Using Regional Flow Regime Classes to Identify Flow Anomalies in a Set of Canadian Rivers Regulated by Dams

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Preface

Thesis Format

This thesis has been written in the monograph format as permitted by McGill University regulations.

Contributions of Authors

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Abstract

It is well established that a river's natural flow regime is a key determinant of ecological integrity and that dam regulated-flow releases can in some cases be detrimental to biotic communities (e.g. Poff and Zimmerman, 2010). Regional flow classes, groups of rivers that share similar natural flow regimes (called 'river types' by Poff and Zimmerman (2010)) and to which regional fish communities are adapted, have been proposed (e.g. Poff, 1996; Poff and Zimmerman, 2010; McManamay *et al.,* 2012a) as units of analysis to identify significant damming related flow alteration. Specifically, the natural range of flow behaviour within regional classes can be used to identify the most anomalous flow features in rivers regulated by dams. Through ordination analysis, 5 flow regime clusters were identified based on 70 ecologically important flow indices. These clusters are distinct classes of regional flow regimes for 96 unregulated rivers in proximity to 16 regulated sites chosen as NSERC HydroNet sites in Eastern and Western Canada. The distinguishing characteristics of natural flow regimes within each flow class are explored through visualization in principal component space. The 16 regulated HydroNet sites were assigned to these flow classes through discriminate function analysis based on shared geographic location and watershed characteristics. Anomalous flow features in the regulated rivers are identified and characterized in terms of type and strength by identification of flow indices that are significantly different from observed natural variability in the relevant regional class. We also discuss the potential biological implications of the dominant flow anomalies in this set of rivers regulated by hydro dams.

Résumé

Selon le paradigme du 'Natural Flow Regime', le régime hydrologique naturel (ou régime de débits) d'une rivière est un déterminant clé de son intégrité écologique. L'altération significative de ce régime par un barrage hydroélectrique peut en effet négativement affecter les communautés biotiques d'un écosystème lotique (Poff and Zimmerman, 2010). Récemment, des auteurs influents (e.g. Poff, 1996; McManamay *et al*., 2012a) ont ainsi proposé qu'afin d'identifier les altérations du régime naturel les plus significatives causés par la régulation par barrage, on utilise un point de référence régional (les 'river type') (Poff and Zimmerman, 2010) constitué de la variabilité présente dans un sous-ensemble de rivières non-régulées coulant dans la région du site régulé, rivières qui partagent naturellement certaines caractéristiques de régime hydrologique (et auxquelles la faune aquatique régionale est adaptée). A cet effet, une analyse d'ordination a été effectuée sur les régimes naturels de débit de 96 rivières non régulées situées à proximité des 16 sites sur rivières régulées par barrage choisis pour étude dans le projet HydroNet, et ce dans deux régions distinctes, l'une dans l'ouest et la seconde dans l'est canadien. Cette ordination, effectuée à partir de 70 métriques de débit reconnus pour leur pertinence écologique, distingue 5 sous-ensembles régionaux de régimes naturels assez distincts (5 'flow classes', sensu McManamay *et al.,* (2012a)) réparties à travers les régions à l'étude. Les caractéristiques contrastantes des régimes de chacune de ces 5 sous-ensembles sont présentées et discutées. Par la suite, une analyse par fonction discriminante permet d'assigner les 16 sites régulés à l'étude à une ou l'autre de ces 5 classes, comme point de comparaison naturel. Cette analyse nous permet par la suite de repérer et de décrire les divers aspects des régimes de débits aux sites régulés qui sont clairement 'hors normes' par rapport à ce qui est observé dans le sous-ensemble régional de référence. Nous discutons brièvement par la suite de certains effets possibles de ces anomalies particulières sur les populations de poisson dans ces écosystèmes.

Chapter 1: General Introduction

Each river ecosystem is a unique and dynamic environment for a wide range of aquatic and riparian flora and fauna. Species reliant on riverine environments for all or part of their life cycle are evolutionarily adapted to a natural range of variability for various environmental variables; including water temperature, water velocity, physical habitat volume and type, water chemistry and discharge or flow regime. Flow regime is widely considered to be the most important determinant of riverine ecosystem structure and function; the 'master variable' of ecosystem health (Poff *et al.,* 1997).

One of the ways that flow influences river habitat is by physically shaping the system. The physical structure of the wetted river habitat is strongly shaped by the 2-5yr recurrence high flow levels in wet temperate climates: in alluvial channels these are responsible for channel dimensions and they affect reach scale bed material composition, substrate mobility levels and sediment transport patterns (Poff *et al.,* 1997; Church, 2002). Additionally, it is known that life cycle patterns as well as locations of preferred feeding and refuge habitats for various benthic invertebrate and fish fauna are adjusted in complex ways to patch and reach scale depth and velocity patterns as these vary with annual flow seasonality, all of which is determined by the natural flow regime of a river (e.g. Riis and Biggs, 2003; Baranyi *et al,.* 2002).

The dynamism of a river's flow regime is widely described as having five broad ecologically important components: flow magnitude, frequency, duration, timing and rate of change; to support this categorization, Poff *et al*. (1997) cite more than 100 articles documenting how such flow features are linked to various ecological outcomes.

After dam construction, river flows can be regulated by dam operators through operator control of spillway gates or numbers of operating turbines. The type and degree of flow alteration that occurs after regulation thus depends on the physical characteristics of the dam (i.e. dam height and the water volume that can be retained in the reservoir, spillway design), hydropower mode of operation (e.g. timing of grid demand, ramping rate restrictions and

environmental baseflow requirements), and the rivers' pre-regulated flow regime. In general, many hydro dams tend to reduce downstream maximum flows, reduce inter-seasonal flow variability, and reduce rise rates (with the exception of hydro peaking systems; discussed below), while increasing minimum flows and number of flow reversals per year (Magilligan and Nislow, 2005; McManamay *et al.,* 2012a). However, these alterations may occur to varying degrees if at all.

In Canada, 60% of electricity used comes from over 470 hydroelectric facilities across the country (Smokorowski *et al*., 2011). This number of facilities is projected to grow and so is the amount of power generated from existing infrastructure. These same trends are expected globally. It is therefore important that we continue to improve our techniques to evaluate and manage the ecological impacts of hydro dam construction and flow regulation.

Beyond simple minimum flow requirements below dams, there is mounting support for environmental flow standards developed to simulate a naturally variable flow regime; this is thought necessary to sustain the integrity of freshwater ecosystems (Poff *et al.,* 1997; Bunn and Arthington 2002; Postel and Richter, 2003; Biggs *et al.*, 2005). The 'Natural Flow Paradigm' postulates that river biodiversity and evolutionary potential is optimized by maintaining the full range of natural flow variability (annual, seasonal and event-based scales) (Black *et al.*, 2005; Poff *et al,.* 1997; Richter *et al.,* 1997; Olden and Poff, 2003). Yet ecological outcomes of altered flow regimes are at times considerably different between sites, so that transferable hydro-ecological relationships required in order to prescribe acceptable flow regimes remain elusive (Black *et al.*, 2005). Understandably, it is difficult to persuade dam operators to modify water release operations which can entail major income losses in the face of this uncertainty.

There is therefore room for scientific improvement in determining acceptable ranges of variability of the different flow regime components (such as magnitude, frequency, timing, etc.) in regulated rivers. Based on an understanding of the variability of hydrologic features maintaining ecosystem structure, function and biotic integrity across individual rivers in a

region, there is a scientific consensus supporting the development of environmental flow standards at the regional scale (Poff *et al.,* 2010). It is however important to recognize that regionally, and this is especially apparent at broad continental scales of analysis, not all rivers exhibit similar flow regimes and it is important to classify rivers into groups with similar flow regimes (flow classes) (McManamay *et al.,* 2012a). In the following analysis, the types and intensity of regionally anomalous flow features are identified in each of a sample of 16 regulated river sites in Canada selected by the HydroNet research Network (more on this network below). Specifically, an analytical technique is presented to identify the flow regime features at regulated sites that are significantly different from the range of observed natural variability within unregulated rivers in the relevant regional flow class (or river type class). We also discuss the potential biological implications of the dominant flow anomalies in this set of rivers regulated by hydro dams. Finally, we explore a method to reduce the dimensionality of the regional anomalies identified in this set of regulated rivers as a means to identify a small set of hydrologic measures that can be used to test flow-ecology relationships across these sites.

Chapter 2: Literature Review

Flow regime is widely considered the most important determinant of riverine ecosystem structure and function; the 'master variable' of ecosystem health (Poff *et al.,* 1997). In this literature review we first explore how flows physically shape riverine environments from a geomorphological perspective. We then outline several known dependencies linking riverine fish ecology to various flow regime features and describe some of the mechanisms behind these complex relationships. This review highlights a range of ecological responses to changes in river flow regimes; this is not surprising considering the diversity of riverine habitats, of natural river flow regimes and of biotic communities in lotic systems. We then proceed to highlight different ways in which flow is altered by hydroelectric regulation and we summarize general patterns of flow alteration by dams. We also describe the classic methods through which regime alteration is quantified or characterized, and discuss new methods proposed that provide tools to manage regulated flow regimes at a regional scale through the identification of acceptable ecological limits to hydrologic alteration. As a basis for our study which covers sites in both eastern and western Canada, we also review some patterns of natural flow regimes across Canada.

Geomorphological Impacts of Flow Regimes and Examples of Ecological Outcomes of Flow Alteration

A river's flow regime drives various physical processes that create heterogeneous habitat types (Tockner *et al.,* 2000). The physical structure of the wetted river habitat is shaped by high flow levels: in alluvial channels in Canada, floods that recur every two to five years are responsible for channel dimensions, reach scale bed material composition, substrate mobility levels and sediment transport patterns (Poff *et al.,* 1997; Church, 2002). In free flowing alluvial systems, high flows mobilize the river bed and recruit sediment input from the banks. Winter ice-jams can also lead to river bed or bank scouring, especially in steep river reaches with incomplete winter ice cover formation. This leads to open water frazil ice formation and consequent ice jamming in low slope reaches (Church, 1995). Winter flow regime alteration can thus alter ice

cover regime and ice jamming patterns with, in some cases, sizable geomorphological effects on pools and riparian zones.

Lotic life cycle patterns are set by the natural flow regime of a river as the latter controls locations of preferred feeding and refuge habitats for various benthic invertebrate and fish fauna. Habitat access and quality reflects in complex ways the variable patch and reach scale depth and velocity patterns and flow timing features (e.g. Riis and Biggs, 2003; Baranyi *et al.,* 2002). The 'Natural Flow Paradigm' postulates that river biodiversity and evolutionary potential is best served by maintaining the full range of natural flow variability (annual, seasonal and event-based scales) (Black *et al.*, 2005; Poff *et al,.* 1997; Richter *et al.,* 1997; Olden and Poff, 2003). Notably, ecological outcomes of altered flow regimes can be considerably different between sites since no two rivers are the same. At the population level, native fish and other river biota are selectively adapted to a river's particular flow conditions. Not only do flows physically shape the channel, flow regime determines the volumes of wetted habitats, influencing competition and support capacity as well as ease of predation. Seasonal flow regimes also determine lateral and longitudinal connectivity across river habitat types, such as backchannels or riparian zones that are used at different life history stages, and also affect migratory cues in response to particular flow magnitudes (Junk *et al.,* 1989; Poff, 1997). The following case studies document observed ecological outcomes of flow alteration by dams and exemplify the range of ecological outcome that can occur following regulation. The purpose here is not to review this wide topic but to give select examples of how different features of flow regimes and different biota interact. Extensive reviews on this subject also exist (e.g. Poff and Zimmerman, 2010).

Ligon *et al.* (1995) found that chinook salmon (*Oncorhynchus tshawytscha)* populations in the McKenzie River decreased by 50% following the construction of two dams on the main channel in the 1960s. The mechanism primarily driving this decline was the loss of island backchannel spawning habitat. The main channel's bed material was too large for the digging of redds, while

the suitable spawning habitat disappeared when floods were reduced by the dams and the majority of backchannels with smaller substrate between islands were abandoned.

Reduced range of flow magnitude (higher annual baseflows and dampened high flows) has led to reduced species richness, greater success of non-native species, altered assemblages, and encroachment of riparian vegetation (Poff and Zimmerman, 2010). Poor recruitment of indigenous riparian vegetation allows invasive trees to proliferate (Stromberg *et al.,* 2007) and non-native, flood intolerant fish species will increase in prevalence (Meffe, 1984). Poff and Zimmerman (2010) found that macroinvertebrate abundance and diversity both generally declined in response to altered magnitudes. Fish also showed consistent negative response to significant magnitude anomalies (however there is a lack of data for documented responses to moderate flow alteration) (Poff and Zimmerman, 2010).

Riparian cottonwood forest, one of the most extensive deciduous forest ecosystems along rivers in arid regions of the Western United States, are threatened by flow alteration and channel degradation (such as channel simplification (Ligon *et al.,* 1995)) in part caused by dams (Lytle and Merritt, 2004). This exemplifies the sensitivity of riparian plant species to changes in natural flow behaviour. Most commonly, birds and other forest fauna face habitat loss following dam construction potentially resulting in species extirpation. Gill (1973) discussed the ecological importance of the edge habitat for northern Canadian wildlife in his documentation of plant succession following point bar growth in the Mackenzie River Delta. The naturally diverse communities of water tolerant species close the river's edge and conifers further inland can change significantly when the timing or volume of flooding is altered by development. Prolonged low flows can dewater floodplain vegetation and shift riparian species composition towards more drought resistant species (Leenhouts, Stromberg and Scott, 2006). Under these conditions, fast flow specialist fish populations may also decrease and be replaced by habitat generalists (Freeman and Marcinek, 2006).

Mims and Olden (2012) tested the ecological theory suggesting that several specific flow regime features (specifically 'variability' (aka flashiness), predictability, and seasonality) are important determinants of the life history composition of fish assemblages in a river. In theory, hydro dam operations can alter each of these key flow dimensions in different directions (although hydro dams are often associated with increased flashiness, increased predictability, and decreased seasonality (Zimmerman *et al.,* 2010)). Using long term discharge data and fish trait survey data for 109 streams in the USA, Mims and Olden (2012) found that 11 out of 18 sites (61%) strongly supported a priori hypotheses relating selected flow indices reflecting variability, predictability, and seasonality to the relative prevalence of species of 3 separate fish life history strategies: opportunistic, periodic and equilibrium. The ecological theory that they tested postulates that increased flow variability and decreased predictability between years benefits species with opportunistic life history strategies (characterized by short generation time and high juvenile survivorship and low fecundity), especially when flows are stable throughout the year (decreased flow seasonality). When flow variability is low and flows are predictable, equilibrium species tend to flourish (characterized by long generation time and low juvenile survivorship and low fecundity) especially when seasonality is not pronounced. When flow seasonality is pronounced in a system, conditions are best suited to species with a periodic life history strategy (characterized by high fecundity) (Mims and Olden, 2012). When high flows become more frequent (increased flashiness), macroinvertebrate communities shift towards species adapted to high mortality rates, in turn altering food sources for fish species (Richards *et al.,* 1997). Changes in seasonality of river flows has also been associated with aseasonal reproduction or reduced reproduction, reduced abundance or extirpation of native fish, and decreased richness of endemic or sensitive species (Poff and Zimmerman, 2010).

Types of Flow Regulation Associated with Hydropower

An advantage of hydropower over other renewable energy sources such as wind and solar is that potential energy can be stored as water volume in reservoirs and (contrary to nuclear power output which can only be varied slowly) hydroelectric power output can be modulated almost instantaneously (by opening or closing individual turbines at a powerhouse) in response

to variable grid demand. However the amount of possible water (and thus hydro-energy) storage in reservoirs varies dependent on reservoir volume, constrained by the height of the dam and shape of the river valley. To simplify we will distinguish here three types of hydro regulation. Run-of-the-River (ROR) facilities have very small reservoirs (relative to annual flow volumes at the site), and thus have limited (if any) influence on the river's flow regime. In contrast, large storage facilities with large reservoirs are capable of retaining a much larger fraction of the total annual flow passing the facility (with longer mean residence times) and are operated in ways that significantly attenuate high flows and increase low flows below the dam, usually with the aim of producing more constant levels of 'base load' power. In contrast, hydropeaking regulation refers to rapid (hourly-scale) variation in releases of water through the powerhouse (reflecting the varying number of turbines put in operation) to generate electricity in response to hourly variations in market demand and meet 'peak demand' levels (Moog, 1993). Hydro peaking operations usually require a reasonable level of reservoir storage and thus often imply attenuation of seasonal high flows. However, contrary to base power storage facilities, in peaking stations the hourly flow variability and annual flashiness aspects of the flow regime (characterized by increased rise and fall rates and number of flow reversals over weeks and months) are most strongly altered (Moog, 1993).

The existing literature on flow alteration by hydropower informs us that hydro dams tend to reduce maximum flows, reduce flow variability (i.e., the range between highest and lowest flows), and reduce rise rates (with the exception of peaking stations), while increasing minimum flows and number of flow reversals per year (Poff *et al.,* 2007; McManamay *et al*., 2012a). Poff *et al.,* (2007) refer to the dampened seasonal and inter-seasonal streamflow variability as a homogenization of flows. However McManamay *et al.* (2012a) nuanced this generalisation that dams homogenize flows. They found that in the South-Eastern United States, some flow regime variables, specifically monthly and seasonal flow magnitudes as well as flow predictability, were altered differently across dammed sites, but were modified in similar ways within classes of rivers defined at the zoographic region and river type scale. Such a regional approach will be followed in this thesis.

Next we review the different approaches used to estimate flow alteration.

Characterizing Flow Alteration or Regional Flow Anomalies

Historically, mode and intensity of flow alteration by dams have been identified by estimating the values of a broad set of ecologically relevant flow indices. These indices are conventionally calculated and contrasted from multi-decade pre-dam versus post-dam flow records, assuming such pre-dam records are available (e.g. Richter *et al.,* 1996). The broad suite of flow regime indices (or flow regime metrics) used relate to five general classes of flow regime features: flow magnitude, frequency, duration, timing and rate of change (Poff *et al.,* 1997)). Such a multi-metric approach to 'environmental flows' emerged from the recognition that, beyond simple minimum flow requirements, a number of features of the naturally variable flow regime should be maintained to sustain the integrity of freshwater ecosystems (Poff *et al.,* 1997; Bunn and Arthington 2002; Postel and Richter, 2003; Biggs *et al.*, 2005). In a regulated river, flow anomalies can be apparent in one or many dimensions of the flow time series compared to the reference class norm (a set of regional naturally flowing rivers characterized for the sake of comparison). In general, flow regime alteration is thus a vector (as various aspects of the regime are altered to various degrees) not a single scalar quantity. Indeed, one of the main challenges in applying the Natural Flow Regime paradigm to flow management in the light of the proliferation of possible flow indices is to reduce the dimensionality of this problem (Olden and Poff, 2003).

The most widely used sets of flow regime indices are the Nature Conservancy's Indicators of Hydrologic Alteration (IHA) (Richter *et al.,* 1996) and the United States Geological Survey's (USGS) Hydrologic Index Toolkit (HIT) (Olden and Poff, 2003), which includes a few hundred indices, among them the IHA indices. It is conventionally recognised that Indices in these large sets can be highly correlated with one another (specific correlations depending on the input data) and some indices should be removed to reduce redundancy and the chance that certain components of the flow regime are over-represented in statistical analyses and thus dominate

ordination and classification of sites, while other flow features are underweighted or overlooked (Olden and Poff 2003; McManamay *et al.,* 2012a).

Due to hundreds of often partially redundant flow indices characterizing flow regime alteration, a first challenge is thus to choose and format an appropriate set of regimes metrics to quantify hydrologic alteration at study sites. In the usual absence of strong, a priori knowledge of responses of local biotic communities to all the various dimensions of flow regime, various approaches are used. Pluckridge *et al.* (1998) support inclusion of a large suite of flow indices to characterize flow alteration. In regional hydrologic alteration analyses, Poff *et al.* (2010) suggest using individual flow indices of identified ecological importance; expressing these indices as percent deviation from the pre-damming baseline condition. However, some form of redundancy analysis is generally used to reduce the dimensionality of the problem. For example, Olden and Poff (2003) used principal component analysis (PCA) to explore the collinearity of the flow indices and found that the technique provides important insight into flow class behaviour. However they note that the top components of flow regime variance (the Principal Component axes) will differ depending on the systems being evaluated, scale of the analysis and time frame of the analysis.

Setting Allowable Thresholds for Flow Alteration

After choosing appropriate flow indices representative of the ecologically relevant hydrograph features to be explored, Richter *et al.* (1996) proposed identifying the natural range of variability in any given index (usually across years of a long flow record for a regulated site including a number of years prior to regulation), and then setting environmental flow regulations for dam operators that attempt to remain within some fraction (or small multiple) of standard deviations of the natural variability in key indices. This simple, range of variability approach is appealing. This is because transferable and empirically based, hydro-ecological relationships useful to prescribe acceptable flow regime alteration based on observed biotic responses are elusive, as ecological relations are expensive to acquire and can be highly site specific and confounded (Black et al., 2005). Setting natural range of variability targets based on

the variability in pre-dam natural flows means that intensive scientific efforts are not required below each dam (although further biological validation of this method remains necessary). However, in Canada pre-dam discharge data is often lacking, leading scientists to explore other methods to quantify flow alteration below dams.

Based on an understanding of the range of hydrologic features affecting ecosystem structure and function amassed from individual river studies, there is a current scientific consensus supporting the development of environmental flow standards at the regional scale (Poff *et al.,* 2010). Poff *et al.* (2010) advocate the implementation of regional environmental flow standards to protect biodiversity and evolutionary potential. They suggest that functional relationships between flow alteration and ecology defined at the zoogeographic region and river type scale are most apt to influence environmental regulations and management decisions, and thus are the effective units of analysis for setting Ecological Limits of Hydrologic Alteration (ELOHA) (Poff *et al.,* 2010). These units of analysis at the zoogeographic region and river type scale have also been called flow regime types/classes (or flow classes), and are becoming increasingly common in the hydrological literature.

ELOHA postulates that functional relationships between flow alteration and ecology defined at the zoogeographic region and river type scale are most likely to influence environmental regulations and management decisions (Poff *et al.,* 2010). The degree of anomaly that exists at a regulated site with respect to the natural range of flow behaviour in the region can be more significant to predicting ecological impacts than an estimation of site specific flow alterations based solely on the pre-impacted regime of that particular system. Regulation may materially alter certain flow regime characteristics on a dammed system, but the new regime may still behave within the range of natural flow behaviour for the region that supports productive ecosystems. This is why McManamay *et al.* (2012a) and others compared indices from altered regimes to the range of index variability within the natural flow regime class within the same period (in effect, comparisons are made over space and across multiple regional sites instead of through time at one site as proposed by Richter *et al.* (1996)). To avoid confusion, in this thesis

we describe post-dam flow features outside regional norms as 'flow anomalies', while reserving the term 'flow alteration' for instances where pre-dam discharge records were used to identify changes in the post-dam flow regime. As advocated by Acreman and Dunbar (2004), Booker and Acreman (2007) and Poff *et al.* (2010), an analysis of flow regime anomalies at regulated rivers in comparison to the range of variability in its river type and region should provide sufficient certainty to support management decisions at broad, regional scales while avoiding unnecessary expense and effort at individual sites.

Flow Classes

McManamay *et al.* (2012a) describe flow classes as "groups of streams that share similar natural hydrology; thus, they provide a stratified approach to evaluate hydrologic alterations or departures from natural baseline conditions." They found regional flow classes to be effective units of analysis in their study of hydrologic alteration throughout the Eastern U.S.A. Flow classes are groups of unregulated rivers that share hydrologic (flow regime) properties and are representative of the regional baseline range of conditions; they provide the template for ecological processes and habitat characteristics as well as micro-adaptation of native and invasive species (Poff, 1996; Lytle and Poff, 2004; Arthington *et al.,* 2006; Poff *et al*., 2006; Poff *et al.,* 2010). Flow classes were first used, to our knowledge, as hydrologic units of analysis by Poff and Ward (1989) when they categorized flow regimes across the United States into nine types and arranged them in a conceptual model along axes related, in order, to flow intermittency, variability and predictability. They argued that this type of categorization would provide a context for lotic environments to be viewed objectively, aiding the generation of a priori hypotheses about biotic impacts (Poff and Ward, 1989). Other authors have advocated the utility of this regional approach in recent years (e.g. Kennard *et al.,* 2010; McManamay *et al.,* 2012a). Arguing against 'over splitting' in regime classifications, Poff *et al.* (2010) advocate using a small number of broad river classes (types) that capture the major dimensions of stream flow variability so that the results can be practical to management. Broader flow classes imply a greater range of flow regime variability within a given class and thus potentially more conservative identification of regime anomalies at regulated sites.

A method used to assign regulated sites to reference flow classes that does not require parameter rich routing modelling to generate pre-damming synthetic hydrographs or reliance on pre-dam discharge data (that may be unavailable or that fail to account for decade scale climatic changes) is the use of discriminant function analysis based on watershed characteristics. By assigning regulated sites to flow classes over a common set of decades based on landscape characteristics and geographic location (as done by Poff, 1996; Poff *et al*., 2006; McManamay *et al.,* 2012a), anomalous flow features can be identified (unusual deviations in regulated systems within their regional reference context). Kennard *et al.* (2010), in Australia, and McManamay *et al.* (2012c), in the U.S. at a finer scale, have both used linear discriminate function analyses to develop functions that assign watersheds to flow classes (derived from hydrologic data only) using physical and geographic attributes only. If regulated rivers can be assigned to unregulated flow classes based on landscape characteristics, the rivers composing the unregulated class are appropriate hydrologic reference systems for the regulated site (Kennard *et al.,* 2010; McManamay *et al.,* 2012c).

The driving principal behind the ELOHA approach is that there is a need for a framework for assessing environmental flow needs for many rivers simultaneously to foster development of regional environmental flow standards (Poff *et al.,* 2010).The logic of this framework suggests that the degree of anomaly that exists at a regulated site with respect to the natural range of flow behaviour in the region may practically be more significant to predict impacts than an estimation of site specific flow alterations based on the pre-impacted regime of the one particular system. Regulation may materially alter certain flow regime characteristics on a dammed system, but the new regime may still behave within the range of natural flow behaviour for the region that supports productive ecosystems. Results from an analysis of flow regime anomalies at regulated rivers when analysed by river type and region should provide sufficient certainty to support management decisions at broad, regional scales while avoiding unnecessary expense and effort at individual sites (as advocated by Acreman and Dunbar, 2004; Booker and Acreman, 2007; Poff *et al.,* 2010). A secondary benefit to this regional comparative

approach is that for many regulated rivers, decade-scale pre-dam flow records are unavailable, from which before-after indices can be compared, and it is time consuming (and potentially inaccurate) to develop synthetic pre-regulation hydrographs as a basis for determining site specific regime alteration (as done by Black *et al.*, 2005), especially when analyzing a large number of regulated watersheds across many regions.

Regional Flow Regime Classifications across Canada

To date, flow classes have been used to characterize flow regime types in Canada but not to the same extent as in the United States. In an analysis of climate and hydrologic variation over time across Canada, Whitfield and Cannon (2000) distinguished between four types of natural Canadian hydrographs (based on five day average discharge from 650 gauges across the country). The dominant regime types of Canadian rivers were found to be driven by snowmelt runoff. Two of the four regime types (or flow classes) described these systems; differentiated from one another in that one class experienced high flows that began later in the spring and lasted longer into the summer. Coastal rivers in British Columbia exhibited a clear rainfall driven pattern whereas southern Ontario and Nova Scotia systems were seen as driven by mixed rain and snow processes (Whitfield and Cannon, 2000). As a precursor for an analysis of trends in flow indices over time across Canada, Monk *et al.* (2011) used weekly discharge data for all of the Reference Hydrological Basin Network (RHBN) systems, which are considered to have truly natural flow regimes and are therefore appropriate as natural reference systems for comparison purposes, to determine regime based groups of Canadian rivers. They differentiated between 6 regime types (flow classes) across the country; largely dependent on the timing of each system's annual flood.

