directly related to ecological flow responses and redundancy among them is high (Olden and Poff 2003). To manage the large number of measures, many studies take a multivariate approach, decomposing many metrics into a few axes to summarize hydrological character. This approach can be somewhat abstract and difficult to interpret because the influence of individual flow metrics is lost.

During the metric selection process, we excluded the Colwell predictability metrics (Colwell 1974) from further consideration. Although these metrics have been used by researchers to quantify flow regime predictability (Poff and Ward 1989, Kennard et al. 2007), we found them not to be meaningful in the context of Ontario flow metrics. Colwell devised these metrics to quantify the predictability of seasonal ecological phenomena with discrete states (e.g., flowering seasonality of fruit trees). Colwell (1974) does provide an example of binning monthly precipitation totals for assessing the predictability of precipitation. The example uses sites with diverse monthly precipitation timing patterns (e.g., British Columbia, Acapulco). In contrast, stream flows in Ontario have relatively similar timing of winter/summer low flows and spring/autumn freshets. We did experiment with creating a more meaningful Colwell metric designed to elucidate the monthly constancy of high flow event counts. This metric had a correlation ($r^2=-0.78$) with open water high flow event count. For this reason, we chose to represent seasonality of the flow regime using open water high flow event count and winter event counts because they were easier to interpret and more meaningful.

As noted by Jones et al. (2014) in their classification of flow regimes across Canada, the freezing of rivers is more related to climate than to the physical characteristics of the drainage basin. They tried to avoid flow metrics that correlated with climate (e.g., flow timing) and noted it was challenging. For example, the number of flood-free days is related not only to the characteristics of the watershed (e.g., high baseflow, many lakes for surface storage) but also to climate (e.g., winter ice dynamics). We prefer to classify climate separately as another key driver of streams in addition to the nutrient, sediment, and thermal regimes (Jones et al. 2010; Melles et al. 2014). In this classification, climate is acknowledged only in relation to the frequency of winter high flow events. By removing climate, we allow the classification to be free of typical climate trends across regions that likely result in contiguous regionalization of flow regimes over broad spatial extents at the expense of finer grained differences in flow regime patterns related to landforms and geology. In addition, climatic zones are somewhat arbitrary because changes in temperature are continuous, requiring researchers to impose breaks on this continuum.

The formation, persistence, and breakup of river ice are important aspects of the physical character of Arctic streams (Beltaos et al. 1993, Prowse 2001a, Power 2002, Beltaos and Burrell 2003) and ice dynamics are an important driver shaping stream fish communities. Jones et al. (2014) found that the flow metric *flood-free interval* was potentially a misleading measure of reduced harshness for high-latitude streams in Canada where ice formation and persistence result in extended flood-free periods. Typically, flood free periods are thought to be less harsh (Poff et al. 1997) but the opposite is likely true in high latitude streams. For example, flow stability measured in flood-free days is much higher in northern latitudes where ice can cover the landscape for 4 to 8 months of the year. Such a long period of stability is not stress free because long winters expose biota to different kinds of harshness factors (e.g., low flows, low oxygen, starvation; Prowse 2001b). Fish habitat can be greatly reduced by the formation of ice (Whalen et al. 1999), compounding harshness, while anchor ice covers riffle areas and frazil ice accumulates in pools, decreasing water volume for fishes (Prowse 1994). In these northern climates winter is often the time of annual flow minima. In high latitudes, many streams will freeze completely, and thus, fish must move to larger overwintering streams and lakes (Jones et al. 2010).

Ice breakup represents a major hydrological event in northern streams (Scrimgeour et al. 1994, Prowse 1994, Power 2002). Variation in hydraulic and meteorological conditions can produce thermal or mechanical breakup, largely depending on ice competency. Thermal breakup, characteristic of standing water bodies, occurs when the ice sheet thins, loses substantial strength, and eventually detaches from the bank. In many cases, thermal breakup is associated with relatively small increases in discharge. By contrast, mechanical breakup occurs when increasing discharge encounters an intact and physically competent ice sheet. Under these conditions, the spring flood wave created by rapid and extensive snowmelt ruptures the ice sheet, driving it downstream as a breaking ice front. Breakup fronts are often interspersed with periods of ice jamming. Ice jams are accompanied by substantial increases in river stage and flooding. Future research could focus on the likelihood of mechanical break-up, which is important to both stream ecosystems and northern communities near large rivers. By splitting the province into winter active vs. dormant, we acknowledge that winter flows and ice dynamics are crucial to understanding environmental harshness faced by biota but must be assessed separately. Southern streams that have several, but more variable, high flow events during winter have shorter winters and longer growing seasons. In contrast, northern streams lock-up hydrologically during winter and stable low flows persist until snowmelt in spring. Which type of environment is more harsh or stressful is difficult to quantify but clearly they are two vastly different environments for biota.

The number of flow types in a region should generally reflect the region’s heterogeneity in climate, surficial geology, and landforms, with diverse regions having more types (Poff et al. 2010). Deciding how many types are appropriate requires a trade-off between detail (i.e., small within type variability) and interpretability (i.e., differences among types). To be practical for management, a relatively small number of flow regimes should be defined that capture the major dimensions of streamflow variability. Most existing regional to continental scale hydrologic classifications have used four to twelve classes, depending on geographic extent, climatic and geologic variation or inclusion of other environmental factors (e.g., Poff and Ward 1989, Poff 1996, Snelder and Biggs 2002, Acreman et al. 2008, Kennard et al. 2010). Indeed, we recognize that classifying flow regimes over larger extents (e.g., North America) or in regions with high of landscape diversity (e.g., British Columbia) should result in more flow regime types. Four flow types in Ontario seems appropriate and further subdivision could be achieved if flow regime types were subdivided by climate factors.

Based on hydrological measures, we grouped streams into four flow regime types. Highly variable streams might be an exception because they are almost entirely related to heavily urbanized watersheds. They may not have existed before European colonization, so are a new flow regime type. In retrospect, perhaps only three fundamental flow regime types exist in Ontario. Highly variable streams may in fact be stable or variable flow regime types that have been altered to such an extent that they have become something new and highly variable.

Many of the predictions made for reaches across Ontario are reasonable, particularly the regional patterns, but we found several issues at finer scales. Overall, we have more confidence in the predictions for reaches with UCAs larger than 100 km^2 as these drainage sizes were represented well in the WSC network (Table 1). Secondly, predictions were made at the stream reach scale defined by up and downstream interconfluences. Consequently, some longitudinal discontinuities are evident where flow classes may alternate between classes. This outcome is largely because these reaches are near the threshold between flow classes and small changes in landscape measures can result in class flipping. In some cases, these longitudinal discontinuities are caused by urbanized areas, as noted above. Reaches with an urbanized IDW value higher than 10 were labelled as urbanized, that is, they were not predicted by the model directly. For example, Willow Creek flows out of Little Lake near Barrie, Ontario, as a stable stream but then transitions into the urbanized class as it passes through the town of Midhurst. Many streams in urbanized areas have highly variable flow regimes as seen in the initial 3-metric classification, but in exceptional cases some may also be variable, stable, or even highly stable. Caution is needed when interpreting the true nature of urbanized flows.

Consistent with previous research (Jones et al. 2014) using a similar ecological framework for classifying flows, the Steel (highly stable) and Batchawana (stable) rivers fall into different flow regime classes (Table 7). This difference provides an example of the influence of lakes in stabilizing flows, specifically higher base flows, smaller high flows, and lower annual range in flow magnitude. The Steel River drainage (1,190 km^2) has almost twice the number of lakes to act as storage to stabilize flows as the Batchawana River (1,230 km^2). Without the stronger influence of lakes directly on the main-stem flow path, the Batchawana River tends to have larger high flow events and smaller low flow events (Table **7**7). While the Steel River rarely has flows higher than 100 $m^3 \cdot s^{-1}$ (recorded maximum, 156 $m^3 \cdot s^{-1}$), the Batchawana River has flows above 100 $m^3 \cdot s^{-1}$ almost every year (estimated maximum 431 $m^3 \cdot s^{-1}$). The dampening effect of lakes highlights the importance of cumulative upstream lake surface area.

Despite the low misclassification rate for the training data set, the number of highly stable stream reaches in Ontario is likely underpredicted. For example, the calculated flow regime types based on the three metrics using actual hydrometric data indicated that the Steel and Batchawana rivers were different (highly stable and variable). However, both rivers were predicted by the model as being stable. In viewing predictions via GIS, we noticed that small drainages were often predicted as stable and sometimes variable when LEI values were well above 1.0, the value at which lake outlet streams

Table 7. Differences in landscape characteristics, flow regime metrics, and hydrology statistics for the Steel and Batchawana rivers in Ontario.

Variable		Steel (02BA006)	Batchawana (02BF001)
Flow regime cluster		Highly stable	Stable
Period of record		2004–2020	1968–2019
Drainage area (km^2)		1190	1230
% coverage by lakes in drainage		8.2	4.8
Lake effect index		3.0	1.2
Open water high flow count (events)		1.41	3.37
Range annual yield ($m^3 \cdot s^{-1} \cdot km^2$)		0.058	0.171
Summer baseflow yield (mm)		30.6	21.7
July-August median flow ($m^3 \cdot s^{-1}$)		6.4	4.2
Daily Data: Percentiles ($m^3 \cdot s^{-1}$)	99%	74.2	148.0
	1%	1.5	1.9
Annual extremes: median ($m^3 \cdot s^{-1}$)	High	63.8	205.5
	Low	2.3	2.6

are strongly influenced by lakes. Many more of these lake-dominated rivers that were assigned to the stable model class occur across northern Ontario but are probably better classified as highly stable (e.g., Petawawa River 7.9% lakes, LEI 2.4).

Our predictive model failed for these types of flowing waters, likely because the hydrometric network is not representative of flow regimes in Ontario. Many hydrometric stations are in the Mixedwood Plains Ecozone where predictions seem reasonable and there is a sufficient range of small and larger drainages (Figure 2). In northern Ontario, where most of the prediction issues are, the hydrometric network is sparse, and most stations are on large drainages (Figure 2). The station density of the MWP Ecozone was 3.14 stations per 1000 km^2 while the density of the non-MWP ecozones was 0.48 stations per 1000 km^2, which translates into a MWP density that is more than six times higher than that elsewhere in the province. In essence, the model is trying to predict beyond the data that was used for training. Ideally, the hydrometric network would consist of a random sample from the more than 400,000 stream reaches in Ontario, and perhaps stratified by drainage size to avoid oversampling the numerous small streams. It is always ill-advised to make inferences when the sample data used to train a model is not representative of the population. No amount of sophisticated modelling can resolve this sampling issue.

To correct this issue, we examined the model predictions in northern Ontario more closely in the context of their LEI. Using GIS maps, we examined three scenarios, LEI values of 1.0, 1.5, and 2.0, for making the adjustment to highly stable, settling on a LEI threshold of ≥ 2.0. Although this approach might seem heavy-handed, we feel the model predictions in non-MWP streams would be misleading if left as modelled, and more useful to fellow researchers and resource managers if adjusted. Reclassifying all stream reaches with LEI values ≥ 2.0 resulted in only a few changes in the Mixedwood Plains (MWP) Ecozone (e.g., Frontenac Axis, Bruce Peninsula, and Manitoulin Island; Table **8** 8). The effect of the LEI based adjustments was more pronounced in areas north of the MWP boundary, where most of Ontario's lakes occur. Here 24,700 stream reaches (~80% of all changes) were made by converting stable stream reaches to highly stable (Figure 14).