NSERC's HydroNet River Study Sites

The context for this analysis is a bio-physical study of fish populations and physical habitat in a set of 16 sites on rivers that are regulated for hydro production. This effort spans various regions of Canada and is part of a research program initiated in 2010: the Canadian NSERC-HydroNet research network. This study of flow regime anomalies is only one component of

HydroNet at these sites. The long-term objective of the HydroNet program is to apply science based management to damming regulation, as knowledge gained about thresholds of ecological response to varying degrees of flow alteration at a network of sites below Canadian dams is applied to other Canadian systems in lieu of data intensive monitoring at an increasing number of sites. For more details about NSERC's HydroNet, see Smokorowski *et al.* (2011).

Many core criteria for HydroNet regulated and reference site selections were practical: rivers had to be small enough and accessible enough to be extensively sampled for fish abundances using electrofishing. Most study sites ultimately selected have drainage areas between 500 and 2000 km^2. For budget reasons, and given field work requirements across various HydroNet projects, sites located in northern Canada or otherwise having poor road access were excluded. The 16 regulated sites were also selected to include a range of types of regulation, including run-of-the-river-type (ROR) operations as well systems with larger capacity reservoir storage allowing significant cross-season flow shifting, with or without hydropeaking (where the volume of water released through the turbines is hourly dependent on grid power demand (Moog, 1993)). Selected rivers also had to have been dammed for at least 3-4 decades. Selected HydroNet study sites are distributed across 3 regions of southern Canada with contrasting physiography and climate (Rocky Mountain rivers in Alberta and BC; Eastern Canadian Shield rivers in central Ontario and Quebec and Lowland or Appalachian rivers in southern Quebec and central New Brunswick). Unfortunately for our study of flow alteration, at most selected HydroNet sites flow monitoring was initiated at the same time as hydro-development so that little or no pre-damming flow records were available on study river segments.

Chapter 3: Objectives of Results Chapters

Chapter 4

In a similar vein as that of McManamay *et al.* (2012c), our general objective in Chapter 4 is to classify a large set of unregulated rivers from HydroNet regions into groups based on flow regime type (into 'flow regime classes'). Specifically we aim: (1) to classify 96 selected unregulated (reference) gauged rivers selected to be of similar sizes and geographically proximal to the 16 regulated (dammed for hydro-power) HydroNet rivers distributed in eastern and western Canada into regional flow classes (and characterise the main differences between these classes). These flow classes aim to be representative of the normal variability of regional, natural flow regimes for watersheds of selected characteristics; and (2) to assign, based on geographic and physical watershed characteristics, the regulated rivers to appropriate flow classes representative of the range of regional regime norms for such rivers before regulation. The next chapter in this thesis makes use of the resulting flow classes as units of analysis to detect the strongest anomalies in the regulated systems, when compared to regime norms within its assigned class. Deviations from regional flow class norms at each regulated site (i.e. significant flow index anomalies) can thus be identified and quantified.

Chapter 5

In Chapter 5, our overall objective is to arrive at estimates of flow regime anomalies at HydroNet regulated sites based on observed clear deviations from natural flow variability within appropriate unregulated regional flow classes. Using principal component analysis and hydrograph visualization, we also aim to reduce the dimensionality of anomaly measures (given the large number of anomalous but inter-correlated flow metrics). We also aim to link the main anomaly components to the type of hydro operation to which these rivers are subjected (storage, peaking, and ROR). Our specific objectives are (1) to identify the features of the regulated flow regimes at regulated HydroNet sites that are most anomalous compared to the appropriate regional flow class reference norms defined in Chapter 4, (2) for each regulated river, to classify and differentiate between anomalous flow features (indices) that are related to

seasonality or timing (and thus have the a-priori potential to clash with regional life history strategies) and (3) to draw a general picture of the main axes of flow regime feature anomalies across all regulated HydroNet sites in Canada. In this thesis we both test and present a methodology that can be applied elsewhere (for example within an ELOHA framework (Poff *et al.,* 2010)), and identify and describe particular flow regime anomalies in the regulated HydroNet rivers that, based on theory and previous studies, may have implications for fish at the community and population levels.

Chapter 4

Selecting Regional Reference River Systems for the Identification of Flow Anomalies in Regulated HydroNet Rivers

Fraser McLaughlin & Michel Lapointe

1. Introduction

Each riverine ecosystem is unique and dynamic. A river's flow regime is known to be an important driver of ecological integrity (Poff *et al.,* 1997). The ecologically important features of a river's flow regime are summarized by sets of hydrologic indices that describe the magnitude, frequency, duration, timing and rate-of-change of flow events (Poff *et al.,* 1997). The most widely used sets of indices are the Nature Conservancy's Indicators of Hydrologic Alteration (IHA) (Richter *et al.,* 1996) and the United States Geological Survey's (USGS) Hydrologic Index Toolkit (HIT) (Olden and Poff, 2003), which includes the IHA. Indices in these sets can be highly correlated with one another (specific correlations depend on the input data) and some indices should be removed to reduce redundancy and the chance that certain components of the flow regime dominate analyses while other flow features are overlooked (Olden and Poff 2003; McManamay *et al.,* 2012a)

After dam construction, river flows are regulated by dam operators. In this analysis regulated sites refer to any gauged river location downstream from a dam. The degree of flow alteration that occurs after regulation depends on the physical characteristics of the dam (i.e. dam height and reservoir volume limit the amount of water that can be retained) and mode of operation (e.g. many operators are obliged to keep ramping rates (increasing flows) below a threshold). To generalize, dams tend to reduce maximum flows, flow variability, and rise rates, while increasing minimum flows and number of flow reversals per year (Magilligan and Nislow, 2005; McManamay *et al.,* 2012a). However, these alterations may occur to varying degrees if at all. Historically these alterations were identified by comparing the range of magnitudes of flow indices calculated from pre-dam versus post-dam flow records (Richter *et al.,* 1996), but presently there is a shift away from such site specific efforts.

Based on an understanding of the range of hydrologic features affecting ecosystem structure and function amassed from individual river studies, there is a scientific consensus supporting the development of environmental flow standards at the regional scale (Poff *et al.,* 2010). Poff

et al. (2010) advocate the implementation of regional environmental flow standards to protect biodiversity and evolutionary potential. They suggest that functional relationships between flow alteration and ecology defined at the zoogeographic region and river type scale are most apt to influence environmental regulations and management decisions, and the basis for setting Ecological Limits of Hydrologic Alteration (ELOHA) (Poff *et al.,* 2010). The degree of anomaly that exists at a regulated site with respect to the natural range of flow behaviour in the region is more important to predicting impacts than an estimation of site specific flow alterations based on the pre-impacted regime of that particular system. Regulation may materially alter certain flow regime characteristics on a dammed system, but the new regime may still behave within the range of natural flow behaviour for the region that supports productive ecosystems. This is why McManamay *et al.* (2012a) and others compared indices from altered regimes to the range of index variability within the natural flow regime class within the same period (i.e. over space at multiple sites instead of through time at one site as advocated by Richter *et al.* (1996)). We consider flows outside regional norms 'flow anomalies' while reserving the term 'flow alteration' for instances where pre-dam discharge was used. Results from an analysis of flow regime anomalies at regulated rivers when analysed by river type and region should provide sufficient certainty to support management decisions at broad, regional scales while avoiding unnecessary expense and effort at individual sites (as advocated by Acreman and Dunbar, 2004; Booker and Acreman, 2007; Poff *et al.,* 2010).

McManamay *et al.* (2012a) describe reference 'flow classes' as "groups of streams that share similar natural hydrology; thus, they provide a stratified approach to evaluate hydrologic alterations or departures from natural baseline conditions" (i.e. anomalies). Although streams in close geographic proximity often share similar climate, landscape and thus flow characteristics, streams should not be managed based solely on their location but primarily on shared hydrologic properties (McManamay *et al.,* 2012a). Using flow classes as units of analysis is also ideal for instances where some regulated systems are lacking pre-disturbance flow data, which is the case with HydroNet sites.

In this first results chapter, our specific objectives were: (1) to classify 96 unregulated (reference) rivers geographically proximal to regulated HydroNet rivers across Canada into flow classes representative of environmental flow norms, and characterise the differences between the classes; and (2) to assign the regulated rivers to flow classes based on pre-damming geographic and physical watershed characteristics. The second results chapter in this thesis (Chapter 5) makes use of these resulting flow classes (from objective 1) as units of analysis to understand patterns of anomaly in the regulated systems assigned to each class (from objective 2). Deviations from regional flow class norms can thus be identified and quantified.

2. Methods

2.1 Outline of Procedures

The statistical procedures in this chapter follow the general approach and guidelines presented by McManamay *et al.* (2012a, 2012b, 2012c). This chapter sets the framework for flow anomaly characterization in the absence of pre-dam discharge data that is pursued in subsequent chapters. First, discharge data was obtained for unregulated rivers of similar watershed size to the previously established set of HydroNet regulated rivers across the study regions. Flow indices (predominately drawn from the HIT (Olden and Poff, 2003)) were calculated using the statistical software package R and subsets of highly correlated flow indices were permanently removed from the analysis. K-Means Clustering analysis was then used to identify groups of unregulated rivers sharing similar hydrology across the country. Once flow classes were established, principal component analysis (PCA) was used to visualize the classes in multivariate Principal Component (PC) space in order to validate the K-Means clustering solutions and to gain insight into unregulated flow regime differences across HydroNet Regions. Finally, the regulated rivers were assigned to flow classes using Discriminant Function Analysis (DFA) based on watershed characteristics.

2.2 Data and Site Selection

The community of HydroNet researchers has chosen 16 sites on small and moderate sized regulated rivers (range of basin areas is: 50-5000km^2) across Canada to study impacts of hydro operations on fish habitat productivity. Selected sites were dammed between four decades and a century ago and regulated for hydro-power production (in most cases). HydroNet site selection was based primarily on regional distribution (Western Cordillera, Ontario and Quebec Shield, Quebec and New Brunswick Appalachian regions), general type of regulation (storage, peaking, ROR), as well as ease of river access and ease of fish sampling. We then identified in each region the maximum number of 'unregulated reference' rivers of a roughly comparable watershed scale (to minimize the effect of watershed size on flow indices) with publically available daily discharge data. Reference gauges are distributed within a radius of about 400km

from each regulated site (this distance was subjectively chosen as a limit when searching for unregulated gauges, but we also suppose that beyond this distance landscape and ecology will be increasingly different, while a smaller search radius would reduce sample size). Daily flow data at 96 reference and 16 regulated sites were obtained from the Canadian Hydrometric Database (HYDAT) (http://ec.gc.ca/rhc-wsc) and the Centre d'Expertise Hydrique du Quebec (CEHQ) (http://www.cehq.gouv.qc.ca)).

Both HYDAT and the CEHQ describe rivers as regulated if there are significant withdrawals or effects of urbanization, or if flow is altered by a dam. We only included rivers labelled as unregulated in this analysis of reference gauges. However, Monk *et al.* (2011) explain that rivers deemed unregulated by HYDAT or CEHQ do not necessarily have 'natural' flow regimes. In Canada only the Reference Hydrological Basin Network (RHBN) rivers are truly believed to be unregulated (because land use change has been less than 5% of the watershed area), but using only these systems would have drastically reduced our sample size. Thus, for the purposes of our analysis, gauged watersheds are deemed unregulated if they have no dams along their main stem or large tributaries and are considered unregulated in hydrological databases. The following analysis thus includes the effects of extant land use changes in the reference watersheds on 'unregulated' flow regime variability within a region, with respect to which regulated flow regimes below dams are contrasted.

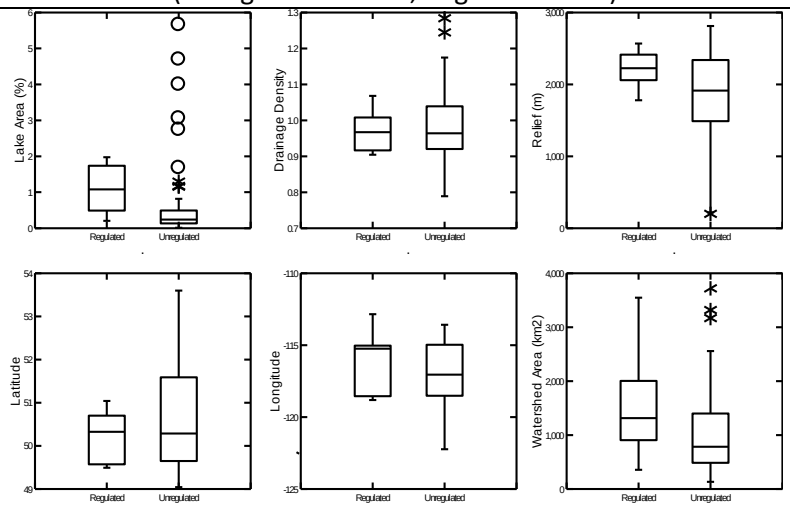
Kennard *et al.* (2010) claim that 15 years of hydrologic data suffices for detecting differences in variables summarized across flow records. Although a shared data period is not always seen as necessary for flow comparisons, we analyzed time series flow data from a shared 1995 – 2009 period to reduce the effect of climatic variability on subsequent analyses. In the end, 96 unregulated rivers deemed appropriate references for the 16 regulated sites were identified across the HydroNet regions of Canada.

A simple set of physical watershed characteristics were extracted for each gauge site: drainage density, percent lake area (minus the reservoir area in regulated sites), total watershed relief

and gauge latitude and longitude. The objective here was not to use these characteristics to explain flow regimes in detail at study sites, but instead to provide insight into some of the landscape features influencing reference flow metrics. More importantly, these physical watershed characteristics were used to assign regulated sites to the appropriate regional unregulated flow classes using discriminant function analysis (explained below) (McManamay *et al.,* 2012b). This relatively small number of watershed characteristics proved sufficient for these purposes.

For the 96 unregulated and 16 regulated gauge sites, watersheds were delineated using the Hydrologic Toolbox (ARCGIS 10) and digital elevation models (DEMs) with approximately 20 by 20m resolution (minimum of 0.75 arc seconds to a maximum 3 arc seconds) acquired from GeoBase's Canadian Digital Elevation Data (GeoBase, 2000). Drainage density was calculated using flow accumulation grids with pixels accumulating water from >1000 pixels set to river pixels. Although some uncertainty exists in the values obtained, the fact that the same techniques were systematically employed makes the results appropriate for our purposes. CanMap Water shapefiles (DMTI, 2012) were also used to calculate the total lake area per watershed (water polygon area minus apparent river polygons (denoting wide river reaches)). Percent lake area coverage was then calculated in each watershed (apparent reservoir coverage was not included as lake area in the regulated watersheds). Our relief index is the difference in elevation from the highest to the lowest pixel in each watershed (GeoBase, 2000). Latitude and Longitude at gauge station were used as simple proxies for climate regime (based on geographic location). The distributions of these watershed characteristics and watershed areas are shown in Figure 1 for Eastern and Western Canada grouped by system type (regulated versus unregulated).

Western Canadian Watershed Characteristics (British Columbia and Alberta)
(Unregulated n = 51, Regulated n = 6)



Eastern Canadian Watershed Characteristics (Ontario, Quebec and New Brunswick)
(Unregulated n = 45, Regulated n = 12)

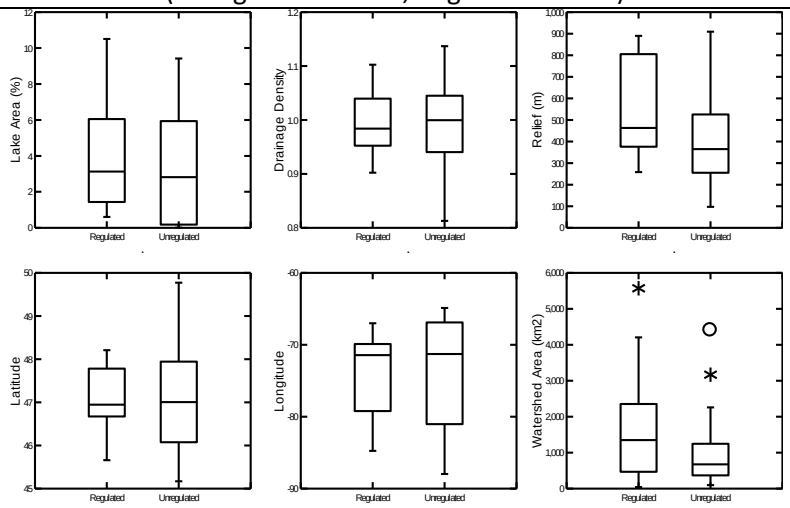


Figure 1. Distributions of watershed characteristics (percent lakes, drainage density, relief, latitude longitude and watershed area) for Eastern and Western Canada grouped by system type (regulated versus unregulated). The asterisks show outliers beyond the inner fence (1.5*Inter Quartile Range (IQR)) and circles are outliers beyond the outer fence (3*IQR).

For a subset of the unregulated rivers and for most of the regulated systems, hourly discharge data was also acquired. This allowed us to further explore sub-daily flow regime characteristics in some cases (this is of notable importance for the peaking systems).

2.3 Calculating Flow Indices and Reducing Index Redundancy

The Hydrologic Index Tool (HIT) consists of 171 widely used flow indices, recommended by the U.S. Geological Survey (USGS) (Olden and Poff 2003). These include the 33 proposed as the indicators of hydrologic alteration (IHA) by Richter *et al.* (1997). By convention, they are classified into categories: magnitude, frequency, timing, duration, and rate of change (Olden and Poff, 2003). The set of metrics aims to explain all of the ecologically relevant components of the hydrograph. Using R, we calculated scores for all of these indices that require daily flow data plus 7 others indices from Steuer *et al.* (2010), resulting in 163 indices. As per McManamay *et al.* (2012b) all metrics expressed as discharge magnitudes were normalized by dividing by the median flow for the entire data record in order to further account for differences in watershed size.

In order to reduce the redundancy, we evaluated a correlation matrix between all 163 variables. Within metric categories (magnitude, frequency, timing, duration, and rate of change) variables with Pearson's $r > 0.75$ and $r < -0.75$ were identified and one variable was chosen to represent the group of correlates (McManamay *et al.,* 2012b). Following McManamay *et al.* (2012) we preferentially kept IHA variables (Richter *et al.,* 1997) or variables presented by Poff (1996). Beyond these criteria, indices were kept based on ease of understanding. Between flow categories, the $r > 0.75$ threshold was relaxed for select cases when the correlated indices described sufficiently different (a subjective decision) components of the hydrograph (e.g. both inter-annual variability across monthly flows (MA36) and normalized maximum 90-day moving average flow (DH5) were kept although they are correlated $r = 0.83$). McManamay *et al.* (2012b) used a similar technique, removing correlates with $r > 0.75$ within index categories, and then further removing highly correlated variables between categories (although they do not specify this threshold for removal). After this process, 70 flow indices remained. 25% of the indices remain correlated $r > 0.75$ with at least one other index and 50% of the 70 indices retain at least one other correlated metric in the set with $r > 0.65$. The list of 70 indices used for all subsequent analyses is included in Table 1 of Appendix 1 (p. 103).

2.4 Cluster Analysis of Unregulated River Flow Indices

Following McManamay *et al.* (2012b), we used K-means clustering to group unregulated rivers into flow classes using hydrologic indices. Indices were standardized (to zero mean and unit standard deviation) prior to clustering (McManamay *et al.,* 2012b). For this process, the user defines an initial number of cluster 'seeds' around which the grouping occurs. Cases are reassigned to different 'seeds' over many iterations (user specified) until the within-groups sum of squares can no longer be reduced (SYSTAT). The simple structure index (ssi) is an output from the vegan cascade KM function in R that allows the user to determine the optimal number of cluster groups based on input data. "Simple Structure Index combines three elements which influence the interpretability of a solution, i.e., the maximum difference of each variable between the clusters, the sizes of the most contrasting clusters and the deviation of a variable in the cluster centers compared to its overall mean. These three elements are multiplicatively combined and normalized to give a value between 0 and 1" (R cclust package). The best partition is indicated by the highest ssi value. Once clusters of rivers with similar flow regimes (flow classes) were identified, we ran principal component analysis (PCA) (described below) on the 70 flow metrics. Plotting the flow classes in PCA space allowed us to visualize and validate the effectiveness of the clustering solutions.

2.5 Characterizing Unregulated Flow Classes using PCA Space

PCA is used to reduce the dimensionality of a dataset. The original matrix is transformed into a much smaller matrix containing new variables. The new variables are the principal components, which are linear combinations of the original hydrologic indices. The first factor is defined such that it maximizes the explained variance of the data set (Daigle *et al.,* 2011).

We performed PCA (using SYSTAT) for two main reasons: for efficient data exploration, and as a means to effectively visualize and interpret a large amount of information. As done by McManamay *et al.* (2012a), flow classes identified by K-Means across the 2 Canadian regions (East and West) were plotted in three-dimensional multivariate space defined by the top three principal components (PCs). To identify the main axes of cross-region flow regime variance, we

ran a PCA for all of the unregulated rivers across the country on correlations of the 70 flow indices. To interpret these PCs, the indices loading each PCA axis were ranked, and the top five indices evaluated. PC loadings are the correlations between each original variables and the PC. For the rivers scoring highest and lowest on each PC axis (and as close to zero as possible on the other 2 of the 3 axes), hydrographs were evaluated to aid the interpretation of PC scores. Based on these interpretations, the axes were named. In doing so, a river's high or low PC score on an axis of interest suggests specific flow characteristics in that system. However, for a full understanding of each system's flow regime, scores of individual indices underlying a principal component must be considered (this concept is explored in Chapter 5 for the regulated systems).

2.6 Assigning Regulated Rivers to their Natural Unregulated Flow Classes for Comparison

Kennard *et al.* (2010), in Australia, and McManamay *et al.* (2012c), in the U.S. at a finer scale, have both used linear discriminant function analyses to assign rivers, using physical and geographic attributes only, to flow classes; the latter derived purely from hydrologic data. If regulated rivers can be assigned to unregulated flow classes based on landscape characteristics, the rivers composing the unregulated class are deemed appropriate hydrologic reference systems for the regulated site (Kennard *et al.,* 2010; McManamay *et al.,* 2012c). We used SYSTAT for this procedure. The data requirements were the watershed characteristics (described in Methods 2.2) for all regulated and unregulated systems, and the flow class assignment results from the K-Means process for the unregulated systems (Methods 2.4). As is usual, we weighted cases so that the discriminant functions (a coefficient and constant for each watershed characteristic) were derived using only the unregulated systems, but applied to both unregulated and regulated systems (the latter yielding class assignments). Posterior probabilities of each classification were calculated using Mahalanobis distances: "distances between cases we want to classify and the center of each group (class) in multidimensional space" (SYSTAT).

The goal of DFA is to find a linear combination of the measures that best classifies or discriminates among the flow classes. The Mahalanobis distances (D^2) are measures of distance and direction to the class mean on a canonical scores plot defined by the input measures (variables) (i.e. not simply a Euclidean distance, this measure accounts for ellipse shaped classes). The closer a case is to a particular mean, the more likely it belongs to that group. The output also provides p-values (posterior probabilities) for the distance of a case to a mean; these are the ratio of EXP(-0.5 * D^2) for the group divided by the sum of EXP(-0.5 * D^2) for all groups. Basically, the Mahalanobis distance is the distance of the test point from the center of mass divided by the width of the ellipsoid in the direction of the test point. In order to determine a threshold for effective classification based on these posterior probabilities, we examined all misclassified unregulated cases (some unregulated cases had watershed characteristics suggestive of alternate class membership) and noted the posterior probability values of these cases. We decided that if the regulated systems scored posterior probability p-values greater than the highest misclassified case, we were confident in the class assignment. Alternatively, in a minority of cases where the classification p-value did not surpass this threshold, the regulated case could not be assigned to a single flow class. In these cases, the regulated river was compared to the two possible candidate flow classes pooled together.

Since the unregulated flow classes are geographically distinct and there are no rivers in our dataset between Ontario and Alberta, we ran the discriminant analyses separately for the Eastern and Western systems, which have quite distinct river regimes. F-to-Remove values indicate the importance of each variable in the discriminating process (DFA can be run so that very low scoring F-to-Remove variables are removed from the analysis automatically) (SYSTAT). Since we only had to account for five variables, we ran the DFA multiple times and manually removed low scoring F-to-Remove variables until the Jackknifed classification was at least as effective (in terms of reducing misclassification) as the normal classification matrix. Once all regulated rivers were assigned to a class(es), the geographical proximity (distance in km) of each regulated river to each reference systems in its flow class was calculated.

3. Results

3.1 Flow Class Identification

Overall, this analysis included flow data from 1995-2009 for 96 unregulated rivers across the country. K-means clustering was used to identify multivariate similarities across numerous sites (cases). Appendix 1 Figure 1 (p. 106) displays the output from the cascadeKM (R package) ssi procedure. Although the ssi method suggests that 11 clusters is optimal given the data, in seeking a balance between group discrimination and a practical number of clusters to interpret results we chose to use 5 clusters. This solution scored the second highest ssi and increasing sample size for each class was preferable for interpretability. This means increased variability in the range of metric values within each unregulated class. It is also notable that the 11 group solution simply subdivides these 5 groups further. More importantly, it also means that the identification of atypical (outlier) flow metric values observed at regulated sites (the aim of the next chapter) is more conservative, as the regional reference comparison base is wider.

The dataset consists of rivers from five provinces: British Columbia, Alberta, Ontario, Quebec and New Brunswick. In the K-Means clustering solution for five groups, there is no overlap between western (B.C. and Alberta) and Eastern rivers (Ontario, Quebec, N.B.); no eastern and western site are assigned to the same flow class. Therefore the five flow classes identified by K-means are subsequently called: West1 (W1), West2 (W2), West3 (W3), East1 (E1) and East2 (E2). Figure 2 shows the locations of these classes across the country. The regulated HydroNet sites are also included on these maps.