Table 8. Overview of changes from reclassifying all stream reaches in two ecoregions as highly stable if their LEI value ≥2.0. UCA=upper catchment area.

Category	Mixedwood Plains	Shield and Hudson Bay Lowlands
Number of reaches >10 km^2 UCA	12,785	114,842
Number of class changes	197	31,077
Percent change	1.5	27.1
Number of reaches manually changed to highly stable		
Urbanized	1	20
Variable	0	874
Stable	132	24,700
Highly stable (no change)	64	5,483

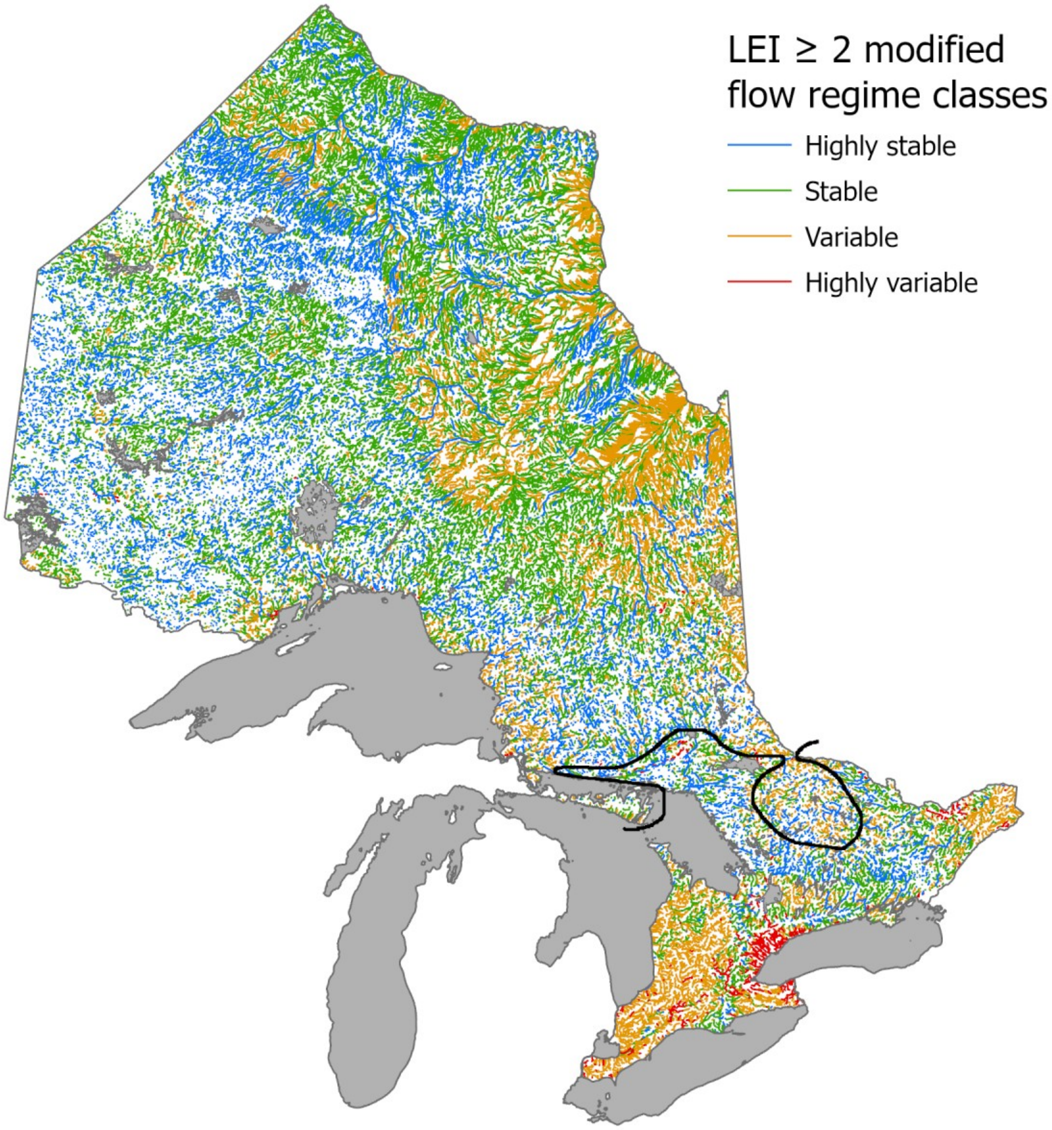


Figure 14. Flow regimes in Ontario modified by reclassifying all stream reaches with lake effect index values ≥2 to highly stable flow regimes. Highly variable streams are typically urbanized streams that have an inverse distance weighted value higher than 10. Highly stable streams are found in regions with many lakes (e.g., Algonquin Provincial Park, Algoma, northwestern Ontario). The black line from Sault Ste. Marie to Mattawa, including the Algonquin dome, represents the division line between winter dormant and active streams. This line corresponds to average growing degree days (air temperature) of around 1500 as defined by Aquatic Ecosystem Classification productivity region boundaries (Jones and Schmidt 2022).

The expectations generated in this study can be used to provide baseline understanding of flow regimes in Ontario. The maps provide an understanding of what type of flow regime could be expected for a stream reach. These predictions can be used to compare with heavily modified watersheds (e.g., urbanized, hydropower) as described in the ELOHA framework (Poff et al. 2010). A key element in the ELOHA framework is defining relationships between altered flow and ecological characteristics that can be empirically tested. These flow class predictions can be used in future research to explore relationships between aquatic biota and flow regime types. That said, we can already see how flow regime types relate to the presence/absence of fish species, such as brook trout, which occur in highly stable flow types in the Mixedwood Plains Ecozone.

References

Acreman, M., M. Dunbar, J. Hannaford, O. Mountford, P.J. Wood, N. Holmes, I. Cowx, R. Noble, C. Extence, J. Aldrick, J. King, A. Black and D. Crookall. 2008. Developing environmental standards for abstractions from UK rivers to implement the EU Water Framework Directive. Hydrological Sciences Journal 53: 1105–1120.

Allan, J. 2004. Landscapes and riverscapes: The influence of land use on stream ecosystems. Annual Review of Ecology, Evolution and Systematics 35: 257–284.

Beltaos, S., D.J. Calkins, L.W. Gatto, T.D. Prowse, S. Reedyk, G.J. Scrimgeour and S.P. Wilkins. 1993. Physical effects of river ice. Pages 12–15 *in* T.D. Prowse and N.C. Gridley, editors. Environmental Impacts of River Ice. National Hydrology Research Institute, Saskatoon, SK. 155 p.

Beltaos, S. and B.C. Burrell. 2003. Climatic change and river ice break-up. Canadian Journal of Civil Engineering 30: 145–155.

Bunn, S.E. and A.H. Arthington. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environmental Management 30: 492–507.

Buttle, J.M., S. Boon, D.L. Peters, C. Spence, H.J. van Meerveld and P.H. Whitfield. 2012. An overview of temporary stream hydrology in Canada. Canadian Water Resources Journal 37: 279–310.

Colwell, R.K. 1974. Predictability, constancy, and contingency of periodic phenomena. Ecology 55: 1148–1153.

[ECCC] Environment and Climate Change Canada. 2021. Water survey of Canada. Government of Canada, Ottawa, ON. <https://www.canada.ca/en/environment-climate-change/services/water-overview/quantity/monitoring/survey.html>. Accessed May 2021.

Growns, J. and N. Marsh. 2000. Characterisation of flow in regulated and unregulated streams in eastern Australia. Cooperative Research Centre for Freshwater Ecology, Canberra, NSW. Technical Report 3/2000. 66 p.

Haines, A.T., B.L. Finlayson and T.A. McMahon. 1988. A global classification of river regimes. Applied Geography 8: 255-–272.

Jones N.E. and B.J. Schmidt. 2016. Tributary effects in rivers: Interactions of spatial scale, network structure, and landscape characteristics. Canadian Journal of Fisheries and Aquatic Sciences 74: 503–510.

Jones, N.E. and B.J. Schmidt. 2022. Aquatic ecosystem classification for Ontario’s rivers and streams, version 2. Ontario Ministry of Northern Development, Mines, Natural Resources and Forestry, Science and Research Branch, Peterborough, ON. Science and Research Technical Report TR-47. 30 p. + appendices.

Jones, N.E., B.J. Schmidt and S.J. Melles. 2014. Characteristics and distribution of natural flow regimes in Canada: A habitat template approach. Canadian Journal of Fisheries and Aquatic Sciences 71: 1616–1624.

Jones, N. E., G. J. Scrimgeour and W. M. Tonn. 2010. Fish species traits and communities in relation to a habitat template for Arctic rivers and streams. *In* Gido, K.B. and D.A. Jackson (editors). Community Ecology of Stream Fishes. American Fisheries Society Special Publication 73: 137–156.

Jowett, I.G. and M.J. Duncan. 1990. Flow variability in New Zealand rivers and its relationship to in-stream habitat and biota. New Zealand Journal of Marine and Freshwater Research 24: 305–317.

Kennard, M.J., J.D. Olden, A.H. Arthington, B.J. Pusey and N.L. Poff. 2007. Multi-scale effects of flow regime, habitat, and their interaction on fish assemblage structure in eastern Australia. Canadian Journal of Fisheries and Aquatic Sciences 64: 1346–1359.

Lake, P.S. 2003. Ecological effects of perturbation by drought in flowing waters. Freshwater Biology 48: 1161–1172.

Legendre, P. and L. Legendre. 1998. Numerical Ecology, 2nd ed. Elsevier, Amsterdam, NLD. 852 p.

Lytle, D.A. and N.L. Poff. 2004. Adaptation to natural flow regimes. Trends in Ecology and Evolution 19: 94–100.

Matthews, W.J. 1998. Patterns in Freshwater Fish Ecology. Chapman and Hall, New York, NY. 756 p.

McManamay, R.A. and E.A. Frimpong. 2015. Hydrologic filtering of fish life history strategies across the United States: Implications for stream flow alteration. Ecological Applications 25: 243–263.

Melles, S.J., N.E. Jones and B.J Schmidt. 2014. Evaluation of current approaches to stream classification and a heuristic guide to developing classifications of integrated aquatic networks. Environmental Management 53: 549–566.

Mosley, M.P. 1981. Delimitation of New Zealand hydrologic regions. Journal of Hydrology 49: 179–192.

Nathan, R.J. and T.A. McMahon. 1990. Evaluation of automated techniques for base flow and recession analyses. Water Resources Research 26: 1465–1473.

Neff, B.P., S.M. Day, A.R. Piggott and L.M. Fuller. 2005. Base flow in the Great Lakes Basin. U.S. Geological Survey, Washington, DC. Scientific Investigations Report 2005-5217.

Olden, J. D. and M.J. Kennard 2010. Intercontinental comparison of fish life history strategies along a gradient of hydrologic variability. American Fisheries Society Symposium 73: 83–107.

Olden, J.D. and N.L. Poff. 2003. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. River Research Applications 19: 101–121.