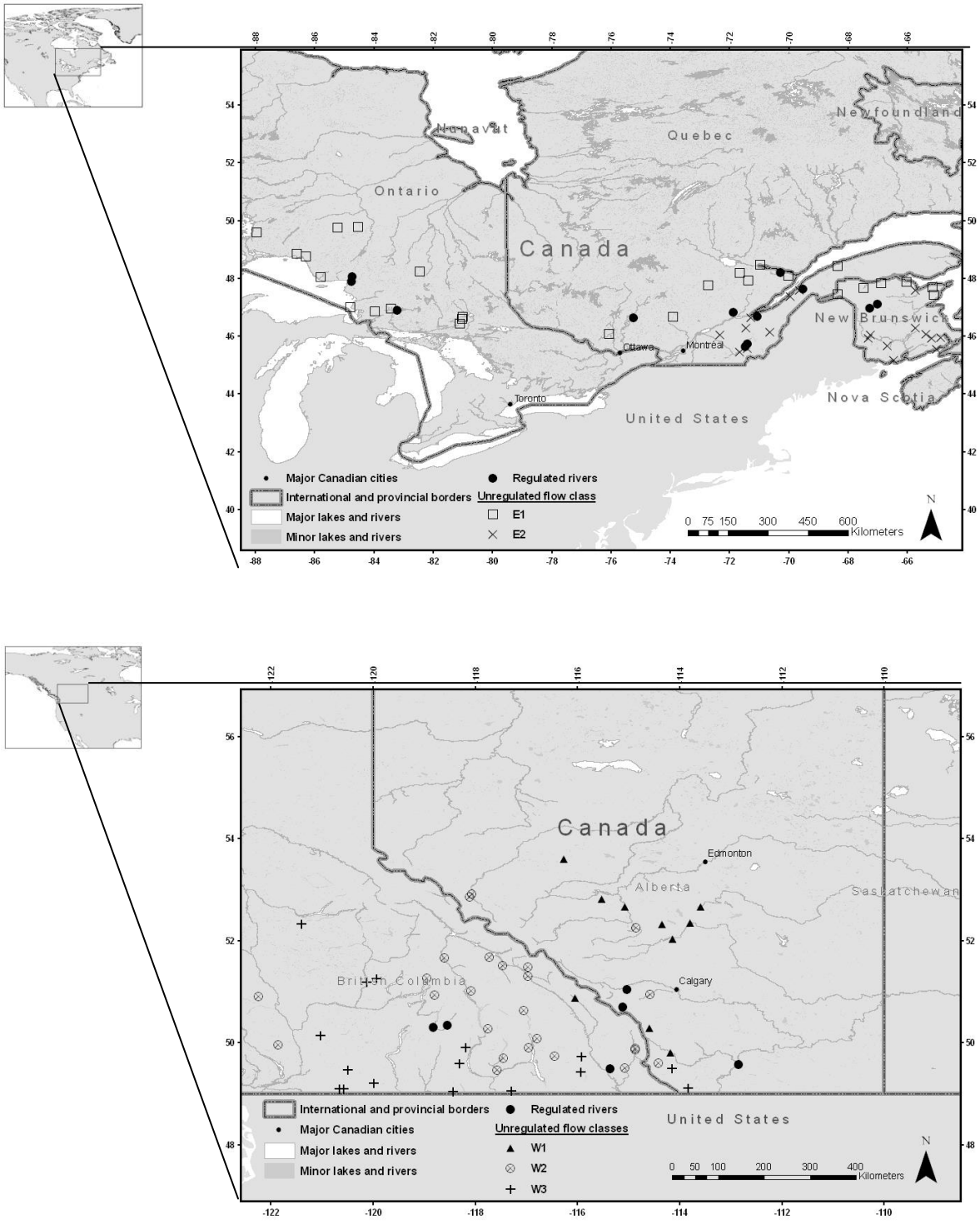


Figure 2 These maps display the unregulated sites sorted by flow class (outcome of K-means clustering) and the regulated HydroNet rivers.

The effectiveness of the clustering process was evaluated by plotting the rivers grouped by flow class in three dimensional principal component space (Figure 3). Rotated to best display the

differentiation of the classes, it is evident that the flow classes identified using K-means clustering are distinguishable groups in PCA space. The top three principal components from the Canada wide unregulated analysis explain 23.9%, 15.6% and 10.5% of the total variance of the 70 flow indices. The five flow classes identified in this process were used for all subsequent analyses.

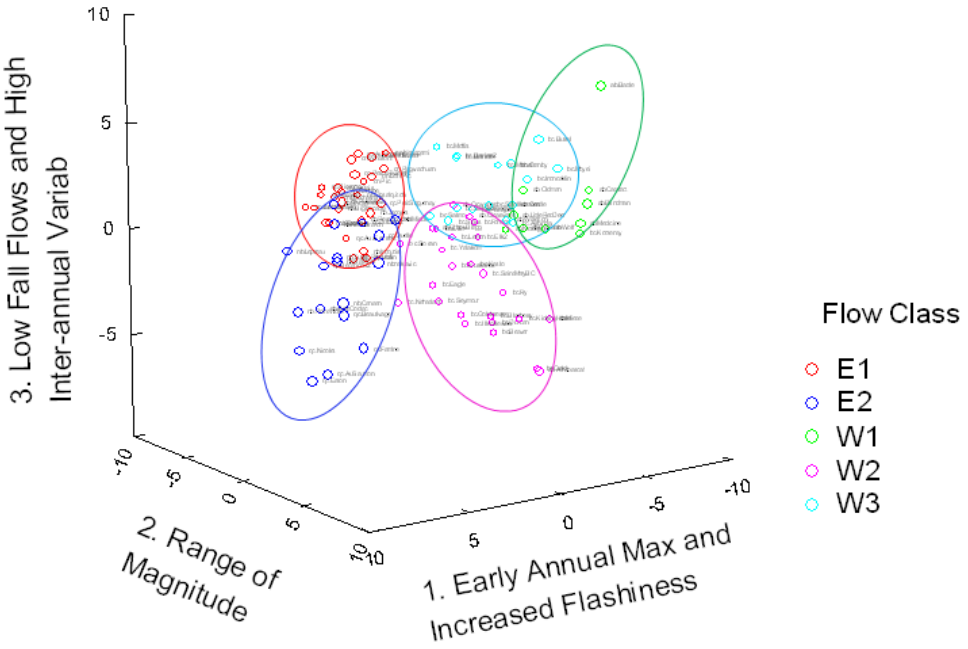


Figure 3 Five flow classes in PCA space. The determination of axis names is discussed in Results 3.2. PC 1, 2 and 3 explain 23.9% 15.6% and 10.5% of the total flow index variance. The K-means process appears to have effectively clustered the sites based on similar flow regimes since the classes are grouped together in PC space. Some transitional sites are expected.

3.2 Characterizing Unregulated Flow Classes across HydroNet Regions using Principal Component Analysis

As Prairie, West Coastal and Northern Rivers (among others) are not included in the study data set, the following analysis is not meant to be a description of flow regime variability across Canada. Rather it is simply a summary of flow regime variability across regions and watersheds representative of the set of 16 selected HydroNet regulated sites.

To interpret the principal components discussed in Methods 3.1 and displayed in Figure 3, the indices loading each PCA axis were ranked, and the top loaders were evaluated for the first three PCs (Table 1). Hydrographs for the rivers scoring highest and lowest on each PC axis (and as close to zero as possible on the other 2 of the 3 axes) were found to be useful aids for further interpretation of the meaning of PC scores (Appendix 1 Figure 2 (p. 107)). Based on these interpretations, the axes were named. Understanding PC axes proved to be a useful tool to generalize differences in flow regime between sites or flow classes. In Chapter 5, the same technique is used to identify regulated rivers that appear to have anomalous flow regimes.

Table 1 Top five loading indices for PC1, PC2 and PC3 for **Unregulated Rivers across Canada**

PC1: Index of Early Annual Max and Increased Flashiness (23.9% of total variability)

Code	PC Loading	Name	Description	*Source
TH1	**-0.88184**	Julian date of annual maximum	Determine the Julian date that the maximum flow occurs for each year. Transform the dates to relative values on a circular scale (radians or degrees). Compute the x and y components for each year and average them across all years. Compute the mean angle as the arc tangent of y-mean divided by x-mean. Transform the resultant angle back to Julian date.	HIT
RA15	**0.855871**	Relative rise rate	Mean of the relative change in daily values for days where change is positive. SUM((value(t) - value(t-1))/value(t)), where value(t) is the daily mean value on day t.	Steuer
nML6	**-0.8101**	Mean minimum monthly flows (June)	For each year, compute the minimum flow for the month of June. ML6 is the mean (or median - Use Preference option) of these values.	HIT
RA5	**-0.80333**	Proportion of rise days (Number of day rises)	Compute the number of days in which the flow is greater than the previous day. RA5 is the number of positive gain days divided by the total number of days in the flow record.	HIT
nMA22	**0.795579**	Mean monthly flow (Nov)	Means (or medians - Use Preference option) of all November flow values over the entire record.	HIT
FH1	**0.794276**	Flood frequency 1 (High flood pulse count)	Compute for each year the number of flow events with flows above a threshold equal to the 75th percentile value for the entire flow record. FH1 is the mean (or median - Use Preference option) number of events per year.	HIT

PC2: Index of Range of Magnitude (15.6% of total variability)

Code	PC Loading	Name	Description	Source
MA3	**0.865227**	Variability in daily flows (%)	Mean (or median - Use Preference option) of the coefficients of variation (standard deviation/mean) for each year. Compute the coefficient of variation for each year of daily flows and then compute the mean of the annual coefficients of variation.	HIT
MH14	**0.843233**	Median of annual maximum flows	Compute the annual maximum flows from monthly maximum flows. Compute the ratio of annual maximum flow to median annual flow for each year. MH14 is the median of these ratios.	HIT
ML17	**-0.82413**	7-day minimum baseflow	Compute the mean annual flows. Compute the minimum of a 7-day moving average flow for each year and divide them by the mean annual flow for that year. ML17 is the mean (or median - Use Preference option) of those ratios.	HIT

MA6	**-0.79074**	Restricted Range in daily flows (10/90)	Range in daily flows is the ratio of the 10 percent to 90 percent exceedance values for the entire flow record. Compute the 10 percent and 90 percent exceedance values for the entire flow record. Exceedance is computed by interpolating between the ordered (descending) flow values. Divide the 10 percent exceedance value by the 90 percent value.	HIT
nDH5	**0.697421**	Annual maximum of 90-day moving average flow	Compute the maximum of a 90-day moving average flow for each year. DH5 is the mean (or median - Use Preference option) of these values.	HIT
PC3: Index of Low Fall Flows, Few Daily Reversals and High Inter-Annual Variability (10.5% of total variability)				
Code	PC Loading	Name	Description	Source
nMH9	**-0.6866**	Mean maximum monthly flows (Sep)	For each year, compute the maximum flow for the month of September. MH9 is the mean (or median - Use Preference option) of these values.	HIT
MA28	**-0.60621**	Variability in monthly flows (May)	Coefficient of variation in monthly flows for May (see MA24)	HIT
RA8	**-0.5927**	Number of reversals (day-to-day)	Compute the number of days in each year when the change in flow from one day to the next changes direction. RA8 is the average (or median - Use Preference option) of the yearly values.	HIT
MA42	**0.576911**	Variability across annual flows (0-100)	Range of annual flows divided by median annual flows. MA42 is the maximum of the annual mean flows minus the minimum of the annual mean flows divided by the median of the annual mean flows.	HIT
FH7	**-0.56746**	Flood frequency 7x median	Compute for each year the number of flow events with flows above a threshold equal to seven times the median flow value for the entire flow record. FH7 is the mean (or median - Use Preference option) number of events per year.	HIT
* For source information, see the bottom of Appendix 1 Table 1 (p. 103).				

The first PC axis is defined by flow indices describing the timing of annual high flows and the degree of flashiness. Since we are using daily discharge data, systems that are characterized as flashy have fast rise and fall rates of change between daily means, and numerous high flow events (of short duration) above given quantile thresholds (e.g. the Q90) of interest each year. A river with a high PC 1 score thus has an earlier annual maximum flow and has increased flashiness compared to rivers with low PC 1 scores. PC 2 scores capture the absolute range of flow magnitudes (normalised by median flow) in these systems. A high score suggests low baseflows and high annual maximum flows (floods), thus the axis is called the index of range of magnitude. PC 3 is more difficult to summarize concisely, but a high PC 3 score suggests that a river has low autumn flows, relatively few flow reversals throughout the year (rising to falling, or vice versa, over days) and has higher inter-annual flow variability.

Figure 4 show the same information as Figure 3 but on two 2D plots. This allows for better visualization of the score differences (between classes or individual sites) along each axis.

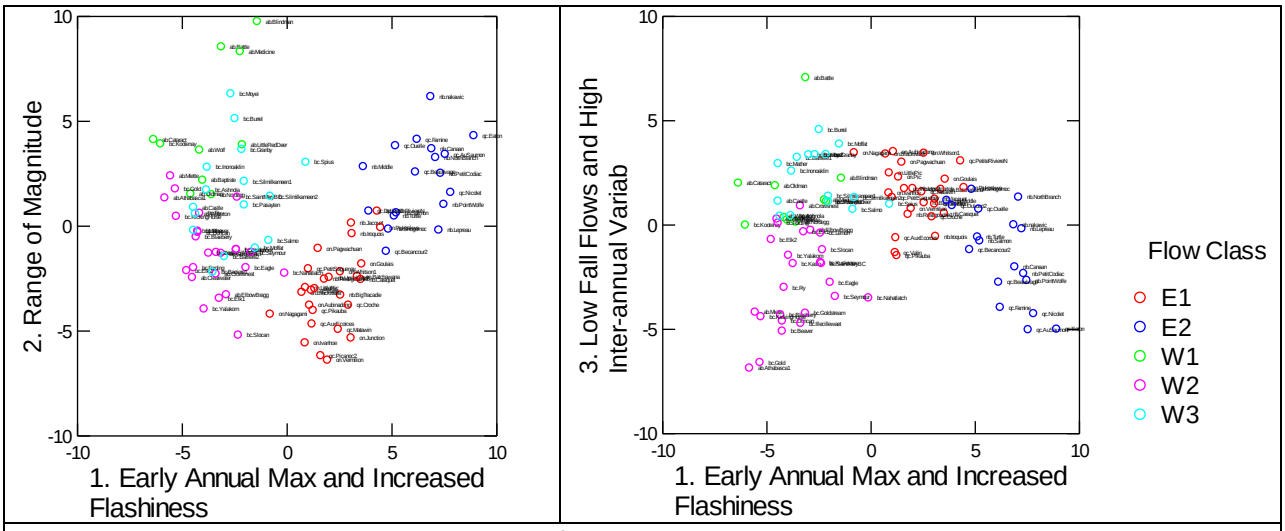


Figure 4 2D Principal Component Score Plots for 96 Unregulated Sites across Canada based on 70 Flow Indices.

The following flow regime trends can be gathered from these graphs: E2 scores highest on PC1, followed by E1. This suggests that the Eastern systems (E1 and E2) exhibit their highest flows earlier in the spring than the selected Western systems (W1-3), and that overall, flows are flashier in the Eastern systems. For E1, it makes sense that flashiness would be lower than the E2 sites since E1 sites are Canadian Shield systems with higher percent lake coverage than any of the other flow classes (shown below in Figure 5 (Results 3.3)). The lakes in E1 watersheds would be expected to buffer flows and reduce flashiness. Following this logic, it makes sense that E1 and W2 score lowest on PC2 (an index of absolute range of variability) since lakes should also buffer high flows and keep baseflow high in E1, while in W2 systems glacier or high elevation snowpack is not expected to melt rapidly in the spring/summer (reducing flood magnitude) and will also provide steady high baseflow through the summer. W2 systems are high relief Cordilleran systems (Figure 5) and thus more likely to contain glaciers.

3.3 Differences in Watershed Characteristics between Flow Classes

Values for the five watershed characteristics used for this analysis are shown as boxplots in Figure 5. The latitude and longitude plots (Figure 5) suggest that flow classes are geographically distinguishable from one another (this is also visible above on the maps presented in Figure 2, more so in the Eastern flow classes). Class W1 captures Western systems that are high latitude

and further east than most of the western sites. These are mostly Rocky Mountains foothills watersheds. These are also the lowest relief Western systems. Class W2 sites have the highest relief, and are thus most likely to capture glacial systems. Class W3 has slightly lower relief than W2, and consists of the westernmost BC interior rivers. The Western classes share similar percent lake areas, and drainage density is slightly higher in W1 systems. Class W1 systems are mostly in Alberta, W2 is split between Alberta and British Columbia (B.C.) and the majority of W3 systems are in B.C.

In the East, Class E1, mostly Canadian Shield drainage basins, is distinct from E2 primarily based on having larger percent lake area coverage. E1 systems also have a slightly higher drainage density on average, and are higher latitude, and further West than E2 systems. E1 consists of sites in central Ontario, on the North Shore of the St. Lawrence River in Quebec, and the North Western Region (Baie des Chaleurs drainages) of New Brunswick (N.B.) (confer Figure2). E2 systems are predominantly set in the Appalachian lowland region (below the Appalachian ridges) located on the South Shore of the St. Lawrence River in Quebec, and South Eastern (Bay of Fundy) region of N.B.

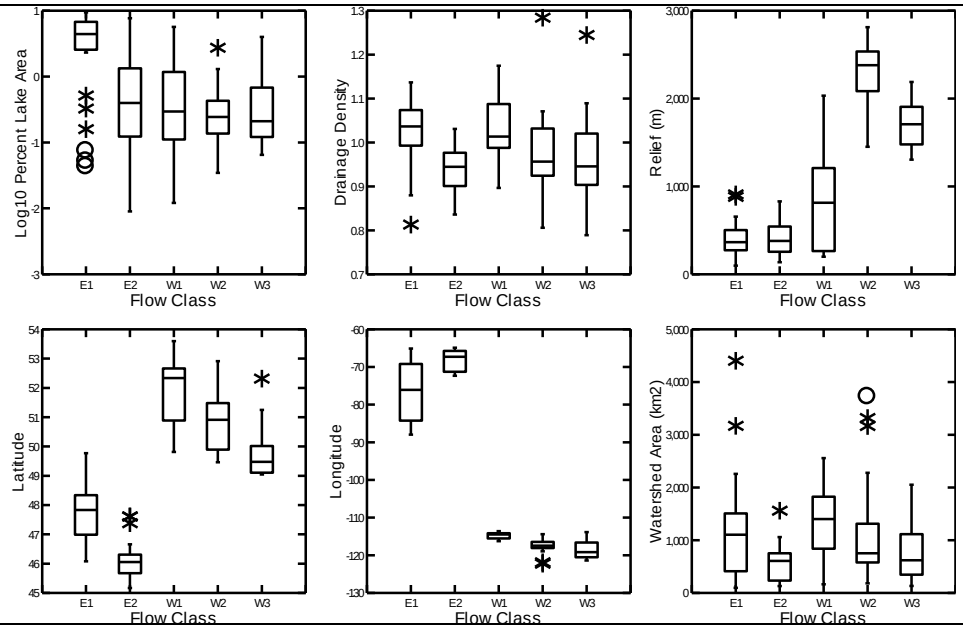


Figure 5. Boxplots of watershed characteristics of the five flow classes (E1 n = 27, E2 n = 18, W1 n = 10, W2 n = 25, W3 n = 16). The asterisks show outliers beyond the inner fence (1.5*IQR) and circles are outliers beyond the outer fence (3*IQR).

3.4 Assigning Regulated Rivers to Unregulated Flow Classes using Discriminant Function Analysis

DFA was used to assign unregulated rivers to predetermined flow classes using only geographic and landscape variables (watershed characteristics). Once functions were established, the regulated systems could be assigned to flow classes based on watershed characteristics (independent of modern flow regimes which because of hydropower development have been altered in most cases). In the Eastern systems, three of the five watershed variables were useful for classifying the rivers into E1 and E2: latitude, percentage of lakes (log10 to normalize the distribution), and drainage density (listed with decreasing discriminating importance). The F-to-Remove values were 19.4, 2.8 and 0.8 (Longitude and relief both had F-to-Remove values less than 0.001 and including them in the analysis led to jackknifed classifications that were less successful (higher misclassification) than normal classification). Based on latitude, percent lakes, and drainage density, 82% of cases were correctly assigned to their flow classes in the classification matrix and the jackknifed classification matrix. Misclassified sites were identified in SYSTAT with an asterisk and these cases were used to determine the threshold p-value that we trust to correctly classify the regulated sites.

Table 2 shows the p-value threshold that we established for regulated site classification based on the p-values (calculated in SYSTAT using Mahalanobis distances) for the misclassified unregulated sites for the eastern systems. The largest p-value that led to misclassification was 0.77, therefore we do not necessarily trust Mahalanobis scores resulting in lower p-values and thus these regulated systems are classified to both sites. Table 2 also shows the p-values for each flow regime class in the east for all eastern regulated sites, and the resulting classification.

Table 2. Eastern regulated river classification using DFA. Classification threshold (based on the highest misclassified unregulated posterior probability) is **p-value > 0.77**

Regulated River	E1 p-value	E2 p-value	Classification
Nb.Dee	0.69	0.31	**E1/E2**
Nb.Serpentine	0.6	0.4	**E1/E2**
On.Magpie	**0.98**	0.02	**E1**
On.Michipicoten	**0.97**	0.03	**E1**
On.Mississagi	**0.81**	0.19	**E1**
qc.Etchemin	0.19	**0.81**	**E2**
qc.Fourchue	0.75	0.25	**E1/E2**
qc.SaintFrancois1	0.08	**0.92**	**E2**
qc.SaintFrancois2	0.06	**0.94**	**E2**
qc.Kiamika	0.61	0.39	**E1/E2**
qc.SaintJean	**0.97**	0.03	**E1**

In the Western systems, the jackknifed classification matrix correctly classified the highest percentage of sites into W1, W2 and W3 when three variables were used in the discriminant function: relief, latitude and longitude (F-to-Remove of 34.7, 13.9, and 9.9 consecutively). Based on these variables, 81% of cases were correctly assigned to their flow classes in the classification matrix and the jackknifed classification matrix. For the western sites, the largest p-value that led to misclassification was 0.89; therefore we do not necessarily trust Mahalanobis scores resulting in lower p-values for western regulated sites. This is shown in Table 3, as are the p-values for each flow regime class in the west and the resulting classification.

Table 3. Western regulated river classification using DFA. Classification threshold (based on the highest misclassified unregulated posterior probability) is **p-value > 0.89**

Regulated River	W1 p-value	W2 p-value	W3 p-value	Classification
Ab.KananaskisBarrier	0.02	**0.93**	0.05	**W2**
Ab.KananaskisPocaterra	0.19	0.72	0.088	**W2***
Bc.Bull	0.00	**0.97**	0.03	**W2**
Bc.ShuswapSugar	0.00	0.68	0.32	**W2/W3**
Bc.ShuswapWilsey	0.00	0.79	0.21	**W2/W3**

* Kananaskis Pocaterra falls within the Kananaskis Barrier watershed and will therefore be considered a W2 system.

In all following analyses, the 16 regulated sites will be considered to have been historically part of the flow classes to which they were classified using DFA. Appendix 1 Table 2 (p. 109) includes tables that display the distances (km) between each regulated site and the sites that will

hereafter be deemed reference systems based on watershed characteristics suggestive of similar historical flow regimes.

4. Discussion

There are evident similarities between the geographic distribution of the five unregulated flow classes identified here by K-Means clustering (Figure 2) and the six Canadian flow classes (called regime type by the authors) identified by Monk *et al.* (2011). Using weekly discharge data for all Reference Hydrological Basin Network (RHBN) systems, they presented similar class differentiation on the north and south shore of the St. Lawrence River. New Brunswick was also split between two flow classes, and the Alberta/British Columbia systems in the HydroNet study region were classified as three different regime types. This suggests that flow regime classes identified by other authors could be re-used in this type of study; however the reference sites that we chose are more geographically suitable for our analysis and based on finer data resolution than Monk *et al.* (2011)'s analysis.

There is no reason to assume that well separated, distinct flow class clusters necessarily exist in nature. Here they are partly a product of geographic clustering. Given the continuum of climatic norms and physiographic variables across a continent, some study systems will exhibit transitional flow regime behaviour (patterns intermediate to the norms of two classes). These cases would likely be assigned to the smaller (in terms of number of cases) flow class, since a limitation of K-Means clustering is the tendency for similar sized clusters (SYSTAT; McManamay *et al.,* 2012b). In our data set, the fact that five flow classes are distinguishably separate in 3 dimensional PCA space is sufficient validation of the interpretability of this clustering solution.

When using PC scores to interpret flow regime trends, the interpreter must be wary however that an elevated score along a given PC does not mean that all of the high loading indices are influencing the score to the degree (or even the direction) suggested by each index's loading value and sign. Revisit Figure 4 and take the PC1 scores for flow class E1 as an example. Individual flashiness metrics (e.g. number of high/low pulses per year or rise/fall rate) should be consulted because there is a good chance that the positive scores at some sites are driven more by the timing of the spring flood. In other words, interpreting these plots is useful for

generalization and gathering a relative understanding of two systems or classes, but does not provide a complete understanding of a given river's hydrograph.

Once the hydrologic anomalies are identified in each regulated system (in Chapter 5), this scale of analysis will inform other HydroNet researchers and allow them to contextualize their own work. More specific regional flow classes could be identified by re-running this analysis for a smaller region; however this would reduce the number of unregulated rivers per flow class, and thus limit our ability to identify the natural range of variability for the different components of flow (the objective of Chapter 5).

5. Summary

Following the methodology presented by McManamay *et al.* (2012a,b,c) adapted to include unregulated rivers in close proximity and of similar size to regulated HydroNet study rivers across Canada, we identified five unregulated flow regime classes. Flow regime differences by class were identified and characterized using PCA. McManamay *et al.* (2012a) remind us that although streams in close geographic proximity often share similar climate, landscape and thus flow characteristics, unregulated streams cannot be considered appropriate hydrologic references for regulated streams based solely on their location. Suitability as a reference should be based on shared flow regime characteristics. This analysis exemplifies the first step of an analysis to characterize flow anomalies associated with damming with respect to regional flow norms. Efficient flow regime characterization is essential to improve our understanding of the morphological and ecological effects of discharge regimes across Canada and advances in these topics will empower dam managers to make informed operational decisions.

Chapter 5

Detecting Anomalous Flow Regime Features in Regulated HydroNet Rivers Compared to Flow Regime Class Norms

Fraser McLaughlin & Michel Lapointe

1. Introduction

A river's flow regime is known to be an important driver of ecological integrity (Poff *et al.,* 1997). The physical structure of the wetted river habitat is shaped by the 2-5yr recurrence high flow levels in wet temperate climates: in alluvial channels these are responsible for channel dimensions, reach scale bed material composition, substrate mobility levels and sediment transport patterns (Poff *et al.,* 1997; Church, 2002). Moreover, it is known that life cycle patterns as well as locations of preferred feeding and refuge habitats for various benthic invertebrate and fish fauna are adjusted in complex ways to variable patch and reach scale depth and velocity patterns and flow timing features set by the natural flow regime of a river (e.g. Riis and Biggs, 2003; Baranyi *et al,.* 2002). Other environmental factors such as water temperature and chemistry, sediment composition and fate of invasive species are also affected by the flow regime and influence river ecosystem structure and function (Poff *et al.*, 1997; Baron *et al.,* 2002; Poff *et al.,* 2010).

After dam construction, river flows become regulated by dam operators. The type and degree of flow alteration that occurs after regulation depends on the physical characteristics of the dam (i.e. dam height and reservoir volume limit the amount of water that can be retained), hydropower mode of operation (e.g. timing of grid demand, ramping rate restrictions and environmental baseflow requirements), and the rivers pre-regulated flow regime. Historically, flow alterations by dams have been identified by contrasting the values of biologically relevant flow indices (a suite of indices that describe the five broad flow regime features: flow magnitude, frequency, duration, timing and rate of change (Poff *et al.,* 1997)) calculated from multi-decade pre-dam versus post-dam flow records (e.g. Richter *et al.,* 1996). This approach emerged with the recognition that, beyond simple minimum flow requirements, a naturally variable flow regime is necessary to sustain the integrity of freshwater ecosystems (Poff *et al.,* 1997; Bunn and Arthington 2002; Postel and Richter, 2003; Biggs *et al.*, 2005).

Based on an understanding of the range of hydrologic features affecting ecosystem structure and function amassed from individual river studies, there is a scientific consensus supporting the development of environmental flow standards at the regional scale (Poff *et al.,* 2010). Poff *et al.* (2010) presented an empirical framework called the Ecological Limits of Hydrologic Alteration (ELOHA) to implement regional environmental flow standards to protect biodiversity and evolutionary potential based on trends between hydrologic parameters and ecological outcomes. An assumption within this framework is that it is unrealistic to generalise from site specific studies that focus on the ecological impacts of individual variations in flow regime. ELOHA rather postulates that functional relationships between flow alteration and ecology defined at the zoogeographic region and river type scale are most apt to influence environmental regulations and management decisions (Poff *et al.,* 2010).