Olden, J.D., M.J. Kennard and B.J. Pusey. 2012. A framework for hydrologic classification with review of methodologies and applications in ecohydrology. Ecohydrology 5: 503–518.

[OMNR] Ontario Ministry of Natural Resources. 2014. Ontario Land Cover Compilation Data Specifications Version 2.0. Ontario Ministry of Natural Resources, Land Information Ontario, Peterborough, ON. <https://www.publicdocs.mnr.gov.on.ca/mirb/Ontario%20Land%20Cover%20Compilation%20-%20Data%20Specification%20Version.pdf>. Accessed Feb 2024.

[OMNR] Ontario Ministry of Natural Resources. 2000. Ontario climate model (CD-ROM). Ontario Ministry of Natural Resources, Ontario Forest Research Institute, Sault Ste. Marie, ON.

[OMNRF] Ontario Ministry of Natural Resources and Forestry. 2023. Ontario Dam Inventory. Ontario Ministry of Natural Resources and Forestry, Peterborough, ON. <https://geohub.lio.gov.on.ca/datasets/mnrf::ontario-dam-inventory>. Accessed November 2023.

Perkin, J.S., T.A. Starks, C.A. Pennock, K.B. Gido, G.W. Hopper and S.C. Hedden. 2019. Extreme drought causes fish recruitment failure in a fragmented Great Plains riverscape. Ecohydrology 12: e2120.

Peterson, E.E., F. Sheldon, R. Darnell, S.E. Bunn and B.D. Harch. 2011. A comparison of spatially explicit landscape representation methods and their relationship to stream condition. Freshwater Biology 56: 590–610.

Peterson, E.E. and A.R. Pearse. 2017. IDW-Plus: An ArcGIS toolset for calculating spatially explicit watershed attributes for survey sites. Journal of the American Water Resources Association 53: 1241–1249.

Poff, N.L. 1992. Why disturbances can be predictable: A perspective on the definition of disturbance in streams. Journal of the North American Benthological Society 11: 86–92.

Poff, N.L. 1996. A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors. Freshwater Biology 36: 71–91.

Poff, N.L. 1997. Landscape filters and species traits: Towards mechanistic understanding and prediction in stream ecology. Journal of the North American Benthological Society 16: 391–409.

Poff, N. L. and J.D. Allan. 1995. Functional organization of streamfish assemblages in relation to hydrological variability. Ecology 76: 606–627.

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

Poff, N.L. and J. K. Zimmerman. 2010. Ecological responses to altered flow regimes: A literature review to inform the science and management of environmental flows. Freshwater Biology 55: 194–205.

Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B. Richter, R. Sparks and J. Stromberg. 1997. The natural flow regime: A new paradigm for riverine conservation and restoration. BioScience 47: 769–784.

Poff, N.L., B.D. Richter, A.H. Arthington, S.E. Bunn, R.J. Naiman, E. Kendy, M. Acreman, C. Apse, B.P. Bledsoe, M.C. Freeman, J. Henriksen, R.B. Jacobson, J.G. Kennen, D.M. Merritt, J.H. O’Keeffe, J.D. Olden, K. Rogers, R.E. Tharme and A. Warner. 2010. The ecological limits of hydrologic alteration (ELOHA): A new framework for developing regional environmental flow standards. Freshwater Biology 55: 147–170.

Power, G. 2002. Chars, glaciations and seasonal ice. Environmental Biology of Fishes 64: 17–35.

Prowse, T D. 1994. Environmental significance of ice to streamflow in cold regions. Freshwater Biology 32:241–259.

Prowse, T.D. 2001a. River-ice ecology. I: Hydrologic geomorphic, and water quality aspects. Journal of Cold Regions Engineering 2001: 1–16.

Prowse, T.D. 2001b. River ice. II: Biological aspects. Journal of Cold Regions Engineering 2001: 17–31.

Resh, V.H., A.V. Brown, A.P. Covich, M.E. Gurtz, H.W. Li, G.W. Minshall, S.R. Reice, A.L. Sheldon, J.B. Wallace and R.C. Wissmar. 1988. The role of disturbance in stream ecology. Journal of the North American Benthological Society 7: 433–455.

Scrimgeour, G. J., T. D. Prowse, J. M. Culp and P. A. Chambers. 1994. Ecological effects of river ice break-up: a review and perspective. Freshwater Biology 32: 261–275

Snelder,T.H., N. Lamouroux, J.R. Leathwick, H. Pella, E. Sauquet and U. Shankar. 2009. Predictive mapping of the natural flow regimes of France. Journal of Hydrology 373: 56–67.

Southwood, T.R.E. 1977. Habitat, the templet for ecological strategies? Journal of Animal Ecology 46: 337–365.

Spence, C. 2006. Hydrological processes and streamflow in a lake dominated watercourse. Hydrological Processes 20: 3665–3681.

Thoms, M.C. and M. Parsons. 2003. Identifying spatial and temporal patterns in the hydrological character of the Conadmine-Balonne river, Australia, using multivariate statistics. River Research and Applications 19: 443–457.

Tonn, W.M. 1990. Climate change and fish communities: A conceptual framework. Transactions of the American Fisheries Society 119: 337–352.

Townsend, C.R. and A.G. Hildrew. 1994. Species traits in relation to a habitat templet for river systems. Freshwater Biology 31: 265–275.

Whalen, K.G., D L. Parrish and M.E. Mather. 1999. Effect of ice formation on selection of habitats and winter distribution of post-young-of-the year Atlantic salmon. Canadian Journal of Fisheries and Aquatic Sciences 56: 87–96.

Winemiller, K.O. 2005. Life history strategies, population regulation, and implications for fisheries management. Canadian Journal of Fisheries and Aquatic Sciences 62: 872–885.

Winemiller, K.O. and K.A. Rose 1992. Patterns of life-history diversification in North American fishes: Implications for population regulation. Canadian Journal of Fisheries and Aquatic Sciences 49: 2196–2218.

Appendix 1. Flow metric descriptive statistics

Table A1.1. Descriptive statistics for each flow regime class (highly stable, stable, variable, and highly variable) and flow metrics in Ontario.

Flow metrics	Minimum	Mean	Standard deviation	Maximum	25th percentile	Median	75th percentile
Highly stable							
WINTER-HFECOUNT	0.00	0.51	0.79	2.50	0.00	0.00	1.00
OPENWATER-HFECOUNT	0.00	2.28	1.99	7.93	1.08	1.55	2.39
COLWELL-C-HFECOUNT	0.21	0.67	0.21	0.89	0.50	0.77	0.81
COLWELL-C-DAILYQ	0.10	0.11	0.00	0.11	0.11	0.11	0.11
CV-MINMONTH-TIMING	0.80	1.69	0.56	3.46	1.23	1.60	2.02
CV-MAXMONTH-TIMING	0.92	1.73	0.40	2.87	1.44	1.64	1.93
MEAN-ANNUALYIELD	205.80	361.52	99.51	584.70	272.90	351.20	426.30
MEAN-CV-DAILYQ	0.26	0.75	0.22	1.29	0.63	0.73	0.88
RANGE-ANNUALYIELD	0.01	0.05	0.04	0.21	0.03	0.04	0.07
MINIMA-ANNUALYIELD	0.001	0.004	0.002	0.012	0.002	0.003	0.005
WINTER-BFYIELD	8.70	32.26	18.37	73.50	16.60	25.40	47.20
SUMMER-BFYIELD	28.00	42.56	9.73	70.00	34.20	40.90	48.50
Stable							
WINTER-HFECOUNT	0.00	0.99	0.88	3.15	0.07	0.87	1.72
OPENWATER-HFECOUNT	0.26	3.28	2.21	11.20	1.52	2.69	4.56

Flow metrics	Minimum	Mean	Standard deviation	Maximum	25th percentile	Median	75th percentile
COLWELL-C-HFECOUNT	0.13	0.50	0.18	0.84	0.34	0.52	0.66
COLWELL-C-DAILYQ	0.10	0.11	0.00	0.15	0.11	0.11	0.11
CV-MINMONTH-TIMING	0.97	1.62	0.32	2.47	1.40	1.61	1.81
CV-MAXMONTH-TIMING	0.80	1.83	0.47	2.89	1.46	1.79	2.16
MEAN-ANNUALYIELD	115.40	371.13	88.99	729.90	321.60	364.85	422.60
MEAN-CV-DAILYQ	0.62	1.27	0.27	2.37	1.08	1.24	1.43
RANGE-ANNUALYIELD	0.01	0.11	0.04	0.20	0.08	0.11	0.13
MINIMA-ANNUALYIELD	0.0000	0.0017	0.0011	0.0048	0.0007	0.0016	0.0025
WINTER-BFYIELD	1.60	29.07	13.88	67.70	18.80	28.65	38.50
SUMMER-BFYIELD	2.40	16.12	7.35	30.40	9.50	15.65	22.10
Variable							
WINTER-HFECOUNT	0.00	1.82	0.98	4.15	1.19	1.88	2.53
OPENWATER-HFECOUNT	1.25	5.35	1.93	11.72	3.97	5.12	6.46
COLWELL-C-HFECOUNT	0.08	0.28	0.11	0.61	0.19	0.27	0.37
COLWELL-C-DAILYQ	0.10	0.11	0.03	0.22	0.11	0.11	0.11
CV-MINMONTH-TIMING	0.67	1.62	0.28	2.56	1.47	1.63	1.82
CV-MAXMONTH-TIMING	0.59	1.52	0.38	2.65	1.25	1.48	1.76
MEAN-ANNUALYIELD	237.60	427.49	111.13	808.20	354.60	411.65	470.30
MEAN-CV-DAILYQ	1.31	2.02	0.42	3.56	1.74	1.97	2.26
RANGE-ANNUALYIELD	0.15	0.24	0.06	0.46	0.19	0.23	0.27
MINIMA-ANNUALYIELD	0.0000	0.0006	0.0006	0.0034	0.0002	0.0004	0.0009

Flow metrics	**Minimum**	**Mean**	**Standard deviation**	**Maximum**	**25th percentile**	**Median**	**75th percentile**
WINTER-BFYIELD	1.90	22.63	11.48	73.40	14.70	21.20	27.40
SUMMER-BFYIELD	0.30	6.59	5.03	23.90	2.80	5.20	8.20
Highly variable							
WINTER-HFECOUNT	2.90	3.41	0.47	4.46	3.07	3.31	3.53
OPENWATER-HFECOUNT	13.25	18.37	3.59	25.77	15.20	18.71	20.95
COLWELL-C-HFECOUNT	0.01	0.08	0.04	0.17	0.07	0.07	0.09
COLWELL-C-DAILYQ	0.11	0.11	0.00	0.11	0.11	0.11	0.11
CV-MINMONTH-TIMING	0.78	1.22	0.30	1.82	1.06	1.13	1.46
CV-MAXMONTH-TIMING	0.56	0.85	0.21	1.27	0.72	0.82	1.02
MEAN-ANNUALYIELD	316.70	448.16	153.48	945.00	371.30	422.80	454.50
MEAN-CV-DAILYQ	0.91	1.78	0.43	2.66	1.60	1.77	1.99
RANGE-ANNUALYIELD	0.12	0.24	0.06	0.37	0.21	0.24	0.27
MINIMA-ANNUALYIELD	0.0001	0.0021	0.0014	0.0048	0.0009	0.0019	0.0027
WINTER-BFYIELD	7.40	21.70	12.02	56.90	15.30	19.90	23.60
SUMMER-BFYIELD	2.60	16.46	9.92	40.10	9.10	15.35	20.20

Table A1.2. The initial set of 36 ecologically relevant flow metrics used in Ontario study. Q = discharge; CV = coefficient of variation; NA=not applicable.