Following the logic of the ELOHA framework and that of other authors who have been influenced by this approach (e.g. McManamay *et al.,* 2012a), we postulate here that the degree of anomaly that exists at a regulated site with respect to the natural range of flow behaviour in the region is more significant to predict faunal impacts than an estimation of site specific flow alterations based on the pre-impacted regime of that particular system. Regulation may materially alter certain flow regime characteristics on a dammed system, but the new regime may still behave within the range of natural flow behaviour for the region that supports productive ecosystems. Results from an analysis of flow regime anomalies at regulated rivers when analysed by river type and region may provide sufficient certainty to support management decisions at broad, regional scales while avoiding unnecessary expense and effort at individual sites (as advocated by Acreman and Dunbar, 2004; Booker and Acreman, 2007; Poff *et al.,* 2010). A secondary benefit to this regional comparative approach is that for many regulated rivers, decade-scale pre-dam flow records are unavailable, from which before-after indices can be compared, and it is costly and data intensive to develop reliable synthetic pre-regulation hydrographs as a basis for determining site specific regime alteration (as done by Black *et al.*, 2005), especially when analyzing a multitude of systems.

McManamay *et al.* (2012a) found regional flow classes to be effective units of analysis in their study of hydrologic alteration throughout the Eastern U.S.A. As explained in Chapter 4, flow classes are groups of unregulated rivers that share hydrologic (flow regime) properties and are representative of the regional baseline range of conditions; they provide the template for ecological processes and habitat characteristics as well as micro-adaptation of native and invasive species (Poff, 1996; Lytle and Poff, 2004; Arthington *et al.,* 2006; Poff *et al*., 2006; Poff *et al.,* 2010). By assigning regulated sites to flow classes based on landscape characteristics and geographic location (as done by Poff, 1996; Poff *et al*., 2006; McManamay *et al.,* 2012a), anomalous flow features can be identified (unusual deviations in regulated systems within their regional reference context). Poff *et al.* (2010) advocate using a small number of broad river class (types) that capture the major dimensions of stream flow variability so that the results can be practical to management. Broader flow classes imply a greater range of flow regime variability within a given class. Anomalous flow features at regulated sites are thus more conservatively detected when they are defined against broader rather than narrower flow classes.

Due to the proliferation of hundreds of often redundant flow indices used to characterize river flow regimes (described in detail in Chapter 4), a first challenge is to choose and format an appropriate set of hydrologic alteration values. Poff *et al.* (2010) suggest using individual flow indices of identified ecological importance (expressed as percent deviation from the baseline condition) in regional hydrologic alteration analyses. In general, flow alteration is a vector, not a single scalar quantity. In a regulated river, flow anomalies can be apparent in one or many dimensions of the flow time series compared to the reference class norm. Pluckridge *et al.* (1998) therefore support inclusion of a large suite of flow indices to characterize flow alteration. Olden and Poff (2003) used principal component analysis (PCA) to explore the collinearity of the flow indices and found that the technique provides important insight into flow class behaviour. However they note that the top components of flow regime variance (the Principal Component axes) will differ depending on the systems, scale and time frame of the analysis.

McManamay *et al.* (2012a) use three-dimensional multivariate space defined by principal component (PC) scores across all reference rivers to visualize differences across reference flow classes (appearing as clusters in PC space) and to observe where regulated sites plot in this reference defined space (since clear divergences from class norms suggest flow anomalies). However to analyze the precise impacts of given dams on flow anomalies, it is better to quantify and study, as per these authors, the anomalies on a large suite of indices and not just on the PC scores defined by ordination of reference rivers. In unregulated reference rivers within a region, certain hydrologic variables are consistently correlated (Olden and Poff, 2003); however individual flow metrics can respond singularly and in uncorrelated ways when flows are artificially regulated by dams (McManamay *et al.*, 2012a). In our analysis we distinguish between anomalies affecting seasonal flow timing or across-year regime constancy-predictability (when compared to flow class norms). The above anomaly types have at least the potential to lead to life history mis-adaptation for some regional species and population level stresses for fish fauna adapted to regional flow norms (Richter *et al.,* 1996; Poff *et al.,* 1997). Seasonality is particularly important in temperate ecosystems since other variables such as temperature and light fluctuate seasonally and have impacts on fish physiology and resource availability (Tockner *et al.,* 2000). We also investigate whether anomalous sets of flow indices at regulated rivers appear to follow the dominant correlations existing in natural regional systems (but in some cases pushing this natural dimension of regional variability to extreme values) or rather create flow regime combinations that are not encountered by fauna in regional, unregulated systems. Careful analysis of the meaning of PC scores for regulated systems is required, especially when scores are defined, as in McManamay *et al.* (2012a) and here, by ordination across flow class reference conditions. An anomalously low (or high) PC score at a regulated site (for example) could be the outcome of an atypically low (high) index score for only one of the indices most strongly aligned with (loading on) the particular PC axis while other indices known to be correlated (within the unregulated systems in the region) can fall within the range of unregulated reference flow behaviour.

As per McManamay *et al.* (2012a), PCA is a useful means to explore flow regime trends of regulated versus unregulated rivers within a given flow class. In addition, here we test whether PCA can also be useful to summarize, across all regulated sites and flow regime classes, the main axes variation in flow anomalies associated with regulation. In theory, this last PCA can reduce the dimensionality needed to describe flow anomalies across a large region, facilitating ELOHA type studies.

The context for this analysis is a bio-physical study of fish populations and physical habitat in a set of 13 rivers selected across various regions of Canada that are regulated for Hydro production. This study was initiated in 2010 by the Canadian NSERC-HydroNet research network. The 16 regulated sites (3 of the rivers have multiple sites below separate dams) were selected to include a range of types of regulation, including run-of-the-river-type (ROR) operations as well as systems with larger capacity reservoir storage allowing significant cross-season flow shifting, with or without hydropeaking (where the volume of water released through the turbines is hourly dependent on grid demand for electricity (Moog, 1993)). HydroNet study sites are distributed across 3 regions of southern Canada with contrasting physiography and climate (Rocky Mountain rivers in Alberta and BC; Eastern Canadian Shield rivers in central Ontario and Quebec and Lowland Appalachian rivers in southern Quebec and central New Brunswick). For the locational information for each site, refer to Appendix 2 Table 1 (p.110). For more details about NSERC's HydroNet, see Smokorowski *et al.* (2011).

Specific Objectives

In this fifth chapter, our objectives are: (1) to identify the features of the regulated flow regimes at HydroNet sites that are most anomalous compared to the appropriate regional reference norms defined in Chapter 4; (2) for each regulated river, to classify and differentiate between anomalous flow features (indices) that are related to seasonality (and thus have the a-priori potential to clash with regional life history strategies) or are features that are aligned with a principal axis of variation in the reference set of rivers versus anomalous indices that are orthogonal to and not part of such an important axis of natural variation; and (3) to draw a

general picture of the main axes of flow regime feature anomalies across all regulated HydroNet sites in Canada. Here we present a methodology that can be applied elsewhere, and also discuss particular flow regime anomalies in the regulated HydroNet rivers that, based on theory and previous studies, may have implications for fish at the community and population levels.

2. Methods

2.1 Establishing Relevant Natural Flow Classes

In Chapter 4, we first pared an comprehensive list of 150+ commonly cited flow indices down to 70 indices representative of the main index groups that describe flow magnitude, frequency, duration, timing and rate of change. This was done by selecting key representatives among groups of strongly inter-correlated and redundant metrics. We then classified 96 unregulated (reference) rivers proximal to the regulated HydroNet rivers across Canada into flow classes representative of environmental flow norms and characterised the differences between these classes. Next, using discriminant function analysis (DFA) based on geographic and physical watershed characteristics, we assigned each HydroNet regulated river to a reference flow class that represents the range of flow regime index values expected of rivers of this type prior to regulation.

2.2 Identifying and Classifying Flow Anomalies in Regulated HydroNet Rivers

To characterize all aspects of anomalous flow behaviour at regulated sites, we present tables of the most anomalous flow metrics for each regulated site, in comparison with the range of the same indices for its reference class. Anomaly identification was based on z-scores at regulated sites for all 70 individual flow indices presented in Chapter 4. Z-scores (also known as standardized scores) were calculated using the unregulated mean and standard deviation for each index, by flow class. Each standardized regulated index or Z-score therefore represents the number of standard deviations above or below the reference class mean for that index. We present all significant anomalies for each regulated river according to a 95% confidence interval with multiple testing correction based on Holm's method. Holm's method is less conservative than Bonferroni correction giving more significant results without being liberal (Legendre and Legendre, 2012). For rivers with no significantly anomalous indices, the indices with the top three z-scores are shown.

These tables of anomalous indices also include the loading of these indices on the top (two or three) principal components reflecting the variance structure within the reference class. Loading values provide a method to identify which indices are represented on the principal component plots used to identify anomalous regulated regimes (discussed next) and which are not. Absolute index loadings above 0.7 on the top PC axes are coloured red, suggesting that these anomalies occur for flow regime features that are part of the dominant axes of natural (reference) flow regime variability (top PC axes). Highly anomalous values of indices that do not load on the top PC axes of the reference class represent anomalies in flow features that display singularities in variability among reference rivers. We have also highlighted the anomalous indices that may have particular ecological significance for fish populations and are thus the focus of our characterization of each regulated river. Anomalous seasonality/timing related indices are coloured blue since timing of flows of certain magnitudes is important to fish life histories, and indices related to anomalies in flow predictability (inter-annual variability and constancy) are coloured green since such changes in flow regimes may also strain or clash with regional life history adaptations (Poff *et al.,* 1997).

2.3 Identifying Flow Anomalies on the Dominant Axes of Natural Variability using PCA

As explained above, McManamay *et al.* (2012a) used multivariate plots defined by principal component axes of flow features across the reference flow class to characterize the direction and visualise the strength of flow anomalies in regulated sites throughout the eastern U.S.A. Although PC plots are effective tools to visualize large amounts of data, and can provide convincing evidence of anomalous flows at certain regulated sites, it is essential to be careful in interpretation of this type of figure. In our study, all anomalous regulated flow features are first identified using the tables described in Methods 2.2. We then use PC plots to identify groups of flow features in each regulated river that are part of a group of indices that naturally covary and thus already form a principal axis of variation in the reference set of rivers.

To do this, we ran PCAs for each reference flow class separately (excluding the regulated sites), using the 70 flow indices described in Chapter 4 as input variables, to identify the principal axes

of natural regime variability within each flow class. This analysis thus excludes the variability associated with a few regulated sites whose anomalous sets of metrics would dominate the PCA. In the next step, we plot regulated sites in the reference defined PCA space (as in McManamay *et al.* (2012a)). To calculate PC scores of regulated sites, the principal component coefficients (eigenvectors) were multiplied by the 70 input variables (flow indices) for the regulated rivers. We then standardized (i.e. z-scored) all PC scores (regulated and unregulated) using the reference (unregulated) mean and standard deviation for each PC. Thus the mean score for reference sites on a PC axis is zero and a score of +1 indicates a PC score one standard deviation above the mean for that reference flow class.

Resultant plots are defined by the top two or three PC axes for each class. The top two PCs explain on average 45% of total unregulated index variance. The PC axes names are based on an analysis of the top loading indices (Table 2 in Appendix 2 (p. 110)) and by analysing the distinct characteristics of river hydrographs with extreme scores along each axis (and close to zero on others) (Table 3 in Appendix 2 (p. 113)). Appendix Table 3 also includes the central reference hydrograph (the hydrograph for the site closest to the flow class centroid in PCA space) for qualitative comparison with individual hydrographs at regulated sites.

Flow regulation through powerhouse and spillway manipulation can alter flow regimes in highly un-natural ways, for example by strongly affecting only one of a group of metrics that are normally correlated in unregulated rivers. Since the multivariate space in this type of analysis (where the dimensionality of multivariate behaviour is reduced) is defined only by the top principal components of the reference class, apparent anomalies on plots of top PC axes suggest only that the regulated system exhibits anomalous values in some or all of the indices that strongly load on these principal axes of reference variability. To properly interpret anomalous PC scores, we thus analyse which metrics or group of metrics (which flow features) were responsible for the anomalous PC scores. To this end we plot and visualize the shared contribution of the high loading indices (defined by the value of the correlation between each original variable and the component) towards the anomalous PC scores. We evaluate whether

changes to all the high loading flow features are equally responsible for an anomalous score in the regulated sites or if only one or a few aspects of the flow are anomalous while the others fall within the normal range of reference values. To illustrate this, we generated bivariate plots defined by two of the highest loading flow indices (that we see as most representative of the particular PC axis) for the PC axes on which the regulated sites of the particular class appear anomalous.

2.4 Characterizing how Flow Anomalies Vary across Regulated HydroNet Sites

To characterize the different axes of variation among anomalous regulated regimes (to identify flow features associated for example with large storage systems, with or without hydropeaking, or run-of-the-river systems), we then analysed observed regulation ascribed anomalies jointly across all regions: i.e. we ran a new PCA on the standardized scores for all flow indices that we found to be significantly anomalous (95% using Holm's correction) in at least one regulated site (37 indices total). The resultant PC scores for each regulated site are then plotted on the top three axes of flow anomaly variability across both Eastern and Western sites. As for the PC plots described in Methods 2.3, PC axis names were derived from an analysis of the top loading indices (Table 6 in Appendix 2 (p. 128)) and by analysing the distinct characteristics of river hydrographs with extreme scores along each axis. This unique approach allows us to identify the principal axes of flow anomaly variability across regulated HydroNet sites.

3. Results

The following results are organized by regional groupings of regulated HydroNet study rivers.

3.1. Flow Regime Anomalies in the Regulated Etchemin and Saint-Francois Rivers: Compared to Reference class E2 - Quebec and New Brunswick Lowland Appalachian Rivers

For the three regulated sites assigned to flow class E2 in Chapter 4, Table 1 presents the set of flow indices that are most anomalous when compared to the distribution of values observed in the unregulated reference rivers in this flow class (which covers Appalachian region rivers in southern Quebec and northern New Brunswick). This table also provides information on whether a given, specific anomalous index is one of a set that co-varies substantially in natural rivers of that class or one of a set that is more orthogonal to the main axes of this variability. The former case suggests that the regulated river is pushed to an extreme along a natural axis of variability among the reference rivers, while the latter points to an anomalous feature that is not part of such an axis. Such a distinction may (or may not) be important with regards to environmental tolerances or adaptability of the regional fish fauna. Each index's loading on the top two principal components of flow index variability in the reference class is presented in columns 3 and 4. In all cases, the top two PCs explain between 40% and 50% of the variance across the reference class indices. The interpretations of the top principal component axes are given below.

As explained above, it is known that timing features of flow regime significantly altered by regulation can stress fish populations by leading to poorly adapted life history strategies. Since we expect limited variability in such timing features within a reference flow region (since these types of indices are driven by regional climate), we do not expect many indices coded in blue or green to be high loaders on the top two PC axes.

Note that of the three sites presented in Table 1, one has no anomalous indices with z-scores above 2.5 while the two others have several highly anomalous flow characteristics (scores

between 5 and 25). It is also notable that nearly none of the seasonality or predictability indices (in green and blue) load highly on PC1 or PC2.

Table 1 The most anomalous flow Indices and their PC loadings for Class E2 regulated rivers
At least the top 3 divergent indices are shown for each river (based on absolute z-scores), in instances where there are fewer than 3 significant anomalies, non-significant p-values (see Methods) are marked with asterisks. The river names in brackets denote how these sites are shown on the graphs below.

Etchemin River, Quebec (qc.Etchemin)

Index Code	p-val	z-score	load1	load2	Index Name	Description	Units	Raw Value	Class Mean	Class SD
TH1	*1.000	**2.10**	0.20	0.52	Julian date of annual maximum	Determine the Julian date that the maximum flow occurs for each year. Transform the dates to relative values on a circular scale (radians or degrees). Compute the x and y components for each year and average them across all years. Compute the mean angle as the arc tangent of y-mean divided by x-mean. Transform the resultant angle back to Julian date.	day of year	149.19	97.60	24.57
TA1	*1.000	**2.06**	0.32	-0.04	Constancy	Constancy is computed via the formulation of Colwell (see example in Colwell, 1974).	dim	0.25	0.15	0.05
RA9	*1.000	**-1.80**	-0.60	-0.21	Variability in reversals	Coefficient of variation in R_A8. Compute the standard deviation for the yearly reversal values. RA9 is 100 times the standard deviation divided by the mean.	%	14.17	39.90	14.32

Saint-Francois River, Quebec, Site 1 (qc.SaintFrancois1)

Index Code	p-val	z-score	load1	load2	Index Name	Description	Units	Raw Value	Class Mean	Class SD
nML1	0.000	**13.26**	-0.45	-0.51	Mean minimum monthly flows (Jan)	For each year, compute the minimum flow for the month of January. ML1 is the mean (or median - Use Preference option) of these values.	dim	1.68	0.47	0.09
RA5	0.000	**8.63**	0.54	0.40	Proportion of rise days (Number of day rises)	Compute the number of days in which the flow is greater than the previous day. RA5 is the number of positive gain days divided by the total number of days in the flow record.	dim	0.42	0.28	0.02
nMA13	0.000	**7.86**	0.45	-0.39	Mean monthly flow (Feb)	Means (or medians - Use Preference option) of all February flow values over the entire record.	dim	1.96	0.63	0.17
ML17	0.000	**7.00**	0.37	-0.46	7-day minimum baseflow	Compute the mean annual flows. Compute the minimum of a 7-day moving average flow for each year and divide them by the mean annual flow for that year. ML17 is the mean (or median - Use Preference option) of those ratios.	dim	0.24	0.06	0.03
MA6	0.000	**6.20**	0.41	-0.50	Ratio of low flow (Q90) to high flow (Q10) quantiles	Range in daily flows is the ratio of the 90 percent to 10 percent exceedance values for the entire flow record (low flow/high flow). Compute the 90 percent and 10 percent exceedance values for the entire flow record. Exceedance is computed by interpolating between the ordered (descending) flow values. Divide the 90 percent exceedance value by the 10 percent value.	dim	0.15	0.04	0.02
nML3	0.000	**5.19**	0.31	-0.68	Mean minimum monthly flows (Mar)	For each year, compute the minimum flow for the month of March. ML3 is the mean (or median - Use Preference option) of these values.	dim	1.14	0.56	0.11
nMA12	0.000	**4.59**	-0.55	-0.56	Mean monthly flow (Jan)	Means (or medians - Use Preference option) of all January flow values over the entire record.	dim	1.91	0.92	0.22
DA4	0.000	**-4.48**	-0.65	-0.32	Median fall period	Median duration of consecutive periods of falling values	days	2.00	4.11	0.47
MA3	0.001	**-4.43**	0.20	**0.90**	Variability in daily flows 1	Mean (or median - Use Preference option) of the coefficients of variation (standard deviation/mean) for each year. Compute the coefficient of variation for each year of daily flows and then compute the mean of the annual coefficients of variation.	%	76.48	144.24	15.28
TA2	0.001	**4.42**	-0.34	0.08	Predictability of flow	Composed of two independent, additive components: constancy (a measure of temporal invariance) and contingency (a measure of periodicity). Predictability is computed from the same matrix as constancy (see TA1; see example in Colwell, 1974). It is computed as (using natural logarithms): 1 - ((uncertainty with respect to interaction of time and state - uncertainty with respect to time) / log (number of state))	dim	0.55	0.39	0.04
FH3	0.002	**-4.14**	-0.01	**0.81**	Days per year above 3x flow median	Compute the number of days each year that the flow is above a threshold equal to three times the median flow for the entire record. FH3 is the mean (or median – Use Preference option) of the annual number of days for all years.	days/year	15.50	73.39	13.97
TH1	0.011	**3.73**	0.20	0.52	Julian date of annual maximum	Determine the Julian date that the maximum flow occurs for each year. Transform the dates to relative values on a circular scale (radians or degrees). Compute the x and y components for each year and average them across all years. Compute the mean angle as the arc tangent of y-mean divided by x-mean. Transform the resultant angle back to Julian date.	day of year	189.26	97.60	24.57
nML8	0.015	**3.66**	0.38	-0.18	Mean minimum monthly flows (Aug)	For each year, compute the minimum flow for the month of August. ML8 is the mean (or median - Use Preference option) of these values.	dim	0.33	0.14	0.05

TA1	0.015	**3.65**	0.32	-0.04	Constancy	Constancy is computed via the formulation of Colwell (see example in Colwell, 1974).	dim	0.32	0.15	0.05
RA15	0.021	**-3.56**	0.66	0.12	Relative rise rate	Mean of the relative change in daily values for days where change is positive. SUM((value(t) - value(t-1))/value(t)), where value(t) is the daily mean value on day t.	%	8.09	25.74	4.96
Saint-Fracois River, Quebec, Site 2 (qc.SaintFrancois2)										
Index Code	**p-val**	**z-score**	load1	load2	Index Name	Description	Units	Raw Value	Class Mean	Class SD
RA5	0.000	**8.54**	0.54	0.40	Proportion of rise days (Number of day rises)	Compute the number of days in which the flow is greater than the previous day. RA5 is the number of positive gain days divided by the total number of days in the flow record.	dim	0.42	0.28	0.02
MA41	0.000	**7.41**	0.41	-0.23	Specific mean annual runoff	Compute the annual mean daily flows. MA41 is the mean of the annual means divided by the drainage area.	$m^3 s^{-1}/km^2$	0.10	0.03	0.01
nML1	0.000	**5.98**	-0.45	-0.51	Mean minimum monthly flows (Jan)	For each year, compute the minimum flow for the month of January. ML1 is the mean (or median - Use Preference option) of these values.	dim	1.01	0.47	0.09
DA4	0.000	**-4.48**	-0.65	-0.32	Median fall period	Median duration of consecutive periods of falling values	days	2.00	4.11	0.47
MA6	0.002	**4.13**	0.41	-0.50	Ratio of low flow (Q90) to high flow (Q10) quantiles	Range in daily flows is the ratio of the 90 percent to 10 percent exceedance values for the entire flow record (low flow/high flow). Compute the 90 percent and 10 percent exceedance values for the entire flow record. Exceedance is computed by interpolating between the ordered (descending) flow values. Divide the 90 percent exceedance value by the 10 percent value.	dim	0.12	0.04	0.02
FH3	0.003	**-4.04**	-0.01	**0.81**	Days per year above 3x flow median	Compute the number of days each year that the flow is above a threshold equal to three times the median flow for the entire record. FH3 is the mean (or median – Use Preference option) of the annual number of days for all years.	days/year	17.00	73.39	13.97
nML3	0.004	**3.99**	0.31	-0.68	Mean minimum monthly flows (Mar)	For each year, compute the minimum flow for the month of March. ML3 is the mean (or median - Use Preference option) of these values.	dim	1.01	0.56	0.11
MA3	0.006	**-3.88**	0.20	**0.90**	Annual Variability in daily flows 1	Mean (or median - Use Preference option) of the coefficients of variation (standard deviation/mean) for each year. Compute the coefficient of variation for each year of daily flows and then compute the mean of the annual coefficients of variation.	%	84.99	144.24	15.28
ML17	0.006	**3.87**	0.37	-0.46	7-day minimum baseflow	Compute the mean annual flows. Compute the minimum of a 7-day moving average flow for each year and divide them by the mean annual flow for that year. ML17 is the mean (or median - Use Preference option) of those ratios.	dim	0.16	0.06	0.03
RA8	0.021	**3.57**	0.59	-0.32	Number of reversals (day-to-day)	Compute the number of days in each year when the change in flow from one day to the next changes direction. RA8 is the average (or median - Use Preference option) of the yearly values.	events /year	128.50	88.94	11.09

In the rest of this section, we first visualise and analyse the nature of these observed flow anomalies in comparison to the main axes of variability (principal components) in the reference class. We end with a description and synthesis of the main features of the regime anomalies at each regulated site. Figure 1 shows the standardized PC scores (on the top two principal component axes) for the class E2 regulated and all unregulated (reference) sites. As explained in Methods, this PC space is defined by the reference sites only in order to analyze the main axes of unregulated variability (a proxy for true natural variability) uncontaminated by highly anomalous behaviours at regulates sites. PC coefficients were used to ascribe scores to the regulated sites. The principal component axes are named based on their top loading indices (refer to Table 2 in Appendix 2 (p. 110)). To further validate our choice of axis names, we also analyzed hydrographs for the unregulated systems scoring highest and lowest on each PC axis (Table 3 in Appendix 2 (p. 113)).

The principal component axis that explains the highest percentage of reference flow variance in class E2 (axis 1) describes degree of flashiness and frequency of low flows. Rivers scoring high on this axis have increased flashiness (with many high magnitude peaks throughout the year with short durations) and infrequent low flows (meaning that it is rare for these systems to ever experience flows as low as 10% of the median volume). The second principal component axis for flow class E2 captures the magnitude of spring flooding and the aggregate volume of high flows each year (as identified by the magnitude of annual maximum 90-day moving average, normalised to the median flow). Note that two of the regulated HydroNet sites in class E2 (located on the Saint-Francois River in Quebec) have PC2 z-scores of -3.4 and -4.2 and thus plot well below the range PC2 scores of all reference rivers.

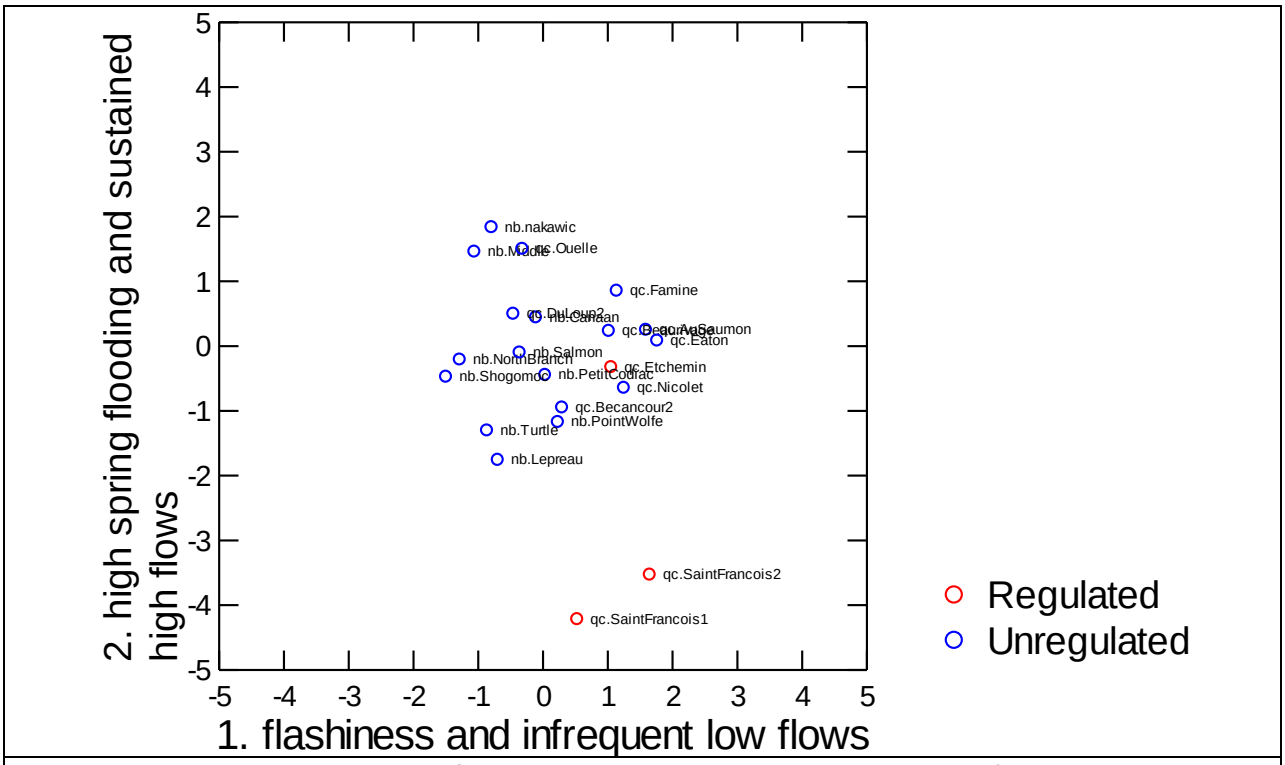


Figure 1 Regulated and unregulated flow class E2 rivers in multivariate PCA space (standardized PC1 and PC2 scores) based on all unregulated rivers of this class (see Methods). If regulated rivers plot well outside the cluster of unregulated reference systems along a PC axis, certain flow indices loading this axis are highly anomalous. As conventional, axes are named based on an evaluation of the top loading indices (Tables 2 and 3 in Appendix 2). Note that the Saint-Francois River plots outside the range of reference scores on PC2 while the Etchemin River falls within the reference range on both PC1 and PC2. PC1 explains 29.5% of the total variance. PC2 explains 19.2% of the total variance within E2 reference sites.