Metric name	**Description**	**Ecological relevance**	**Calculation**	**Olden and Poff (2003)**
ANNUAL_HFECOUNT^	Mean annual high flow event count	High flow events act as a disturbance throughout the whole year, with a higher event count indicating harsher conditions.	Number of events per year averaged across the period of record.	FH1
WINTER_HFECOUNT*^	Mean mid-winter event counts	High flow events act as a disturbance during the mid-winter low flow period, with a higher event count indicating harsher conditions.	Number of events occurring during January and February (winter dynamic vs. stable) per year averaged across the period of record.	NA
SUMMER_HFECOUNT^	Mid-summer event counts	High flow events act as a disturbance during the mid-summer low flow period, with a higher event count indicating harsher conditions.	Number of events occurring during July and August per year averaged across the period of record.	NA
OPENWATER_HFECOUNT**^	Mean open water season event counts	High flow events act as a disturbance during open water season, with a higher event count indicating harsher conditions.	Number of events occurring May through November per year averaged across the period of record.	NA

Metric name	Description	Ecological relevance	Calculation	Olden and Poff (2003)
WSRATIO_HFECOUNT^	Mean mid-winter event count divided by mid-summer event count	A measure of which low flow season (mid-winter or summer) has the harsher conditions, where values below zero indicate harsher winter and above zero harsher summers.	Ratio of the period of record average count of high flow events (mid-winter divided by mid-summer count), with a value less than zero indicating harsher summers and values above zero harsher winters. Division by zero error when summer count is zero.	NA
COLWELL_P_HFECOUNT^	Colwell predictability of monthly high flow event counts	Higher values are more ecologically benign.	Colwell Predictability of the frequency of occurrence of monthly high flow event counts (1,2,3,4,5+ events) for the period of record. See Colwell (1974) for calculation method.	NA
COLWELL_C_HFECOUNT*^	Colwell constancy of monthly high flow event counts	Higher values are more ecologically benign.	Colwell Constancy of the frequency of occurrence of monthly high flow event counts (1,2,3,4,5+ events) for the period of record. See Colwell (1974) for calculation method.	NA
COLWELL_M_HFECOUNT^	Colwell contingency of monthly high flow event counts	Higher values are more ecologically benign.	Colwell Contingency of the frequency of occurrence of monthly high flow event counts (1,2,3,4,5+ events) for the period of record. See Colwell (1974) for calculation method.	NA
COLWELL_P_DAILYQ	Colwell predictability of daily flows	Higher values are more ecologically benign.	Colwell Predictability of the frequency of occurrence of daily flow within period of record flow percentile bins (5, 10, 25, 50, 75, 90, 95). See Colwell	TA1 (modified)

Metric name	Description	Ecological relevance	Calculation	Olden and Poff (2003)
			(1974) and Poff (1989) for calculation method.	
COLWELL_C_DAILYQ*	Colwell constancy of daily flows	Higher values are more ecologically benign.	Colwell Constancy of the frequency of occurrence of daily flow within period of record flow percentile bins (5, 10, 25, 50, 75, 90, 95). See Colwell (1974) and Poff (1989) for calculation method.	NA
COLWELL_M_DAILYQ	Colwell contingency of daily flows	Higher values are more ecologically benign.	Colwell Contingency of the frequency of occurrence of daily flow within period of record flow percentile bins (5, 10, 25, 50, 75, 90, 95). See Colwell (1974) and Poff (1989) for calculation method.	NA
CV_MINMONTH_TIMING*	Intra-annual dispersion of annual minima timing	The consistency of the timing of the annual minima, used to identify which rivers whose lowest annual flow can occur across multiple months	CV of the counts of annual mode of annual minima occurrence months during the period of record. This is an adaptation of the HIT metric which uses annual minima day of year instead of monthly modes.	TL2
MODE_MINIMA_MONTH	Timing of annual minima occurrences	The prevalent timing of the annual minimum (e.g., during winter or summer).	The month with the highest count of annual minima.	NA

Metric name	Description	Ecological relevance	Calculation	Olden and Poff (2003)
COUNT_MINMONTH_MODE	Multi-modal timing of annual minima occurrences	The frequency of equal annual minima counts per month occurring during several months of the year, with a larger occurrence window or multiple windows being harsher.	The count of equal mode months occurring throughout the period of record.	NA
CV_MAXMONTH_TIMING*	Intra-annual dispersion of annual maxima timing	The average amount of flow that biota can expect at the station.	CV of the counts of annual mode of occurrence of the annual maxima months during the period of record. This metric is an adaptation of the HIT metric, which uses annual maxima day of year instead of monthly modes.	TH2
MODE_MAXIMA_MONTH	Timing of annual maxima occurrences	The prevalent timing of the annual maximum (e.g., during spring or autumn).	The month with the highest count of annual maxima.	NA
COUNT_MAXMONTH_MODE	Multi-modal timing of annual maxima occurrences	The frequency of equal annual maxima counts per month occurring during several months of the year, with a larger occurrence window or multiple windows being harsher.	The count of equal mode months occurring throughout the period of record.	NA
MEAN_ANNUALQ	Mean annual flow	The average amount of flow that biota can expect each year at the station.	The average of all flows of the period of record.	NA
MEAN_ANNUALYIELD*	Mean annual yield	The range in yield, with a larger range indicating harsher conditions.	Mean of the annual yields divided by the drainage area.	MA41

Metric name	Description	Ecological relevance	Calculation	Olden and Poff (2003)
MEAN_CV_DAILYQ*	Mean annual coefficient of variation of daily flows	A measure of day to day flow variability, with a higher value indicating harsher conditions.	Mean of the annual CVs of flow (SD/mean) across the period of record.	MA3
RANGE_ANNUALQ	Mean annual range of flows	A measure of the difference in magnitude between the annual extreme high and low flow conditions, with larger range indicating harsher conditions.	Mean maximum annual flow − mean minimum annual flow	NA
RANGE_ANNUALYIELD**	Ratio of mean annual range of flows standardized by drainage area	A larger range indicates harsher conditions.	(Mean maximum annual flow − mean minimum annual flow)/drainage area	NA
MINIMA_ANNUALQ	Mean minimum annual flow magnitude	A measure of extreme low flow conditions, with lower values indicating harsher conditions.	The average of the annual minima flows for the period of record.	ML14
MINIMA_ANNUALYIELD*	Mean minimum annual flow divided by drainage area	A measure of extreme low flow conditions standardized by drainage area, with lower values indicating harsher conditions.	The ratio of mean annual minimum over drainage area.	NA

Metric name	Description	Ecological relevance	Calculation	Olden and Poff (2003)
PRCTL8020_QRATIO	Mean annual ratio of high to low flow	The relationship between non-extreme annual low and high flow conditions, with a larger ratio indicating harsher conditions.	Ratio of sub-extreme percentiles 80th/20th percentiles that is less susceptible to extreme event influence (dimensionless and drainage area independent). Division by zero errors when 20th percentile is zero.	NA
ANNUAL_BFI	Annual baseflow index	A measure of low flow stability throughout the year, with a lower value indicating harsher conditions.	Baseflow index (BFI) is the ratio of the baseflow volume over total flow volume. Baseflow was derived by passing a digital recursive filter over the hydrograph (Nathan and McMahon 1990) and for this metric consist of groundwater and waterbody contributions throughout the year.	NA
WINTER_BFI	Mid-winter baseflow index	A measure of low flow stability during mid-winter, with a lower value indicating harsher conditions.	Baseflow index (BFI) is the ratio of the baseflow volume over total flow volume. Baseflow was derived by passing a digital recursive filter over the hydrograph (Nathan and McMahon 1990) and for this metric consist of groundwater and waterbody contributions during January and February.	NA

Metric name	Description	Ecological relevance	Calculation	Olden and Poff (2003)
SUMMER_BFI	Mid-summer baseflow index	A measure of low flow stability during mid-summer, with a lower value indicating harsher conditions.	Baseflow index (BFI) is the ratio of the baseflow volume over total flow volume. Baseflow was derived by passing a digital recursive filter over the hydrograph (Nathan and McMahon 1990) and for this metric consist of groundwater and waterbody contributions during July and August.	NA
OPENWATER_BFI	Open water season baseflow index	A measure of low flow stability throughout the open water season, with a lower value indicating harsher conditions.	Baseflow index (BFI) is the ratio of the baseflow volume over total flow volume. Baseflow was derived by passing a digital recursive filter over the hydrograph (Nathan and McMahon 1990) and for this metric consist of groundwater and waterbody contributions May through November.	NA
WINTER_BFYIELD*	Mid-winter baseflow yield	A measure of drainage area standardized low flow stability during mid-winter, with a lower value indicating harsher conditions.	Drainage area standardized baseflow volume during January and February. The total (i.e., sum) open water period volume of baseflow (m^3) divided by drainage area (m^2) multiplied by 1000 to convert to millimetres.	NA
SUMMER_BFYIELD**	Mid-summer baseflow yield	A measure of drainage area standardized low flow stability during mid-summer, with a	Drainage area standardized baseflow volume during July and August. The total (i.e., sum) open water period volume of baseflow (m^3) divided by	NA

Metric name	Description	Ecological relevance	Calculation	Olden and Poff (2003)
		lower value indicating harsher conditions.	drainage area (m^2) multiplied by 1000 to convert to millimetres.	
WSRATIO_BFYIELD	Ratio of the means winter/summer baseflow yields	The relationship between drainage area standardized low flow, with a ratio <1 indicating harsher winter compared to summer low flow conditions and >1 indicating harsher summers.	The ratio of the mean winter/summer baseflow yields. Division by zero error when summer yield is zero.	NA
MEAN_POSROC	Mean rising rate of change	The rate at which flow can increase over time, with a higher rate being harsher because biota cannot adapt or move fast enough.	Average daily rate of change values	RA1
MEAN_REL_POSROC	Drainage area standardized mean rising rate of change	The drainage area standardized rate at which flow can increase over time, with a higher rate being harsher because biota cannot adapt or move fast enough.	Average daily rate of change values divided by drainage area	NA
MEAN_NEGROC	Mean falling rate of change	The rate at which flow can decrease over time, with a higher rate being harsher because biota cannot adapt or move fast enough.	Raw values and values standardized by mean annual flow	RA3

Metric name	Description	Ecological relevance	Calculation	Olden and Poff (2003)
MEAN_REL_NEGROC	Drainage area standardized mean falling rate of change	The drainage area standardized rate at which flow can decrease over time, with a higher rate being harsher because biota cannot adapt or move fast enough.	Average daily rate of change values divided by drainage area	NA

* = subset of 12 metrics
** = final subset of 3 metrics
^ = High flow events are defined as flow peaks that are a multiple (e.g., 2x) larger than their adjacent flow troughs on the hydrograph. Event with peaks below the period of record 20th flow percentile are excluded.

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