Regulation can decouple sets of indices (flow features) that naturally co-vary in natural systems within a region. Indeed, regulation operations at dams (spillway and power station regimes) can in some cases be tailored in ways that affect only select flow indices (by imposing strict minimum environmental flows higher than natural Q90, for example, Q90/Q75 ratios can be highly modified from typical reference values). Thus, next we test whether the strong PC2 axis anomaly observed at the Saint-Francois sites reflects a coherent level of anomaly in the key indices driving PC2 in natural systems or instead reflect an anomaly affecting only one or a few particular regime features (indices) among this natural axis of variability. Figure 2 is a bivariate plot defined by two of the highest loading PC2 flow indices (the PC axis on which the two Saint-Francois sites appear anomalous on Fig 1). Figure 2 illustrates that the two Saint-Francois sites have scores that appear similarly anomalous on both these specific, high loading PC2 indices. This coherence for Saint-Francois sites affects all high loading indices on PC2 (all have broadly comparable z-scores, in magnitude and direction). The alignment with the trend for reference sites illustrates that the PC2 anomaly can be characterized as an extreme case along a coherent gradient of flow behaviour in the reference systems, involving multiple metrics beyond these two.

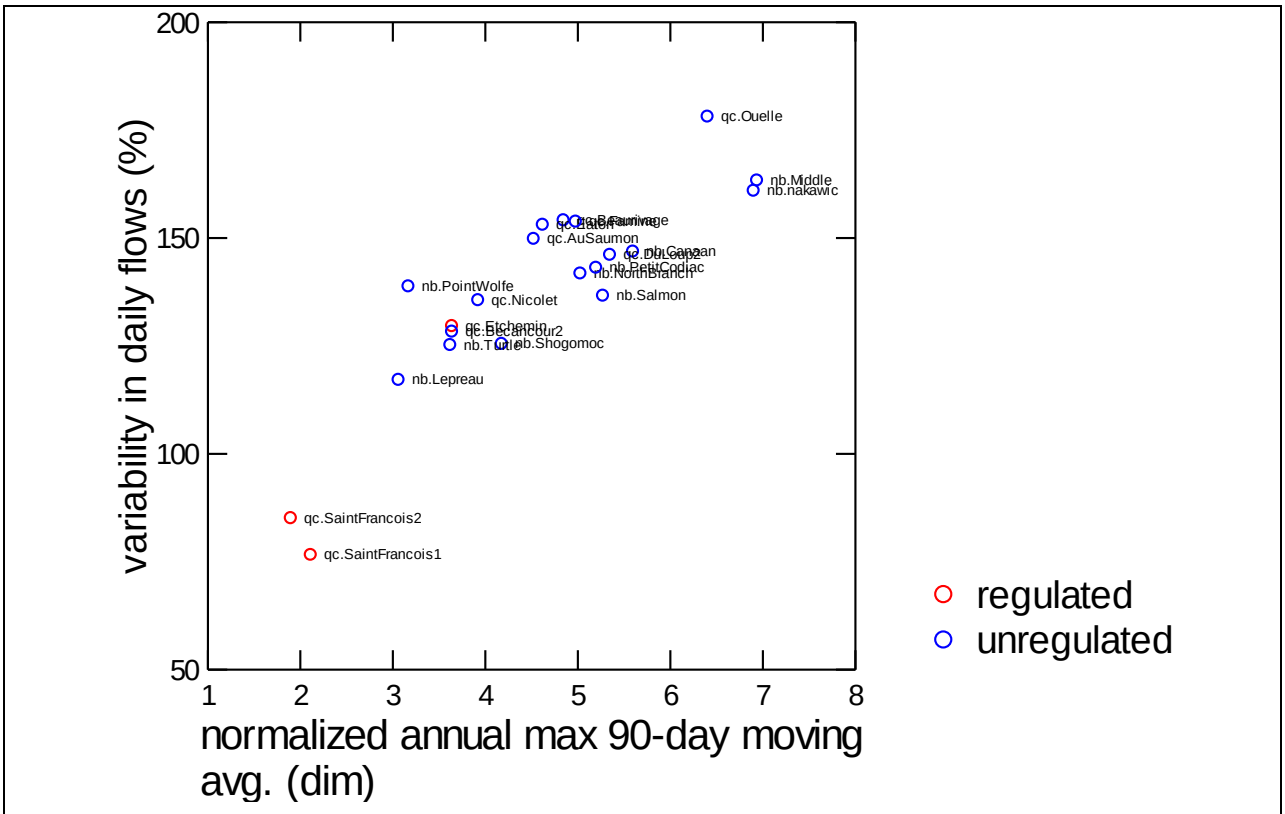


Figure 2 This plot displays 2 of the top 4 loading indices on flow class E2 PC2, the gradient on which the two Saint-Francois sites display anomalous behaviour (nDH5 vs. MA3). It is apparent from this plot (and also true for the other high loading PC2 indices that we explored) that the Saint-Francois has systematically reduced index scores for the indices that highly influence PC2.

Etchemin River

Based on Table 1, Figure 1 and Figure 2, it is evident that the regulated Etchemin river does not exhibit clearly anomalous flow characteristics compared to the regional reference systems. Table 1 shows that the most divergent standardized index scores (a relatively higher level of constancy and later date of annual peak) are not significant and no more than 2.1 standard deviations away from the reference class means. The PC plot (Figure 1) shows that the Etchemin River falls within the range of reference PC scores on PC1 (axis of flashiness and infrequent low flows) and PC2 (axis of high spring flooding and sustained high flows). This system indeed plots near the center of the cluster of reference rivers on these axes. As is therefore expected, the Etchemin River also plots with the references ranges of the high loading PC2 indices shown in Figure 2 (confer: the red point somewhat hidden within the blue points). The above analysis indicates that, to a first approximation, the flows in this system can

be characterized as low-anomaly based on the natural variability in regional reference systems (and may effectively be characterised as almost ROR).

Saint-Francois River Sites

Alternatively, the Saint-Francois River sites do exhibit strongly anomalous flow regime characteristics in comparison with the observed norms for its flow class. The two sites are summarized together since their anomalies are similar. Analysis of the most anomalous standardized indices (Table 1) suggests that winter flows in the Saint-Francois River are much higher than winter flows in the reference class rivers (in particular, with z-scores above 13 and 5 for mean minimum January flows). Predictability (z-score of 4.4 for Saint-Francois 1) is also much higher than the class range (meaning less inter-annual variability). However, many of the most anomalous specific indices at these sites (such as the timing of high flows and higher than normal very low flows) are not high principal component loaders (for PC1 or PC2) and thus their effect is not represented on the PC plot (Table 1, Figure 1). Regardless, Figure 1 shows that there are high loading PC2 indices sufficiently anomalous that the Saint-Francois sites plot outside the reference range of PC2 scores. The low scores on the y-axis of Figure 1 (axis of high spring flooding and sustained high flows) suggest that these 2 sites experience milder spring floods and that flows do not remain high for extended periods of time when flooding does occur. Attenuated high flows and elevated low flows are common characteristics of rivers reaches below hydro dams with reservoirs capable of storing significant volumes of water. Based on Table 1 and an analysis of the indices responsible for the low PC2 score (Figure 1), the Saint-Francois sites seem to show very strong dampening of high flow volume periods and reduced annual variability of flows, behaviour that is at an extreme along a gradient of flow variability that occurs naturally within flow class E2. Saint-Francois sites also show extreme anomalies in winter flows and unusually strong regime constancy, characteristics that vary less among class E2. Some potential implications of this type of result for fish populations are discussed in the Discussion section.

Further understanding of all of the regulated flow regimes presented in this chapter can be gathered from the hydrographs presented in Table 4 of Appendix 2 (p. 120). The central reference flow regime (identified using the PC plot: Figure 1 for flow class E2) is also presented for each class as a basis for comparison.

3.2. Flow Regime Anomalies in the Regulated Fourchue, Kiamika, Dee and Serpentine Rivers: Compared to Reference Class E1/E2 - Eastern Shield and Lowland Appalachian Rivers in Ontario, Quebec and New Brunswick

Following the steps and colour conventions used in 3.1 to analyse flow regime anomalies in region E2, Table 2 presents the most anomalous flow indices for each regulated river assigned in Chapter 4 to flow class E1/E2 (eastern Shield and some Appalachian rivers, in Ontario, Quebec and New Brunswick) compared to the distribution of regional reference index values. Recall that assignment of a regulated site to a composite of two flow reference classes occurred when the DFA could not uniquely assign the site to either class with overwhelming confidence, based on watershed and location characteristics (Chapter 4). Since natural variability in metrics across the E1/E2 reference set is greater than within either class on its own, the anomalous z-scores in Table 2 are thus generally conservative (most z-scores would be higher with respect to a narrower reference set). For example, the Kiamika River's most anomalous flow index is normalized mean minimum January flows (4.5 standard deviations above the E1/E2 reference class mean). Standardized by class E1 only, the z-score is lower (z= 3.95), however when standardized by class E2, the Kiamika river's minimum January flows are apparently more anomalous (7.5 standard deviations away from the flow class E2 mean).

Many z-scores higher than 5, some as high as 38 (for the Serpentine River, New Brunswick), can be noted in Table 2 for some of these regulated sites. Also notice that for some of the sites, such as the Dee and Serpentine, few or no anomalous indices are high loaders on PC1 or PC2, suggesting that the most unusual regime features in these systems are not part of coherent sets of features that vary importantly across the reference class. As in Table 1, the majority of the

indices that capture anomalous seasonality (blue) and flow predictability (green) are not high loading indices on the first two principal components of natural flow class variability across E1/E2; however, some seasonality/timing metrics such as some March and November flow metrics are high loaders, possibly because the greater geographical range of this combined reference set (the Kiamika River has the longest mean distance to reference gauge sites, 560km, while none of the regulated rivers assigned to flow class E2 (Results 3.1) have mean distances greater than 300km).

Table2 The most anomalous flow indices and their PC loadings for Class E1/E2 regulated rivers

Fourchue River, Quebec (qc.Fourchue)

Index Code	p-val	z-score	load1	load2	Index Name	Description	Units	Raw Value	Class Mean	Class SD
RA5	0.000	**4.75**	-0.06	-0.50	Proportion of rise days (Number of day rises)	Compute the number of days in which the flow is greater than the previous day. RA5 is the number of positive gain days divided by the total number of days in the flow record.	dim	0.40	0.28	0.03
nMA22	*0.094	**-3.20**	0.31	**0.74**	Normalized mean monthly flow (Nov)	Means (or medians - Use Preference option) of all November flow values over the entire record.	dim	0.38	1.72	0.42
RA2	*0.105	**3.16**	0.02	0.22	Variability in rise rate	Coefficient of variation in R_A1 (Mean rate of positive changes in flow from one day to the next. Compute the change in flow for days in which the change is positive for the entire flow record). Compute the standard deviation for the positive flow changes. RA2 is 100 times the standard deviation divided by the mean.	%	313.23	217.37	30.31

Kiamika River, Quebec (qc.Kiamika)

Index Code	p-val	z-score	load1	load2	Index Name	Description	Units	Raw Value	Class Mean	Class SD
nML1	0.000	**4.50**	-0.49	-0.41	Mean minimum monthly flows (Jan)	For each year, compute the minimum flow for the month of January. ML1 is the mean (or median - Use Preference option) of these values.	dim	1.15	0.54	0.14
MA3	0.000	**-4.30**	**0.74**	0.53	Annual Variability in daily flows 1	Mean (or median - Use Preference option) of the coefficients of variation (standard deviation/mean) for each year. Compute the coefficient of variation for each year of daily flows and then compute the mean of the annual coefficients of variation.	%	35.68	129.67	21.84
nMA13	0.008	**3.85**	-0.35	-0.29	Normalized mean monthly flow (Feb)	Means (or medians - Use Preference option) of all February flow values over the entire record.	dim	1.31	0.62	0.18
FH2	0.009	**3.79**	-0.33	0.32	Variability in Flood frequency 1	Coefficient of variation in F_H1. Compute the standard deviation in the annual pulse counts for FH1. FH2 is 100 times the standard deviation divided by the mean pulse count.	%	68.34	37.75	8.07
FH3	0.029	**-3.51**	0.46	**0.77**	Days per year above 3x flow median	Compute the number of days each year that the flow is above a threshold equal to three times the median flow for the entire record. FH3 is the mean (or median – Use Preference option) of the annual number of days for all years.	days/ year	0.00	64.39	18.36
MA6	0.036	**3.45**	-0.66	-0.64	Ratio of low flow (Q90) to high flow (Q10) quantiles	Range in daily flows is the ratio of the 90 percent to 10 percent exceedance values for the entire flow record (low flow/high flow). Compute the 90 percent and 10 percent exceedance values for the entire flow record. Exceedance is computed by interpolating between the ordered (descending) flow values. Divide the 90 percent exceedance value by the 10 percent value.	dim	0.21	0.07	0.04

Dee River, New Brunswick (nb.Dee)

Index Code	p-val	z-score	load1	load2	Index Name	Description	Units	Raw Value	Class Mean	Class SD
nMA13	0.000	**18.43**	-0.35	-0.29	Normalized mean monthly flow (Feb)	Means (or medians - Use Preference option) of all February flow values over the entire record.	dim	3.9	0.62	0.18
nML1	0.000	**8.13**	-0.49	-0.41	Mean minimum monthly flows (Jan)	For each year, compute the minimum flow for the month of January. ML1 is the mean (or median - Use Preference option) of these values.	dim	1.65	0.54	0.14
nMA12	0.000	**7.52**	0.28	-0.42	Mean monthly flow (Jan)	Means (or medians - Use Preference option) of all January flow values over the entire record.	dim	2.35	0.83	0.20

DA1	0.000	**5.61**	-0.58	0.37	Longest rise period	Maximum duration of consecutive periods of rising values	days	78.00	21.67	10.05
DA2	0.001	**-4.23**	-0.25	0.31	Median rise period	Median duration of consecutive periods of rising values	days	1.00	2.07	0.25
TH1	0.010	**-3.77**	-0.49	0.33	Julian date of annual maximum	Determine the Julian date that the maximum flow occurs for each year. Transform the dates to relative values on a circular scale (radians or degrees). Compute the x and y components for each year and average them across all years. Compute the mean angle as the arc tangent of y-mean divided by x-mean. Transform the resultant angle back to Julian date.	day of year	31.35	110.26	20.94
RA2	0.020	**3.60**	0.02	0.22	Variability in rise rate	Coefficient of variation in R_A1 (Mean rate of positive changes in flow from one day to the next. Compute the change in flow for days in which the change is positive for the entire flow record). Compute the standard deviation for the positive flow changes. RA2 is 100 times the standard deviation divided by the mean.	%	326.51	217.37	30.31
nMH2	0.039	**3.42**	0.67	-0.35	Mean maximum monthly flows (Feb)	For each year, compute the maximum flow for the month of February. MH2 is the mean (or median - Use Preference option) of these values.	dim	4.94	1.31	1.06

Serpentine River, New Brunswick (nb.Serpentine)

Index Code	p-val	z-score	load1	load2	Index Name	Description	Units	Raw Value	Class Mean	Class SD
nMA13	0.000	**37.99**	-0.35	-0.29	Normalized mean monthly flow (Feb)	Means (or medians - Use Preference option) of all February flow values over the entire record.	dim	7.38	0.62	0.18
nMA12	0.000	**32.63**	0.28	-0.42	Mean monthly flow (Jan)	Means (or medians - Use Preference option) of all January flow values over the entire record.	dim	7.42	0.83	0.20
nML1	0.000	**16.01**	-0.49	-0.41	Mean minimum monthly flows (Jan)	For each year, compute the minimum flow for the month of January. ML1 is the mean (or median - Use Preference option) of these values.	dim	2.73	0.54	0.14
TH1	0.000	**11.96**	-0.49	0.33	Julian date of annual maximum	Determine the Julian date that the maximum flow occurs for each year. Transform the dates to relative values on a circular scale (radians or degrees). Compute the x and y components for each year and average them across all years. Compute the mean angle as the arc tangent of y-mean divided by x-mean. Transform the resultant angle back to Julian date.	day of year	360.70	110.26	20.94
nMH2	0.000	**7.91**	0.67	-0.35	Mean maximum monthly flows (Feb)	For each year, compute the maximum flow for the month of February. MH2 is the mean (or median - Use Preference option) of these values.	dim	9.70	1.31	1.06
MH17	0.000	**7.55**	0.44	**0.79**	25% exceedance value	Compute the 25 percent exceedance value for the entire data record. MH17 is the 25 percent exceedance value divided by the median flow for the entire record.	dim	5.56	2.28	0.43
DA1	0.000	**5.61**	-0.58	0.37	Longest rise period	Maximum duration of consecutive periods of rising values	days	78.00	21.67	10.05
RA2	0.000	**5.39**	0.02	0.22	Variability in rise rate	Coefficient of variation in R_A1 (Mean rate of positive changes in flow from one day to the next. Compute the change in flow for days in which the change is positive for the entire flow record). Compute the standard deviation for the positive flow changes. RA2 is 100 times the standard deviation divided by the mean.	%	380.77	217.37	30.31
FH3	0.001	**4.28**	0.46	**0.77**	Days per year above 3x flow median	Compute the number of days each year that the flow is above a threshold equal to three times the median flow for the entire record. FH3 is the mean (or median – Use Preference option) of the annual number of days for all years.	days/ year	143.00	64.39	18.36
nML8	0.005	**3.94**	**-0.82**	-0.05	Mean minimum monthly flows (Aug)	For each year, compute the minimum flow for the month of August. ML8 is the mean (or median - Use Preference option) of these values.	dim	0.94	0.30	0.16
RA8	0.011	**-3.74**	0.67	-0.52	Number of reversals (day-to-day)	Compute the number of days in each year when the change in flow from one day to the next changes direction. RA8 is the average (or median - Use Preference option) of the yearly values.	events/year	12.50	76.98	17.24
MA41	0.017	**3.63**	0.43	-0.41	Specific mean annual runoff	Compute the annual mean daily flows. MA41 is the mean of the annual means divided by the drainage area.	$m^3 s^{-1}/km^2$	0.06	0.02	0.01

Following the approach in section 3.1 (cf. Figure 1, pertaining to flow class E2), Figure 3 shows the standardized PC scores on the top two principal component axes (accounting for 44% of the variability) for the class E1/E2 regulated and unregulated sites. Since this reference set deliberately combines the two eastern classes E1 and E2 distinguished by cluster analysis in Chapter 4, their 'clouds' plot somewhat separately.

Several of the regulated sites (coloured green) plot in the lower range of the reference range of PC2 scores. This suggests that these rivers have relatively short lived annual freshets with low intensity. As usual, this PC2 aspect will be analysed further below. The Kiamika River plots well below the reference range (z-score of -3 on PC2) suggesting that high flows are significantly attenuated in this system. All regulated sites plot within the PC1 reference range suggesting that these systems do not exhibit anomalous flashiness, inter-annual variability or baseflows. PC1 axis does however suggest that all regulated sites do exhibit low flashiness, low inter-annual variability and high baseflow compared to the reference class averages, especially compared to the E2 subset.

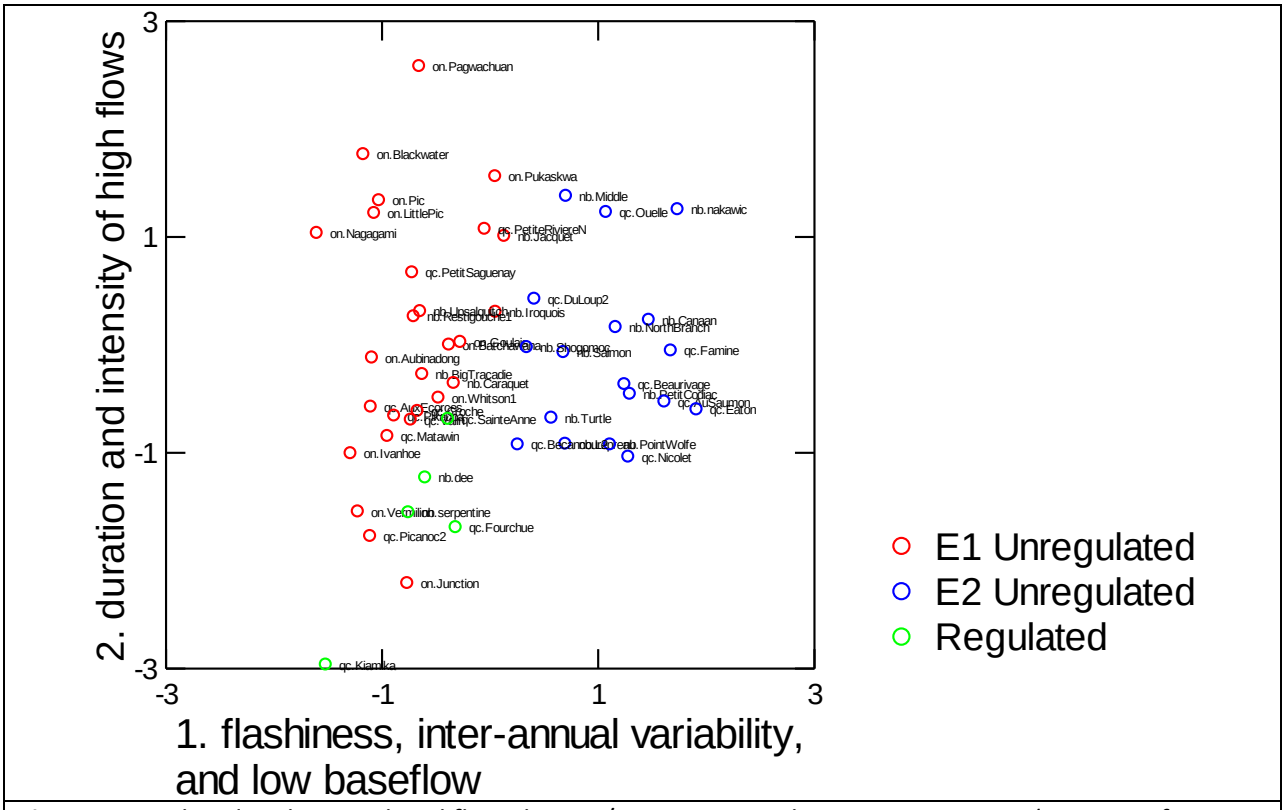


Figure 3 Regulated and unregulated flow class E1/E2 rivers in multivariate PCA space (z-scores of PC1 and PC2 scores). Regulated river location denotes number of standard deviations away from the unregulated class PC means. Axes have been named based on an evaluation of the top loading indices (Appendix 2 Table 2). PC1 explains 28.6% of the total variance. PC2 explains 16.1% of the total variance.

Similar to the analysis procedure followed in Results 3.1 (cf. Figure 2 pertaining to flow class E2), Figure 4 shows a bivariate plot defined by two of the highest loading PC2 flow indices (the

PC axis on which the Kiamika site appears most anomalous). The axes of this figure are defined by two flow indices that are top loaders and chosen as most representative of PC2 variability. Notice that two or the regulated sites plot within the range of reference class values while two others (Kiamika and Dee) appear consistent with the regional trend, but well below the natural range of index values. One regulated site (Serpentine) does not appear to follow the metric correlation pattern among E1/E2 references and this will be further discussed below.

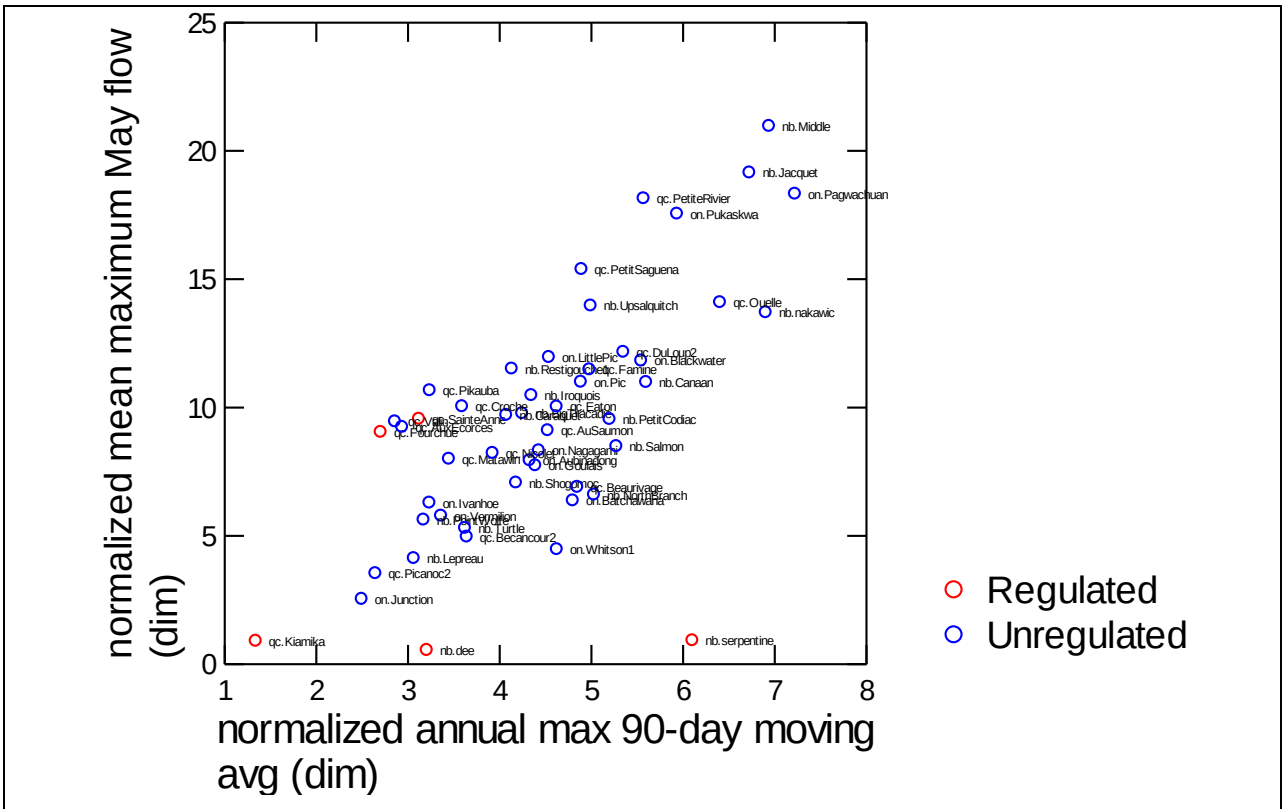


Figure 4 This plot displays 2 of the top loading indices on class E1/E2 PC2, the gradient on which the Kiamika river displays anomalous behaviour in Figure 3 (nDH5 vs. nMH5). Note that the Serpentine River does not appear to follow the trend that is apparent within the reference systems.

Fourchue River

Like the Etchemin River described in Results 3.1, Table 2 suggests that the Fourchue River's flow regime is within the range of reference values for most indices (based on a short list of anomalous metrics) but certain features are unusual. Notably, November flows are lower (z=-3.2) than the reference class distribution and March flows are higher (+2.6). Variability in daily rise rate is also anomalously high (+3.2). A below average score on the y-axis of the PC plot (Figure 3) suggests that the Fourchue river may exhibit annual freshets of lower intensity and

shorter duration compared to reference class average, but not to the extent that they can be considered regionally anomalous. Figure 4 illustrates that this is mostly due to a normalised, low 90-day moving average flow (on x-axis) that is on the low end of the range for reference systems.

The Kiamika (QC), Dee and Serpentine (N.B.) Sites

The most anomalous indices for the Kiamika River (Table 2) are similar to those described above for the Saint-Francois (Results 3.1) and thus are not characterized extensively here. Overall, based on Table 2, Figure 3 and Figure 4, it is apparent that the Kiamika River exhibits a clearly anomalously low range of flow magnitudes (lower floods and elevated baseflow) compared to the reference class. This is consistent with the extremely buffered and even somewhat inverted annual hydrograph (cf. Table 4 in Appendix 2 (p. 120)). The Kiamika hydrograph indicates unusually high and steady winter flows (z= 3.85 for February mean flows, Table 2) and very low late winter and spring discharges below the dam, as the annual snowmelt pulse is stored in the reservoir.

Flow anomalies in the Dee River and Serpentine River, New Brunswick, appear qualitatively similar based on Table 2, although anomalies are more extreme in the Serpentine River (The top three z-scores for the Serpentine describing anomalously high winter flows are greater than 15, while the Dee River only exhibits one z-score above 10 (mean February flow)). In fact, the maximum flows each year tend to occur in the first half of winter while mid-spring is most common in the reference systems (Julian date of annual maximum for the Dee is day 31 (late January) and Serpentine is day 361 (late December), while the class mean is day 110 (late April), Table 2). Despite some major flow anomalies (Table 2), neither the Dee nor Serpentine plot outside of the range of reference PC scores in Figure 3. Figure 4 shows that there is a linear correlation between the annual 90-day moving average and the maximum May flow throughout the reference sites (two top loading PC2 indices), but the Serpentine River does not follow this trend. This is evidence that the Serpentine River's PC2 score is not systematically loaded by the top loading PC2 indices in the same way as the reference class. Although the

Serpentine's normalized mean maximum May flow is lower than the range of reference values, the 90-day moving average is actually slightly higher than the reference class mean.

3.3. Flow Regime Anomalies in the Regulated Shuswap River: Compared to Reference Class W2/W3 - Western Cordillera Rivers in Albert and British Columbia

Table 3 presents the most anomalous flow indices for the 2 sites on the Shuswap river (BC) assigned to pooled flow classes W2/W3 (western cordillera rivers in Alberta and British Columbia). Here again most seasonality/timing indices (blue) and predictability indices (green) are not high loaders on the top principal components of the W2/W3 reference set, suggesting that throughout the reference systems, other groups of flow regime features dominate variability. Many specific anomalies exceed 3 and some range up to 5.1.

Table 3 The most anomalous flow indices and their PC loadings for Class W2/W3 regulated rivers

Shuswap River, British Columbia, Site 1 (bc.Shuswap1.Sugar)

Index Code	p-val	z-score	load1	load2	Index Name	Description	Units	Raw Value	Class Mean	Class SD
TL2	0.000	**5.11**	0.48	-0.17	Variability in Julian date of annual minimum	Circular variance in T_L1. Compute the sum of the cosines of the difference between each angle (dates on a circular scale) and the circular mean (TL1 before the back-transformation). TL2 is 1 minus the ratio of the sum of cosines divided by the sample size (number of years).	dim	0.76	0.2	0.11
ML17	0.000	**4.45**	-0.29	**-0.86**	7-day minimum baseflow	Compute the mean annual flows. Compute the minimum of a 7-day moving average flow for each year and divide them by the mean annual flow for that year. ML17 is the mean (or median - Use Preference option) of those ratios.	dim	0.38	0.14	0.06
DL12	0.009	**3.82**	0.06	**-0.79**	Normalized 7-day annual minimum flow	Annual minimum of 7-day moving average flow divided by the median for the entire record. Compute the minimum of a 7-day moving average flow for each year. DL12 is the mean of these values divided by the median for the entire record.	dim	0.63	0.33	0.09
RA8	0.021	**-3.6**	-0.42	0.54	Number of reversals (day-to-day)	Compute the number of days in each year when the change in flow from one day to the next changes direction. RA8 is the average (or median - Use Preference option) of the yearly values.	events/year	34	90.45	15.69
nML1	0.040	**3.42**	**0.8**	-0.25	Mean minimum monthly flows (Jan)	For each year, compute the minimum flow for the month of January. ML1 is the mean (or median - Use Preference option) of these values.	dim	0.76	0.4	0.10
MA6	0.041	**3.41**	-0.32	**-0.81**	Ratio of low flow (Q90) to high flow (Q10) quantiles	Range in daily flows is the ratio of the 90 percent to 10 percent exceedance values for the entire flow record (low flow/high flow). Compute the 90 percent and 10 percent exceedance values for the entire flow record. Exceedance is computed by interpolating between the ordered (descending) flow values. Divide the 90 percent exceedance value by the 10 percent value.	dim	0.17	0.06	0.03

Shuswap River, British Columbia, Site 2 (bc.Shuswap2.Wilsey)

Index Code	p-val	z-score	load1	load2	Index Name	Description	Units	Raw Value	Class Mean	Class SD
TL2	0.000	**4.54**	0.48	-0.17	Variability in Julian date of annual minimum	Circular variance in T_L1. Compute the sum of the cosines of the difference between each angle (dates on a circular scale) and the circular mean (TL1 before the back-transformation). TL2 is 1 minus the ratio of the sum of cosines divided by the sample size (number of years).	dim	0.69	0.20	0.11
ML17	0.003	**4.06**	-0.29	**-0.86**	7-day minimum baseflow	Compute the mean annual flows. Compute the minimum of a 7-day moving average flow for each year and divide them by the mean annual flow for that year. ML17 is the mean (or median - Use Preference option) of those ratios.	dim	0.36	0.14	0.06
DL12	0.006	**3.91**	0.06	**-0.79**	Normalized 7-day annual minimum flow	Annual minimum of 7-day moving average flow divided by the median for the entire record. Compute the minimum of a 7-day moving average flow for each year. DL12 is the mean of these values divided by the median for the entire record.	dim	0.63	0.33	0.08

Figure 5 shows the standardized PC scores (on the top two principal component axes) for the class W2/W3 for the regulated and unregulated sites. Again, it is easy to distinguish between the two subclasses forming reference flow class W2/W3. Notice that both of the regulated sites fall within the range of reference scores on PC1 but both are anomalously low on PC2, with z-scores approaching -2.5 to -3 on PC2. This suggests that the range of flow magnitude is low relative to the reference class (floods are not severe and baseflow is high).

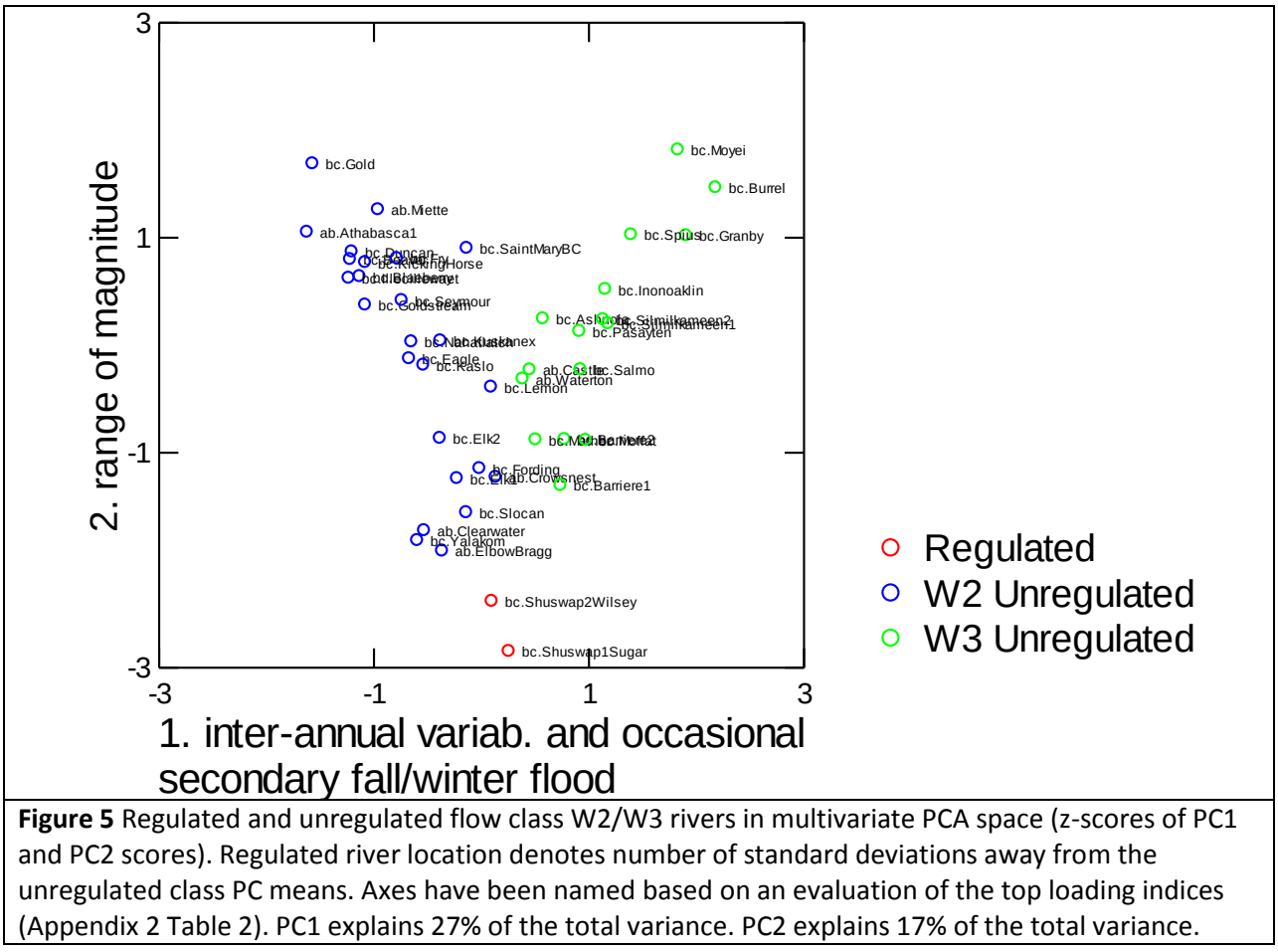


Figure 5 Regulated and unregulated flow class W2/W3 rivers in multivariate PCA space (z-scores of PC1 and PC2 scores). Regulated river location denotes number of standard deviations away from the unregulated class PC means. Axes have been named based on an evaluation of the top loading indices (Appendix 2 Table 2). PC1 explains 27% of the total variance. PC2 explains 17% of the total variance.

Figure 6 is a bivariate plot defined by two of the highest loading PC2 flow indices (the PC axis on which the regulated Shuswap sites appear anomalous). Overall, the regulated sites exhibit relatively systematic anomalous behaviour on the indices loading PC2, however this plot suggests that increased baseflow (x-axis) is larger driver of the low PC2 scores for these sites than indices characterizing high flows (such as days/year above 3x median flow on the y-axis).

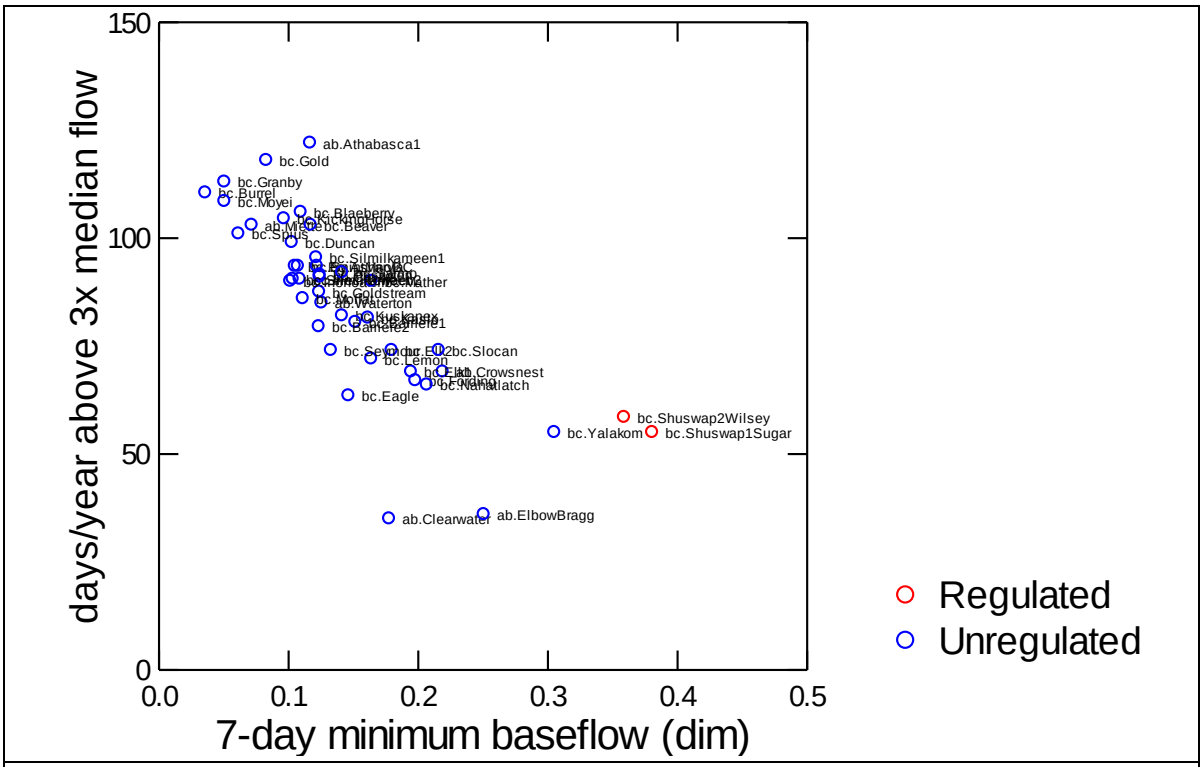


Figure 6 This plot displays 2 of the top 4 loading indices on flow class W2/W3 PC2, the gradient on which the Shuswap river sites display anomalous behaviour (ML17 vs. FH3).

Shuswap River Sites

The two regulated sites in flow class W2/W3 are both located on the Shuswap River (below two separate dams). First it is notable that the flow regimes are similar at these regulated sites. The strongest anomaly at both sites is the high variability of the date of minimum flow, with z-scores of 4.5 to 5.1 (Table 3). Many of the other top anomalies are important loaders on PC2 (describing range of magnitude for flow class W2/W3). Figure 5 suggests that, in general terms, the Shuswap systems have unusually low ranges of magnitudes (PC2 z-scores between -2.5 and -3). Figure 6 zooms in on two specific metrics that are high loaders on PC2 over the reference set. It shows that both elevated baseflows and relatively low flows (few days 3x median) at the Shuswap river sites contribute to the anomalously low range of magnitude, with the former effect the stronger anomaly with respect to the trend association for reference rivers.

3.4. Flow Regime Anomalies in the Regulated Bull and Kananaskis Rivers: Compared to Reference Class W2 - High Relief Western Cordillera Rivers in Alberta and British Columbia

Table 4 presents the most anomalous flow indices for 3 regulated river sites that were assigned to flow class W2 (as described in Chapter 4, these are high relief rivers with Rocky Mountain headwaters in Alberta and British Columbia). Unlike equivalent tables in previous sections, Table 4 lists index loadings for the top three, rather than top two, principal components of W2 reference site variability. This is because PC2 and PC3 explain roughly the same amount of index variance across the reference set. It is notable that for the two regulated Kananaskis River segments presented in Table 4, the lists of anomalous indices are very long. In more instances than any other flow class presented above, seasonality/timing flow indices are important loaders to the principal components of variability characterizing the unregulated reference class. This seems to reflect the variable effect across this reference set of the range of watershed elevations in timing of recession of glacier and high mountain snowpack runoff. The Kananaskis sites also have anomalous z-scores as high as 10-25 on some indices. These two regulated sites, Kananaskis Pocaterra and Kananaskis Barrier, lie below hydropeaking dams and the effects of this mode of regulation on our analyses will be discussed below.

Table 4 The most anomalous flow indices and their PC loadings for Class W2 regulated rivers

Bull River, British Columbia (bc.Bull)

Index Code	p-val	z-score	load1	load2	Load3	Index Name	Description	Units	Raw Value	Class Mean	Class SD
nMA15	*1.000	**2.39**	0.46	**-0.79**	0.08	Mean monthly flow (Apr)	Means (or medians - Use Preference option) of all April flow values over the entire record.	dim	1.74	0.95	0.33
TL2	*1.000	**-2.19**	0.22	-0.12	-0.13	Variability in Julian date of annual minimum	Circular variance in T_L1. Compute the sum of the cosines of the difference between each angle (dates on a circular scale) and the circular mean (TL1 before the back-transformation). TL2 is 1 minus the ratio of the sum of cosines divided by the sample size (number of years).	day of year	0.04	0.15	0.05
TH1	*1.000	**-1.67**	-0.39	0.59	-0.47	Julian date of annual maximum	Determine the Julian date that the maximum flow occurs for each year. Transform the dates to relative values on a circular scale (radians or degrees). Compute the x and y components for each year and average them across all years. Compute the mean angle as the arc tangent of y-mean divided by x-mean. Transform the resultant angle back to Julian date.	day of year	147.99	161.85	8.29

Kananaskis River, Alberta, Below Pocaterra Dam (ab.KananaskisPocaterra)

Index Code	p-val	z-score	load1	load2	Load3	Index Name	Description	Units	Raw Value	Class Mean	Class SD
ML20	0.000	**24.08**	-0.61	-0.46	-0.32	5-day-block baseflow (inverse measure)	Divide the daily flow record into 5-day blocks. Find the minimum flow for each block. Assign the minimum flow as a base flow for that block if 90 percent of that minimum flow is less than the minimum flows for the blocks on either side. Otherwise, set it to zero. Fill in the zero values using linear interpolation. Compute the total flow	dim	3.54	1.33	0.09

							for the entire record and the total base flow for the entire record. ML20 is the ratio of total flow to total base flow.				
TH1	0.000	**23.00**	-0.39	0.59	-0.47	Julian date of annual maximum	Determine the Julian date that the maximum flow occurs for each year. Transform the dates to relative values on a circular scale (radians or degrees). Compute the x and y components for each year and average them across all years. Compute the mean angle as the arc tangent of y-mean divided by x-mean. Transform the resultant angle back to Julian date.	day of year	352.58	161.85	8.29
FH10	0.000	**20.85**	-0.07	0.31	0.38	Flood frequency 4	Compute for each year the number of flow events with flows above a threshold equal to the median of the annual minimums for the entire flow record. FH10 is the mean (or median - Use Preference option) number of events per year.	events/year	8.50	1.56	0.33
FL1	0.000	**19.20**	0.10	0.04	-0.30	Low flow frequency 1 (Low flood pulse count)	Compute for each year the number of flow events with flows below a threshold equal to the 25th percentile value for the entire flow record. FL1 is the mean (or median - Use Preference option) number of events per year.	events/year	28.50	4.04	1.27
nMA12	0.000	**17.32**	**0.81**	0.02	0.23	Mean monthly flow (Jan)	Means (or medians - Use Preference option) of all January flow values over the entire record.	dim	2.10	0.45	0.10
nMH2	0.000	**17.07**	**0.85**	0.02	-0.05	Mean maximum monthly flows (Feb)	For each year, compute the maximum flow for the month of February. MH2 is the mean (or median - Use Preference option) of these values.	dim	2.52	0.48	0.12
FH1	0.000	**16.16**	-0.39	-0.47	-0.68	Flood frequency 1 (High flood pulse count)	Compute for each year the number of flow events with flows above a threshold equal to the 75th percentile value for the entire flow record. FH1 is the mean (or median - Use Preference option) number of events per year.	events/year	28.00	3.74	1.50
RA15	0.000	**14.65**	-0.44	-0.67	-0.39	Relative rise rate	Mean of the relative change in daily values for days where change is positive. SUM((value(t) - value(t-1))/value(t)), where value(t) is the daily mean value on day t.	%	37.31	8.24	1.98
DL7	0.000	**13.66**	0.23	0.14	-0.17	Variability of annual minimum of 3-day moving average flow	Coefficient of variation. Compute the standard deviation for the minimum 3-day moving averages. DL7 is 100 times the standard deviation divided by the mean.	%	102.76	21.38	5.96
ML18	0.000	**9.27**	0.42	0.41	-0.18	Variability in Baseflow Index 1	Coefficient of variation in ML17. Compute the standard deviation for the ratios of 7-day moving average flows to mean annual flows for each year. ML18 is the standard deviation times 100 divided by the mean of the ratios.	%	87.96	23.64	6.94
DA4	0.000	**-7.51**	0.36	-0.09	0.17	Median fall period	Median duration of consecutive periods of falling values	days	1.00	3.08	0.28
RA8	0.000	**5.58**	-0.64	-0.15	-0.24	Number of reversals (day-to-day)	Compute the number of days in each year when the change in flow from one day to the next changes direction. RA8 is the average (or median - Use Preference option) of the yearly values.	events/year	168.00	95.16	13.05
nML6	0.004	**-4.00**	-0.45	-0.14	**0.82**	Mean minimum monthly flows (Jun)	For each year, compute the minimum flow for the month of June. ML6 is the mean (or median - Use Preference option) of these values.	dim	0.01	4.39	1.10
FH3	0.015	**-3.64**	**-0.91**	0.02	0.23	Days per year above 3x flow median	Compute the number of days each year that the flow is above a threshold equal to three times the median flow for the entire record. FH3 is the mean (or median – Use Preference option) of the annual number of days for all years.	days/year	0.00	81.54	22.38
nMA22	0.027	**3.48**	0.35	-0.50	0.00	Mean monthly flow (Nov)	Means (or medians - Use Preference option) of all November flow values over the entire record.	dim	1.16	0.83	0.10
DL12	0.029	**-3.46**	**0.81**	0.06	0.36	Normalized 7-day annual minimum flow	Annual minimum of 7-day moving average flow divided by the median for the entire record. Compute the minimum of a 7-day moving average flow for each year. DL12 is the mean of these values divided by the median for the entire record.	dim	0.05	0.33	0.08

Kananaskis River, Alberta, Below Barrier Dam (ab.KananaskisBarrier)

Index Code	**p-val**	**z-score**	load1	load2	Load3	Index Name	Description	Units	Raw Value	Class Mean	Class SD
FL1	0.000	**26.26**	0.10	0.04	-0.30	Low flow frequency 1 (Low flood pulse count)	Compute for each year the number of flow events with flows below a threshold equal to the 25th percentile value for the entire flow record. FL1 is the mean (or median - Use Preference option) number of events per year.	events/year	37.50	4.04	1.27
FH1	0.000	**18.50**	-0.39	-0.47	-0.68	Flood frequency 1 (High flood pulse count)	Compute for each year the number of flow events with flows above a threshold equal to the 75th percentile value for the entire flow record. FH1 is the mean (or median - Use Preference option) number of events per year.	events/year	31.50	3.74	1.50
DL7	0.000	**9.10**	0.23	0.14	-0.17	Variability of annual minimum of 3-day moving	Coefficient of variation. Compute the standard deviation for the minimum 3-day moving averages. DL7 is 100 times the standard deviation divided by the mean.	%	75.62	21.38	5.96

						average flow					
TL2	0.000	**8.91**	0.22	-0.12	-0.13	Variability in Julian date of annual minimum	Circular variance in T_L1. Compute the sum of the cosines of the difference between each angle (dates on a circular scale) and the circular mean (TL1 before the back-transformation). TL2 is 1 minus the ratio of the sum of cosines divided by the sample size (number of years).	day of year	0.58	0.15	0.05
RA15	0.000	**8.10**	-0.44	-0.67	-0.39	Relative rise rate	Mean of the relative change in daily values for days where change is positive. SUM((value(t) - value(t-1))/value(t)), where value(t) is the daily mean value on day t.	%	24.31	8.24	1.98
ML20	0.000	**7.67**	-0.61	-0.46	-0.32	5-day-block baseflow (inverse measure)	Divide the daily flow record into 5-day blocks. Find the minimum flow for each block. Assign the minimum flow as a base flow for that block if 90 percent of that minimum flow is less than the minimum flows for the blocks on either side. Otherwise, set it to zero. Fill in the zero values using linear interpolation. Compute the total flow for the entire record and the total base flow for the entire record. ML20 is the ratio of total flow to total base flow.	dim	2.04	1.33	0.09
MA6	0.000	**6.97**	**0.89**	0.26	-0.28	Ratio of low flow (Q90) to high flow (Q10) quantiles	Range in daily flows is the ratio of the 90 percent to 10 percent exceedance values for the entire flow record (low flow/high flow). Compute the 90 percent and 10 percent exceedance values for the entire flow record. Exceedance is computed by interpolating between the ordered (descending) flow values. Divide the 90 percent exceedance value by the 10 percent value.	dim	0.32	0.07	0.04
nMA12	0.000	**6.84**	**0.81**	0.02	0.23	Mean monthly flow (Jan)	Means (or medians - Use Preference option) of all January flow values over the entire record.	dim	1.10	0.45	0.10
nMH2	0.000	**6.49**	**0.85**	0.02	-0.05	Mean maximum monthly flows (Feb)	For each year, compute the maximum flow for the month of February. MH2 is the mean (or median - Use Preference option) of these values.	dim	1.26	0.48	0.12
RA8	0.000	**5.97**	-0.64	-0.15	-0.24	Number of reversals (day-to-day)	Compute the number of days in each year when the change in flow from one day to the next changes direction. RA8 is the average (or median - Use Preference option) of the yearly values.	events/year	173.00	95.16	13.05
ML17	0.000	**4.82**	**0.91**	0.09	-0.07	7-day minimum baseflow	Compute the mean annual flows. Compute the minimum of a 7-day moving average flow for each year and divide them by the mean annual flow for that year. ML17 is the mean (or median - Use Preference option) of those ratios.	dim	0.43	0.15	0.06
MA3	0.000	**-4.46**	-0.50	-0.29	**0.75**	Annual variability in daily flows 1	Mean (or median - Use Preference option) of the coefficients of variation (standard deviation/mean) for each year. Compute the coefficient of variation for each year of daily flows and then compute the mean of the annual coefficients of variation.	%	46.29	113.78	15.14
FH10	0.001	**4.33**	-0.07	0.31	0.38	Flood frequency 4	Compute for each year the number of flow events with flows above a threshold equal to the median of the annual minimums for the entire flow record. FH10 is the mean (or median - Use Preference option) number of events per year.	events/year	3.00	1.56	0.33
DH16	0.003	**4.02**	-0.02	0.56	-0.31	Variability in High flow duration 1	Coefficient of variation in D_H15. Compute the standard deviation for the yearly average high flow durations. DH16 is 100 times the standard deviation divided by the mean of the yearly average high pulse durations.	%	123.69	58.55	16.21
DA4	0.005	**-3.90**	0.36	-0.09	0.17	Median fall period	Median duration of consecutive periods of falling values	days	2.00	3.08	0.28
FH3	0.015	**-3.64**	**-0.91**	0.02	0.23	Days per year above 3x flow median	Compute the number of days each year that the flow is above a threshold equal to three times the median flow for the entire record. FH3 is the mean (or median – Use Preference option) of the annual number of days for all years.	days/year	0.00	81.54	22.38
DL16	0.032	**-3.43**	-0.40	-0.07	0.19	Low flow pulse duration	Compute the average pulse duration for each year for flow events below a threshold equal to the 25th percentile value for the entire flow record. DL16 is the median of the yearly average durations.	days	2.10	22.74	6.03
TA1	0.039	**3.37**	0.46	0.25	-0.36	Constancy	Constancy is computed via the formulation of Colwell (see example in Colwell, 1974)	dim	0.43	0.18	0.07
nML6	0.039	**-3.37**	-0.45	-0.14	**0.82**	Mean minimum monthly flows (Jun)	For each year, compute the minimum flow for the month of June. ML6 is the mean (or median - Use Preference option) of these values.	dim	0.70	4.39	1.10

Figure 7 shows the standardized scores for PC1 versus PC2 for the class W2 regulated and unregulated sites. Figure 8 shows the standardized scores for PC1 versus PC3. Note that the

three regulated sites plot within the range of principal component scores for PC1 and PC2 (although in the lower range for PC2), while the two Kananaskis regulated sites plot well below the reference range of PC3 scores (Figure 8). Based on high loading metrics driving PC3 (confer. Table 2 in Appendix 2 (p. 110)), this suggests that the range of monthly mean flows and the overall range of magnitudes of daily flows are anomalously low at these sites compared to the reference class flow regimes.

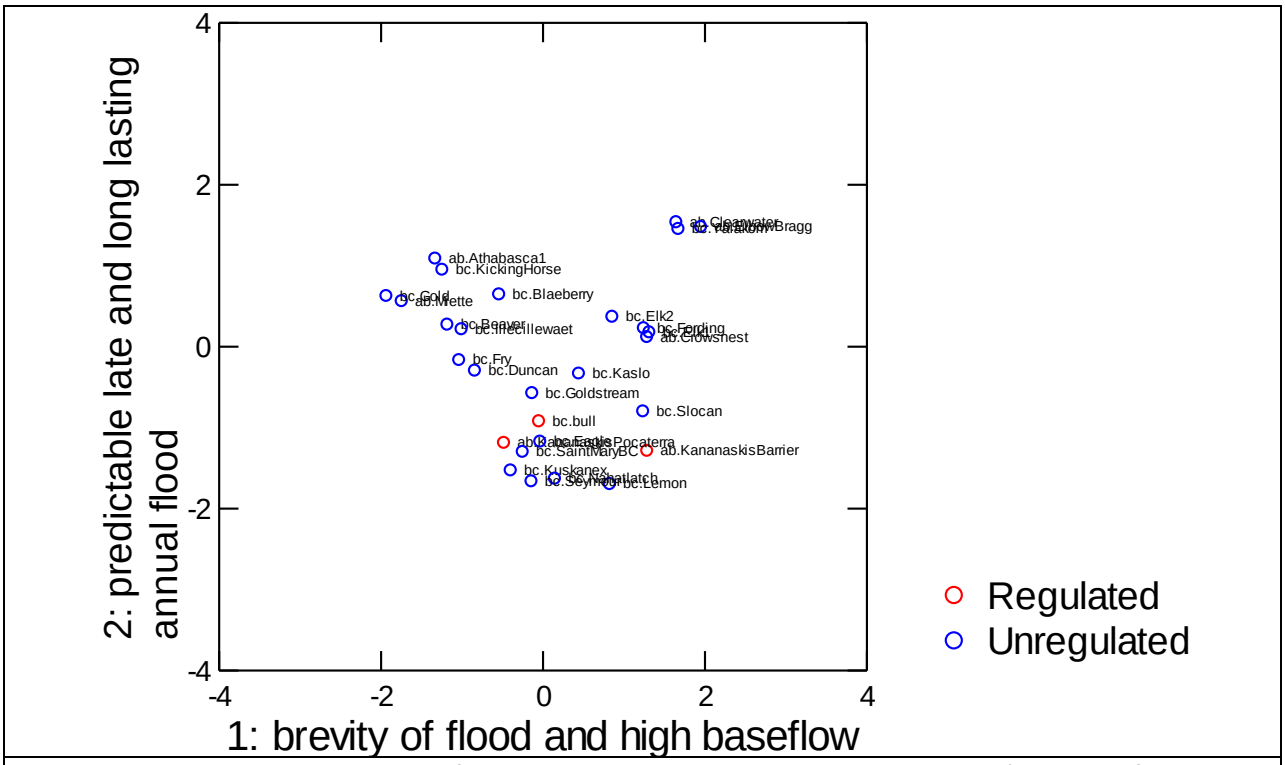


Figure 7 Regulated and unregulated flow class W2 rivers in multivariate PCA space (z-scores of PC1 and PC2 scores). Regulated river location denotes number of standard deviations away from the unregulated class PC means. Axes have been named based on an evaluation of the top loading indices (Appendix 2 Table 2). PC1 explains 30.1% of the total variance. PC2 explains 13.9% of the total variance.

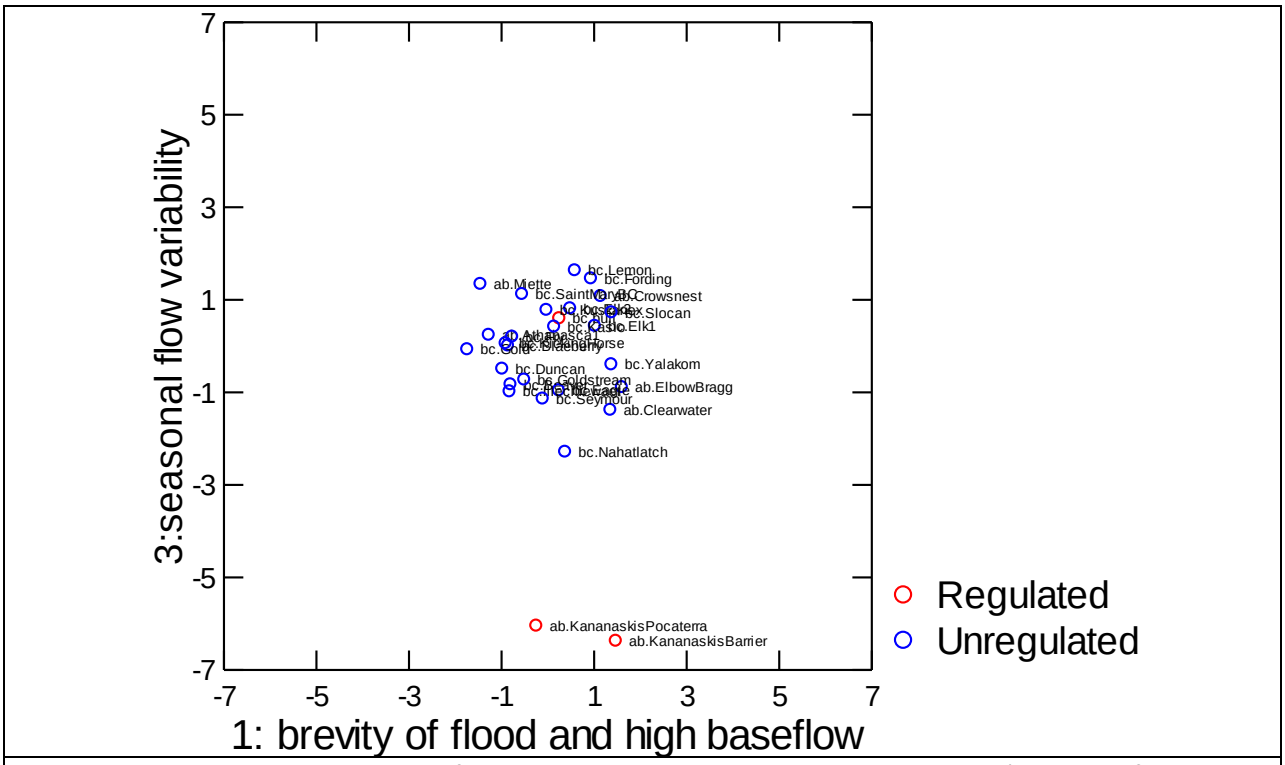


Figure 8 Regulated and unregulated flow class W2 rivers in multivariate PCA space (z-scores of PC1 and PC3 scores). Regulated river location denotes number of standard deviations away from the regulated class PC means. Axes have been named based on an evaluation of the top loading indices (Appendix 2 Table 2). PC1 explains 30.1% of the total variance. PC3 explains 13.1% of the total variance.

Figure 9 is a bivariate plot defined by two of the highest loading PC3 flow indices (the W2 PC axis on which two Kananaskis sites appear anomalous, with PC3 z-scores below -5). The high loading PC3 indices are anomalous on both axes for the two segments of the Kananaskis River (confer the red points that plot in the bottom left portion of the graph). However, Figure 9 illustrates again how anomalies on PC scores can be driven by different specific indices at each site. The Kananaskis Pocaterra site on Figure 9 lies at the low end but nearly within the range of reference values for the variability in daily flows (y-axis).

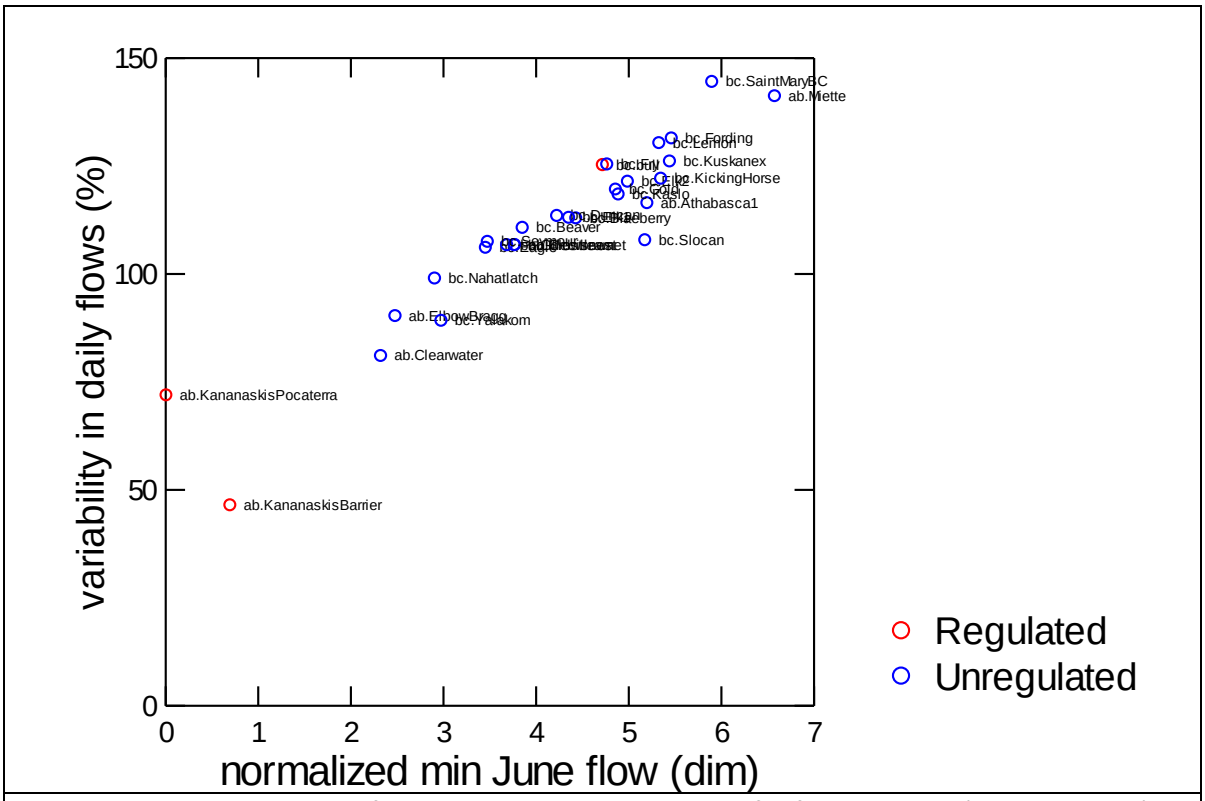


Figure 9 This plot displays 2 of the top loading indices on PC3 for flow class W2 (nML6 vs. MA3), the axis on which the Kananaskis river sites display anomalous behaviour.

Bull and Kananaskis Rivers

Like the Etchemin River in Quebec, the Bull River in B.C. displays flows within the range of unregulated reference variability: it does not exhibit clearly anomalous flow index scores compared to the regional reference class W2 (Table4), it plots near the centre of the cluster of unregulated W2 reference rivers in Figures 8 and 9 and in Table 4 its highest z-scores are barely over 2, and this for only a few indices.

The two sites on the Kananaskis River, Alberta, (below Barrier Dam and Pocaterra Dam) have many highly anomalous flow index scores. Table 4 suggests that at both of these sites, spring mean daily flows are atypically low (z=-4 at Pocaterra and -3.4 and Barrier for mean minimum June flows), while winter mean daily flows are much higher than those in the reference region (z= 17.3 at Pocaterra and 6.8 and Barrier for mean January flow). Downstream from the Pocattera dam, the date of annual maximum mean daily flow occurs in most often in mid-December whereas the reference class average data of annual maximum occurs in mid-June

(See the raw values for the Julian date of annual maximum index, Table 4). The date of annual maximum flow below the Barrier dam does not appear anomalous.

Note however that the dams' operation on the Kananaskis River involves daily hydropeaking. As hourly data was available only for a subset of study rivers, metrics of peaking are not fully analysed in this chapter where we concentrate on daily flow series. However, in peaking systems sub-daily time scale flow behaviour is strongly anomalous compared to regional reference systems. This is exemplified in our preliminary analysis of hydrologic indices using hourly flow data for the rivers affected by hydropeaking facilities (Table 5 in Appendix 2 (p. 126)).

Because of complex sub-daily behaviour, inter-day variability in daily flow series on peaking systems may have multiple interpretations. For example a higher daily mean than previous days may reflect more hours that day at the same peak powerhouse discharge, with no greater peak flow released. Periods ascribed as baseflow based on daily series may be multi-day periods with stable, moderate flows but no peaking releases, while minimum flows on some peaking days may be lower than this flow level. Thus the interpretation of certain daily flow indices must be carefully considered on peaking systems based on additional data.

However, we argue that the aspects of anomalous overall seasonality, timing of multi-day high flow or low flow periods based on daily series may have ecological significance in themselves, over and beyond the issues of physiological stresses and possible mortality imposed by hourly peaking.

3.5. Flow Regime Anomalies in the Regulated Saint-Jean, Magpie, Mississagi and Michipicoten Rivers: Compared to Reference Class E1 - Eastern Shield Rivers in Ontario and Quebec

Table 5 presents the most anomalous flow indices for each regulated river assigned to flow class E1 in Chapter 4 (eastern shield rivers in Ontario and Quebec). Similarly to flow class W2, several seasonality/timing indices are important determinants of the top two principal

component scores (high loaders) within flow class E1. Three of the sites listed in Table 5 are characterized by many highly anomalous indices. As in flow class W2, several sites (on the Magpie, Michipicoten and Mississagi Rivers) are also below hydropeaking dams.

Table 5 The most anomalous flow indices and their PC loadings for Class E1 regulated rivers

Saint-Jean River, Quebec (qc.SaintJean)

Index Code	p-val	z-score	load1	load2	Index Name	Description	Units	Raw Value	Class Mean	Class SD
MA42	*1.000	**-2.49**	0.58	-0.17	Variability across annual flows (0-100)	Range of annual flows divided by median annual flows. MA42 is the maximum of the annual mean flows minus the minimum of the annual mean flows divided by the median of the annual mean flows.	dim	0.31	0.71	0.16
RA9	*1.000	**2.29**	0.01	0.28	Variability in reversals	Coefficient of variation in R_A8. Compute the standard deviation for the yearly reversal values. RA9 is 100 times the standard deviation divided by the mean.	%	135.53	54.20	35.55
FH1	*1.000	**2.28**	-0.28	0.20	Flood frequency 1 (High flood pulse count)	Compute for each year the number of flow events with flows above a threshold equal to the 75th percentile value for the entire flow record. FH1 is the mean (or median - Use Preference option) number of events per year.	events/year	10.50	5.61	2.15

Magpie River, Ontario (on.Magpie)

Index Code	p-val	z-score	load1	load2	Index Name	Description	Units	Raw Value	Class Mean	Class SD
FL1	0.000	**13.93**	-0.19	0.64	Low flow frequency 1 (Low flood pulse count)	Compute for each year the number of flow events with flows below a threshold equal to the 25th percentile value for the entire flow record. FL1 is the mean (or median - Use Preference option) number of events per year.	events/year	26.00	4.20	1.56
RA8	0.000	**7.54**	-0.52	0.49	Number of reversals (day-to-day)	Compute the number of days in each year when the change in flow from one day to the next changes direction. RA8 is the average (or median - Use Preference option) of the yearly values.	events/year	190.00	69.00	16.04
RA5	0.000	**7.08**	-0.64	-0.04	Proportion of rise days (Number of day rises)	Compute the number of days in which the flow is greater than the previous day. RA5 is the number of positive gain days divided by the total number of days in the flow record.	dim	0.50	0.28	0.03
FH1	0.000	**6.47**	-0.28	0.20	Flood frequency 1 (High flood pulse count)	Compute for each year the number of flow events with flows above a threshold equal to the 75th percentile value for the entire flow record. FH1 is the mean (or median - Use Preference option) number of events per year.	events/year	19.50	5.61	2.15
nMH2	0.000	**5.11**	**-0.72**	0.39	Mean maximum monthly flows (Feb)	For each year, compute the maximum flow for the month of February. MH2 is the mean (or median - Use Preference option) of these values.	dim	1.87	0.73	0.22
ML17	0.001	**4.28**	**-0.82**	-0.40	7-day minimum baseflow	Compute the mean annual flows. Compute the minimum of a 7-day moving average flow for each year and divide them by the mean annual flow for that year. ML17 is the mean (or median - Use Preference option) of those ratios.	dim	0.39	0.16	0.06
MA6	0.017	**3.65**	**-0.92**	-0.16	Ratio of low flow (Q90) to high flow (Q10) quantiles	Range in daily flows is the ratio of the 90 percent to 10 percent exceedance values for the entire flow record (low flow/high flow). Compute the 90 percent and 10 percent exceedance values for the entire flow record. Exceedance is computed by interpolating between the ordered (descending) flow values. Divide the 90 percent exceedance value by the 10 percent value.	dim	0.23	0.09	0.04
DL12	0.027	**3.52**	-0.61	-0.44	Normalized 7-day annual minimum flow	Annual minimum of 7-day moving average flow divided by the median for the entire record. Compute the minimum of a 7-day moving average flow for each year. DL12 is the mean of these values divided by the median for the entire record.	dim	0.49	0.29	0.06
DA2	0.032	**-3.47**	0.32	-0.28	Median rise period	Median duration of consecutive periods of rising values	days	1.00	2.11	0.32
nMA13	0.049	**3.34**	-0.29	-0.34	Mean monthly flow (Feb)	Means (or medians - Use Preference option) of all February flow values over the entire record.	dim	1.24	0.62	0.19

Mississagi River, Ontario (on.Mississagi)

Index Code	p-val	z-score	load1	load2	Index Name	Description	Units	Raw Value	Class Mean	Class SD
FL1	0.000	**16.81**	-0.19	0.64	Low flow frequency 1 (Low flood pulse count)	Compute for each year the number of flow events with flows below a threshold equal to the 25th percentile value for the entire flow record. FL1 is the mean (or median - Use Preference option) number of events per year.	events/year	30.50	4.20	1.56
nMH2	0.000	**13.41**	**-0.72**	0.39	Mean maximum monthly flows (Feb)	For each year, compute the maximum flow for the month of February. MH2 is the mean (or median - Use Preference option) of these values.	dim	3.72	0.73	0.22

RA8	0.000	**8.70**	-0.52	0.49	Number of reversals (day-to-day)	Compute the number of days in each year when the change in flow from one day to the next changes direction. RA8 is the average (or median - Use Preference option) of the yearly values.	events/year	208.50	69.00	16.04
nMA13	0.000	**8.45**	-0.29	-0.34	Mean monthly flow (Feb)	Means (or medians - Use Preference option) of all February flow values over the entire record.	dim	2.19	0.62	0.19
FH1	0.000	**8.11**	-0.28	0.20	Flood frequency 1 (High flood pulse count)	Compute for each year the number of flow events with flows above a threshold equal to the 75th percentile value for the entire flow record. FH1 is the mean (or median - Use Preference option) number of events per year.	events/year	23.00	5.61	2.15
RA5	0.000	**7.28**	-0.64	-0.04	Proportion of rise days (Number of day rises)	Compute the number of days in which the flow is greater than the previous day. RA5 is the number of positive gain days divided by the total number of days in the flow record.	dim	0.50	0.28	0.03
MA24	0.000	**4.59**	-0.13	0.44	Variability in monthly flows (Jan)	Variability (coefficient of variation) of January flow values. Compute the standard deviation for January in each year over the entire flow record. Divide the standard deviation by the mean for January in each year. Average (or median - Use Preference option) these values across all years.	%	0.50	0.28	0.03
nMH8	0.001	**4.43**	0.23	-0.51	Mean maximum monthly flows (Aug)	For each year, compute the maximum flow for the month of August. MH8 is the mean (or median - Use Preference option) of these values.	dim	64.30	22.90	9.02
nMA12	0.002	**4.13**	-0.61	0.49	Mean monthly flow (Jan)	Means (or medians - Use Preference option) of all January flow values over the entire record.	dim	1.48	0.77	0.17
RA15	0.005	**3.94**	0.32	0.57	Relative rise rate	Mean of the relative change in daily values for days where change is positive. SUM((value(t) - value(t-1))/value(t)), where value(t) is the daily mean value on day t.	%	27.86	12.71	3.84
DA4	0.008	**-3.80**	0.38	-0.12	Median fall period	Median duration of consecutive periods of falling values	days	1.00	4.22	0.85
ML20	0.010	**3.76**	0.62	0.43	5-day-block baseflow (inverse measure)	Divide the daily flow record into 5-day blocks. Find the minimum flow for each block. Assign the minimum flow as a base flow for that block if 90 percent of that minimum flow is less than the minimum flows for the blocks on either side. Otherwise, set it to zero. Fill in the zero values using linear interpolation. Compute the total flow for the entire record and the total base flow for the entire record. ML20 is the ratio of total flow to total base flow.	dim	2.10	1.58	0.14
DA2	0.030	**-3.47**	0.32	-0.28	Median rise period	Median duration of consecutive periods of rising values	days	1.00	2.11	0.32

Michipicoten River, Ontario (on.Michipicoten)

Index Code	p-val	z-score	load1	load2	Index Name	Description	Units	Raw Value	Class Mean	Class SD
FL1	0.000	**13.29**	-0.19	0.64	Low flow frequency 1 (Low flood pulse count)	Compute for each year the number of flow events with flows below a threshold equal to the 25th percentile value for the entire flow record. FL1 is the mean (or median - Use Preference option) number of events per year.	events/year	25.00	4.20	1.56
RA8	0.000	**6.86**	-0.52	0.49	Number of reversals (day-to-day)	Compute the number of days in each year when the change in flow from one day to the next changes direction. RA8 is the average (or median - Use Preference option) of the yearly values.	events/year	179.00	69.00	16.04
RA5	0.000	**6.55**	-0.64	-0.04	Proportion of rise days (Number of day rises)	Compute the number of days in which the flow is greater than the previous day. RA5 is the number of positive gain days divided by the total number of days in the flow record.	dim	0.48	0.28	0.03
nMA13	0.002	**4.3**	-0.29	-0.34	Mean monthly flow (Feb)	Means (or medians - Use Preference option) of all February flow values over the entire record.	dim	1.42	0.62	0.19
nMH2	0.005	**3.94**	**-0.72**	0.39	Mean maximum monthly flows (Feb)	For each year, compute the maximum flow for the month of February. MH2 is the mean (or median - Use Preference option) of these values.	dim	1.61	0.73	0.22
FH1	0.006	**3.91**	-0.28	0.20	Flood frequency 1 (High flood pulse count)	Compute for each year the number of flow events with flows above a threshold equal to the 75th percentile value for the entire flow record. FH1 is the mean (or median - Use Preference option) number of events per year.	events/year	14.00	5.61	2.15
ML17	0.009	**3.80**	**-0.82**	-0.40	7-day minimum baseflow	Compute the mean annual flows. Compute the minimum of a 7-day moving average flow for each year and divide them by the mean annual flow for that year. ML17 is the mean (or median - Use Preference option) of those ratios.	dim	0.37	0.16	0.06
MA3	0.026	**-3.53**	**0.72**	0.57	Annual variability in daily flows 1	Mean (or median - Use Preference option) of the coefficients of variation (standard deviation/mean) for each year. Compute the coefficient of variation for each year of daily flows and then compute the mean of the annual coefficients of variation.	%	48.46	119.96	20.24
DA2	0.032	**-3.47**	0.32	-0.28	Median rise period	Median duration of consecutive periods of rising values	days	1.00	2.11	0.32

Figure 10 shows the standardized PC scores (on the top two principal component axes) for the class E1 regulated and unregulated sites. All four regulated sites plot within the reference range

of scores on PC2, but the three hydropeaking sites are divergent on PC1. These scores suggest that all three of these rivers have anomalously low ranges of flow magnitudes.

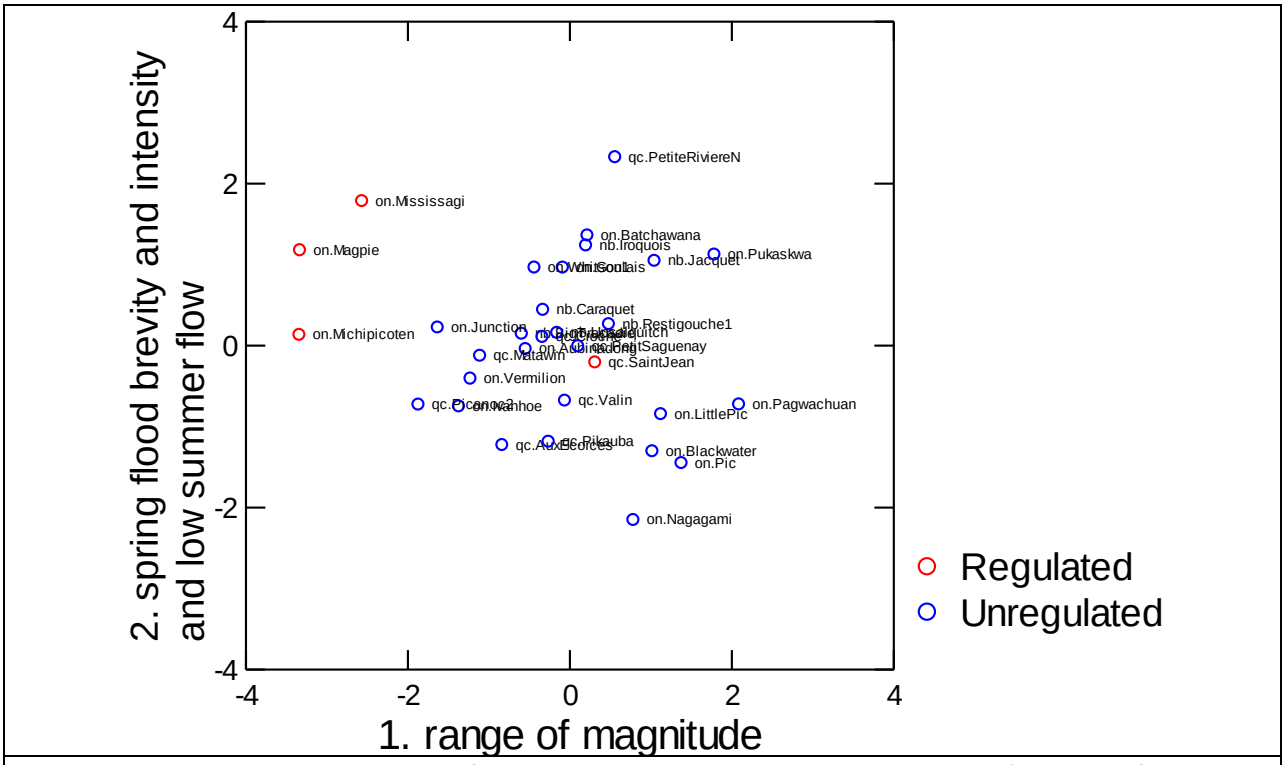


Figure 10 Regulated and unregulated flow class E1 rivers in multivariate PCA space (z-scores of PC1 and PC2 scores). Regulated river location denotes number of standard deviations away from the unregulated class PC means. Axes have been named based on an evaluation of the top loading indices (Appendix 2 Table 2). PC1 explains 25.4% of the total variance. PC2 explains 16.1% of the total variance.

Figure 11 is a bivariate plot defined by two of the highest loading PC1 flow indices (the PC axis on which three regulated E1 sites appear anomalous). This figure clarifies the interpretation of the low PC1 scores: it highlights that the three hydropeaking sites (red points in the lower left corner) are not entirely consistently anomalous for all of the indices that load PC1. In all three cases, the reduced number of days with flows 3x the median is more responsible for low PC1 scores than the 25% exceedance values, which are low but not anomalous for the reference group.

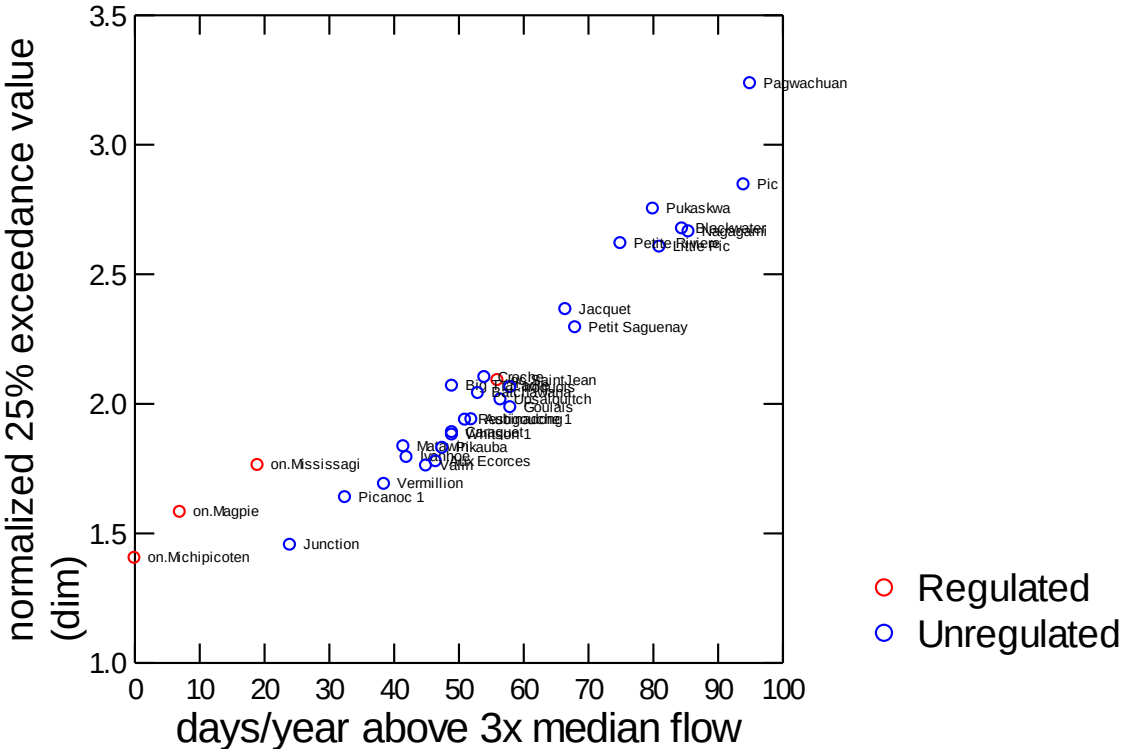


Figure 11 This plot displays two of the top loading indices on flow class E1 PC1 (FH3 vs. MH17), the axis on which the three regulated Ontario sites display anomalous behaviour.

Saint-Jean (QC), Magpie, Mississagi and Michipicoten (On) Rivers

The Saint-Jean River, Quebec, is another example of a system that does not exhibit anomalous flows compared to its regional reference flow class.

Like the Kananaskis systems in Alberta (Results 3.4), the three regulated E1 sites located in Ontario, the Mississagi, Magpie and Michipicoten River, experience flows driven by hydropeaking and thus similar critical interpretation of the top anomalies is required. The anomalies in seasonality at these sites include, high winter flows at all three sites (z=3.3 for Magpie, 8.4 for Mississagi and 4.3 for Michipicoten for mean February flow), and high late summer flows in the Mississagi (z=4.4 for mean maximum August flows). Potential misinterpretations of these peaking systems' anomalies are discussed below.

3.6. Characterizing how anomalous flow features vary across all regulated HydroNet sites, Eastern and Western

Figure 12 is a plot of the top two principal component scores analysing the main axes of variability in all significant anomalous indices found at regulated sites (37 indices in total). In each case index scores analysed are z-scores of regulated river flow indices compared to its own reference class**.** PC scores are not standardized. The distribution of the points in multivariate space illustrates differences in constellations of types of flow anomalies exhibited in these systems. Overall, this figure displays the groupings of flow anomalies that are most variable across the regulated sites.

The regulated sites downstream from hydropeaking facilities are coloured red. These sites scores consistently lower than the other sites on PC1, the axis of low flashiness and high baseflow (the derivation of the axis name is based on analysis of the top loading z-scores (Table 6 of Appendix 2 (p. 128)). Low scores on this axis for peaking sites suggest that these five sites exhibit increased flashiness and lower total baseflow (an index of total annual flow/total annual baseflow) compared to their regional references systems. Baseflow can be quantified in diverse ways. PC1 quantifies total baseflow, because the second highest loading is the index called 5-day-block baseflow (Table 6 of Appendix 2). This index uses interpolation between the days with the lowest flow throughout the year to quantify the total flow input from baseflow through the year. The peaking systems (the red points) score low on PC1 in Figure 12 (the red points) suggesting that the total baseflow is very low in these systems. However, this particular baseflow index may be misleading in peaking systems. Since we are using daily flow series data, this result simply captures the days with no peaking (usually at least one day each week). When these non-peaking days are denoted using daily mean values, they register well below the median flow for these rivers.

On PC2, the axis characterizing range of magnitude and minimum baseflow (annual 7-day flow minimum divided by the median flow, capturing only the week with the lowest flow and not the baseflow component of the flow regime throughout the year as in PC1), the sites known to

exhibit dampened flows based on the previous results (in green) plot slightly negatively suggesting reduced range of magnitude and high baseflows. The sites with few or no flow anomalies (in blue) plot near zero on this axis suggesting no major anomalies in the flow features loading PC2. The New Brunswick Sites with unique flow anomalies (in pink) plot somewhat close together on the upper end of the PC2 axis suggesting that the range of magnitude is increased and minimum baseflow is low.

We know that the blue sites on Figure 12 (low anomaly regulated rivers) do not exhibit significant anomalies for any of the top loading indices for PC1 and PC2. The fact that these sites plot near the centroid of the Figure 12 PCA space suggests that the other regulated systems are anomalous in both directions (negative and positive anomalies) in the flow indices loading these PCs. A PC score of zero does not inherently mean that a site has no/few anomalies as is demonstrated next in relation to Figure 13.

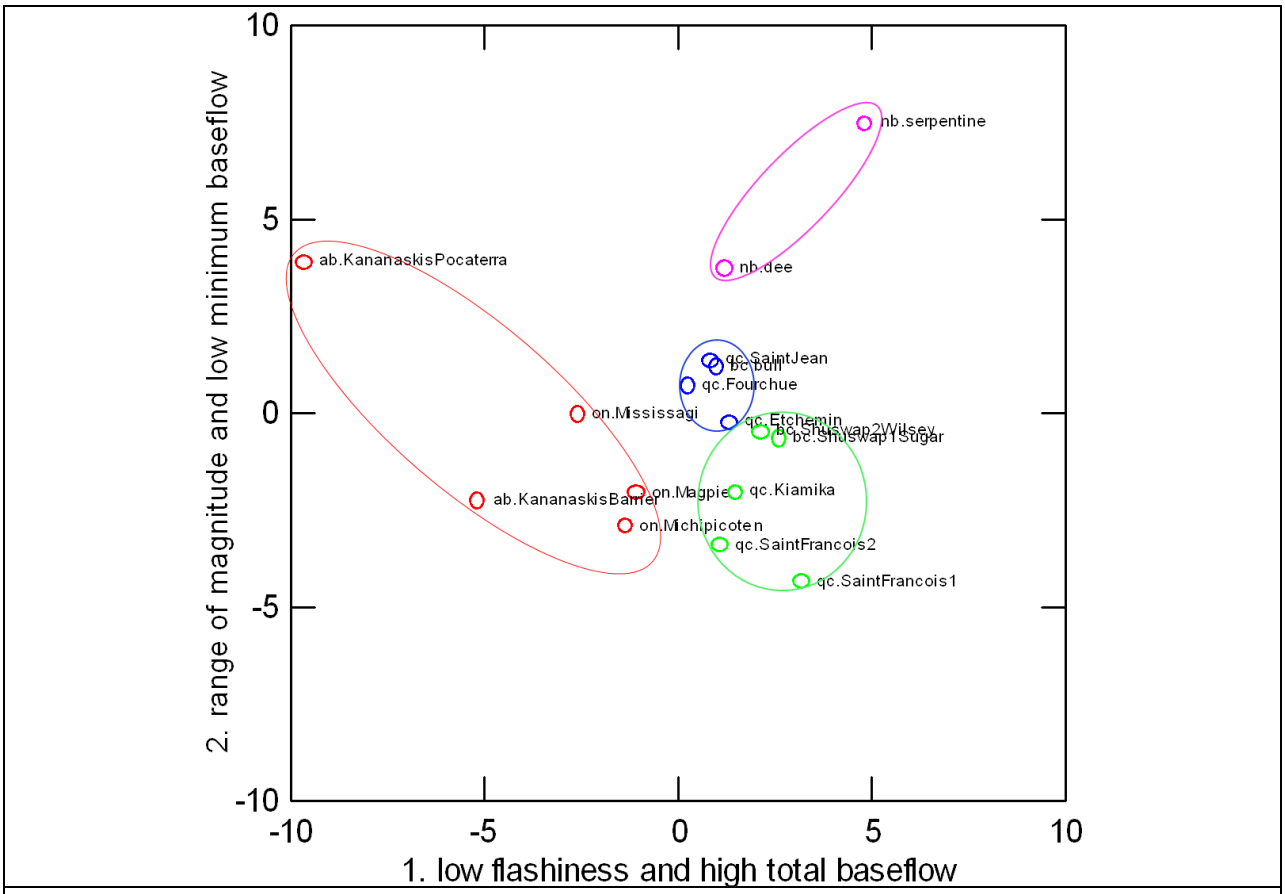


Figure 12 Plot of the top two principal component scores of flow anomalies (z-scores of regulated river flow indices compared to particular reference class norms) in all regulated HydroNet rivers. The site colours indicate sites with similar flow anomalies (or lack of anomalies) based on the results above. Red sites are below hydropeaking power facilities in both Alberta and in Ontario, blue sites do not exhibit major anomalies, green sites located in BC and Quebec exhibit dampened (attenuated) flow compared to regional references and pink sites in NB denote the sites with unique anomalies. Axis names were derived from the top loading anomalies on each PC (Table 6 in Appendix 2 – p.129). PC1 explains 27.1% and PC2 explains 21% of total index variance.

Figure 13 is a plot of PC1 and PC3 scores analysing the main axes of variability in all anomalous indices found at regulated sites. Based on an analysis of the top loading PC3 indices (Table 6 of Appendix 2 (p. 128)), this axis captures seasonal flow variability and January flow magnitude anomalies (i.e. typical seasonal high flows are low as they are retained so that flows can remain atypically high through winter). Unlike their position on PC1 and PC2 (Figure 12), the low anomaly regulated systems (blue) score low on PC3. We know that these systems have no or few anomalies, so these negative PC3 scores do not mean that these sites have anomalously high seasonal variability and low January flows, but simply that the anomalies exhibited in all of

the other regulated sites are unidirectional. Since all of the other regulated sites score higher than the low anomaly sites on PC3 (Figure 13), this suggests that they (the red, green and pink sites) all have anomalously low seasonal flow variability and anomalously high January flow. There is no clear trend between the level of anomaly captured on PC3 and the type of regulated regime between the hydropeaking (red), attenuated (green), and unique (pink) sites.

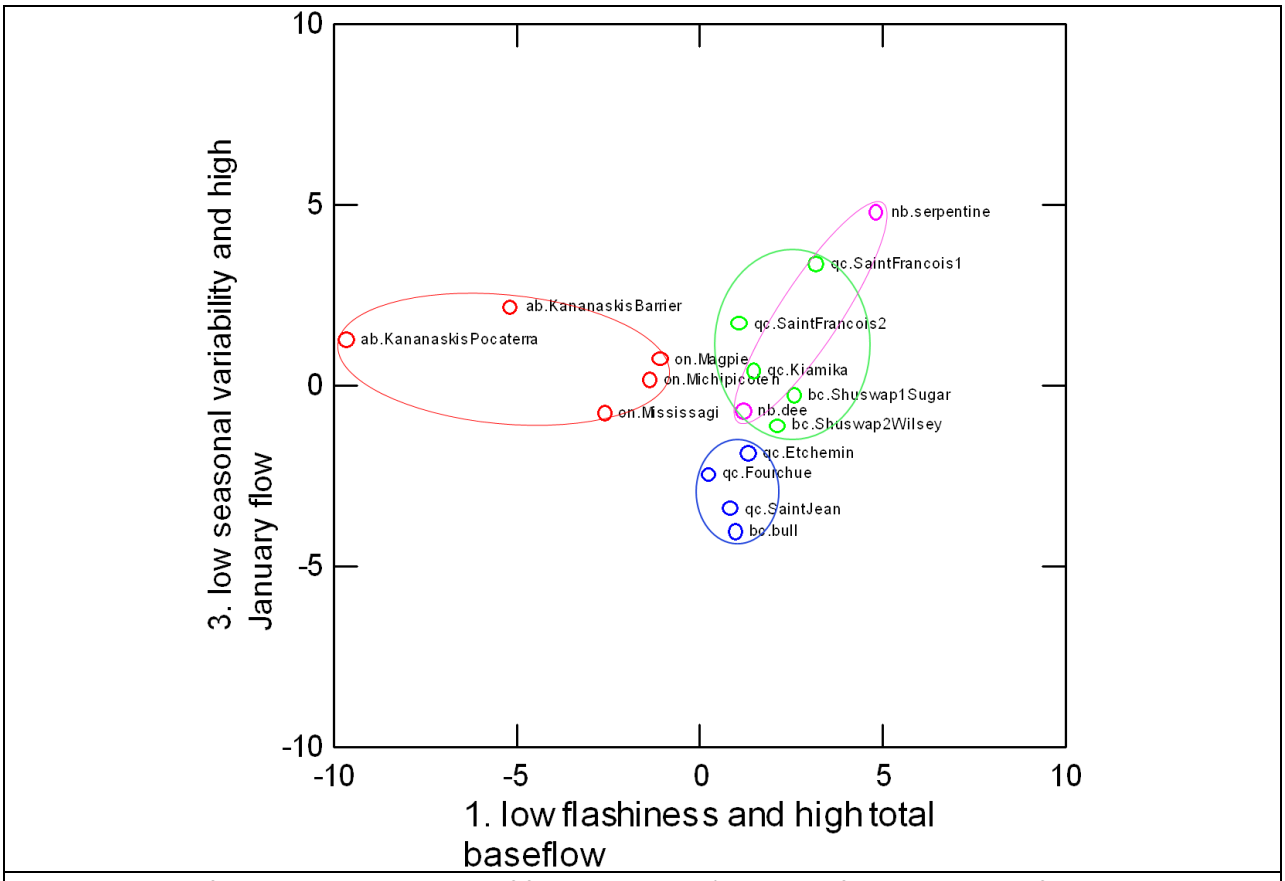


Figure 13 Plot of PC1 versus PC3 scores of flow anomalies (z-scores of regulated river flow indices compared to particular reference class norms) in all regulated HydroNet rivers. The site colours indicate sites with similar flow anomalies (or lack of anomalies) based on the results above. The site colours are explained in Figure 12. Axis names were derived from the top loading anomalies on each PC (Table 6 in Appendix 2 – p. 129). PC1 explains 27.1% and PC3 explains 12.5% of total index variance.

4. Discussion

It is notable in Fig 12 and 13 that clusters of rivers identified by regulation type (and by colour) usually include representatives from different regions and natural flow classes across Canada. For example, although anomaly scores for peaking rivers in the Rockies and those for peaking rivers on the Shield in Ontario were defined based on different flow reference groups, they show broadly similar PC scores for index anomalies and are broadly clustered together in these figures. This suggests that the analysis presented above, of the main axes of regime alteration by operation type, is robust across regions. Our study illustrates that the dominant axes of variability in anomalous flow regime features across 16 regulated HydroNet sites (the axes of Figure 12 and Figure 13) can be summarized as the: 1) axis of low flashiness and high baseflow; 2) axis of range of magnitude and minimum baseflow; and 3) axis of seasonal flow variability and January magnitude. A regulated river may thus show more or fewer flow reversals and events per year than unregulated norms (more or less 'flashiness'), show , independently of this, a greater or lesser annual range of flow levels (normalised by median flow) and, again independently, a greater or, theoretically but not observed, lesser level of inter-seasonal shifting of flow volumes. These three axes summarise 60.6% of the variability across Canada in a reduced set of 37 metrics that show strong anomalies (compared to regional norms) at one or more HydroNet regulated sites. We are unable to 'ground truth' these results by comparing anomalous flows at a regulated site to indices calculated on the same river prior to dam construction because these data are not available.

Since general regional patterns are thought to be more useful for environmental management than detailed site specific results (Poff *et al.,* 2010), we present some potential ecological implications of negative and positive anomalies on these three axes following this results chapter (Chapter 6: Predicted Ecological Outcomes, p. 95). This is more useful than discussing every major anomalous metric seen at any given site (as presented through Results 3.1-3.5). However, these long tables of anomalous indices are useful reference datasets for the HydroNet effort or for anyone else interested in the drivers of ecology in these particular rivers. These tables allow us to identify components of the flow regime that are so regionally atypical

that they may constrain some specific fish species and populations. Ecological relationships with flow alteration are hypothesized to vary among the river types (flow classes) since ecological response to flow alteration will depend on the historic flow regime, the biotic communities present, and the geomorphic context (Poff *et al.,* 2010).

The flow regime anomalies in the regulated HydroNet systems that contribute the greatest variance (27.1 % of total variance) across sites are related to intensity of flashiness and total baseflow (this name summarizes the most anomalous indices loading high on PC1 in Results 3.6). A low score on this axis suggests that a site exhibits increased flashiness and lower total baseflow (total annual flow/total annual 'baseflow' (an inverse measure defined by dividing the year into five day 'blocks' and interpolating between the minimum flow value within each block)) compared to their regional references systems while a high score reflects reduced flashiness and increased total baseflow. On figures 12 and 13 when using the blue low anomaly sites as a visual representation of reference class behaviour, it is notable that all peaking sites (and only peaking sites), most notably the Kananaskis River below the Pocaterra dam, have lower PC1 scores and thus increased flashiness and decreased total baseflow. On the other hand, all of the other regulated sites range from no anomalies to positive anomalies (high annual baseflow, reduced flashiness) in these flow features. The Serpentine River and the Saint-Francois River (site 1) appear to have the lowest flashiness and highest total baseflow. Of course these interpretations should be validated by examining the longer suites of indices for each of these rivers presented earlier in the results, but this PCA plot allows us to generalize and suggest potential ecological implications of anomalies in these flow regime features.

The fact that we analyzed daily instead of hourly data for peaking rivers means that these results do not capture the sub-daily increases in flashiness (as well as the corresponding anomalously high rise rates and fall rates) that the fish and other biota experience in the four hydropeaking rivers (five sites) in this dataset. Zimmerman *et al*. (2010) found the mean number of annual reversals calculated using daily flow data to be significantly correlated with three out of four sub-daily metrics of flashiness and flow variability for 30 streams in the

Connecticut River basin. The daily index explained between 40% and 50% of the sub-daily index variation in the significant cases, suggesting that daily indices are far from perfect predictors of sub-daily flow flashiness behaviour. Zimmerman *et al*. (2010) concluded that all rivers may exhibit variable subdaily flows, but altered rivers exhibit this variability more frequently; while hydropeaking operations exhibited the most highly anomalous subdaily flows (although certain storage and ROR systems also exhibited anomalously high sub-daily flashiness).

Table 5 in Appendix 2 (p. 126), showing selected flow indices calculated from hourly flow data for the subset of systems where these data were available, shows that the Richards-Baker Flashiness Index scores (an index that uses time-series path length to identify flashy behaviour (see Zimmerman *et al.,* 2010)) are between 29 and 40 standard deviations above respective reference class means. This suggests that the use of daily data in this analysis has led to an underestimation of flashiness anomalies in the hydropeaking systems. On the other hand, the results that suggest that total baseflow is atypically low in all of the hydropeaking systems (e.g. PC 1 in Figure 12) does not truly capture true baseflow from groundwater input. Based on visual analyses of hourly data for the hydropeaking systems, it is apparent that the fraction of total flow volume determined to be baseflow (through the interpolation of five day minimum flows throughout the time series), represents instead an interpolation between flow volumes on days when hydropeaking did not occur. We therefore do not focus on the ecological implications of anomalously low total baseflow, since this result seems to be an artifact of the data quality.

The second most dominant set of covarying indices (aligned on PC 2 which explains 21% of variability, cf. Results 3.6) describes anomalies in various metrics describing the range of flow magnitudes (from the minimum baseflow to the highest peaks). Compared to the low anomaly systems in our dataset, Figure 12 shows that there are both positive and negative anomalies along this axis of variation in the other regulated systems. The Saint-Francois river, Kiamika river, three of the five hydropeaking sites (two from Ontario and one from Alberta) and to a lesser extent the Shuswap river sites in BC appear to have reduced range of magnitudes and high minimum baseflow (low PC2 scores on Figure 12). Conversely the Dee River and

Serpentine River in New Brunswick, and the Kananaskis River (Pocaterra site in Alberta) have unusually high ranges of magnitude (atypically low 7day minimum flow and atypically severe annual floods).

The third most important set of indices (aligned on PC 3 of Results 3.6, an axis explaining 12.5% of index variance) captures anomalies in seasonal flow variability (the range in magnitude of monthly means); especially anomalies in winter flows (captured primarily by indices quantifying January flows). All of the regulated rivers score higher than the group of low anomaly regulated rivers (coloured blue on Figures 12 and 13.) This suggests that all of these regulated systems experience abnormally high winter flows (potentially caused by the demand for electricity during the Canadian winter). The strongest anomalies observed along this axis are in the Serpentine River, New Brunswick, and the Saint-Francois River, Quebec. For this anomalous seasonal shift in elevated winter flows, a period where flows are usually low in all reference regions in this study, water must be retained from the wetter months thus reducing total high flow months and dampening the seasonal range of flow magnitude.

A limitation of the PCA plots of top anomalies in results 3.6 is that the regulated sites from different flow classes were pooled together in order to identify anomaly variance across a sufficiently large sample size of regulated sites. The error terms on anomaly scores differ from site to site since certain regulated sites were assigned to one flow class while others had to be compared to two reference flow classes pooled together (see Chapter 4 Results). In the latter cases (Fourchue, Kiamika, Dee and Serpentine Rivers and the Shuswap River (see Figures 12 and 13)), the direction (sign) of anomaly scores are generally clear but the potential error of the PC score values are increased. To avoid having to pool across regions, a subsequent study could obtain within each flow class data for a large sample of regulated rivers with a range of operation regimes and re-run PCAs of top anomalies for a clearer idea of the gradient of flow regime anomalies across a set of regulated sites compared to a common flow norm data set. Nonetheless, these results provide substantial flow regime context to regress indices of flow regime anomaly against ecological metrics (as suggested in the ELOHA method outlined by Poff

et al. (2010)). To determine functional relationships between level of flow alteration and metrics of ecology (such as density or biomass of particular fish species or species richness, etc., the next step of this project – the overall HydroNet effort) there is a need for a sufficient sample size of regulated systems (with flows altered to different degrees), thus at this stage we accepted the level of error added by pooling regulated sites from different classes together.

As an alternative to using single flow indices (percent deviation from baseline conditions) in flow-ecology models as advocated by Poff *et al.* (2010), PC scores of top flow anomalies could be used (such as those presented in Results 3.6). Or if it is preferable to choose a set of particular flow indices to regress against ecological variables, this type of analysis could be used to guide the selection of indices to appropriately represent the broad types of anomalies (orthogonal to the other types of anomalies) in the set of regulated rivers in question (e.g. 2 indices from each of the top 3 PCs presented in results 3.6). Another option would be to regress the number of significant anomalies in river systems (regulated and unregulated) against an ecological metric, or perform a multiple regression of the number of significant anomalies that are important loaders to the top PCA axes of anomaly against an ecological metric.

More specific regional flow classes could be identified by re-running this analysis for a smaller region; however identifying anomalies at a broad regional scale that captures a large range of reference conditions suggests that outlying systems experience real anomalous flow conditions and we expect some to be accompanied by ecological anomalies. The identified reference ranges of variability, of principal component scores and of individual flow indices, are useful to prioritize management and identify sites that should receive immediate attention.

5. Summary

In this analysis, we identify flow regime anomalies (or absence of anomalies) at 16 HydroNet sites compared to broad (and thus conservative) regional reference norms. We present long lists of significant anomalous flow indices to characterize the regulated flow regimes at each site and the present composite scores (principal components) to summarize the different types of flow anomalies across the regulated HydroNet sites. These results may provide the flow foundation needed to detect significant flow-ecology relationships within the HydroNet study region, thus contributing to a widespread effort of understanding the 'ecological limits of hydrologic alteration' (Poff *et al.,* 2010).

Chapter 6: Predicted Ecological Outcomes

Although we have not yet compared our results to ecological anomalies in these study rivers, in the following paragraphs we speculate about ecological outcomes that may have occurred in these systems based on flow driven mechanisms identified in the literature.

Several general process-based ecological implications have been identified in rivers exhibiting altered flow flashiness (Figure 5 and 6 PC1). The following ecological responses have been documented following strong increases in river flashiness (an extreme outcome of hydropeaking operations, flashiness can also be enhanced by artificial drainage of large areas or urban expansion in watershed). Small bodied species, with early reproductive maturation and low juvenile survivorship, and opportunistic strategists are favoured when floods are frequent (and also when floods are intense) (Winemiller and Rose, 1992; Mims and Olden, 2011). Macroinvertebrate communities tend to shift towards species adapted to high mortality rates, altering food sources for fish species (Richards *et al.,* 1997). Increased flashiness also favours fish species with general (non- specialized) foraging strategies (Poff and Allen, 1995), which can lead to a reduced or aseasonal fish reproduction and to reduced abundance or extirpation of native fish and decreased richness of endemic or sensitive species (Poff and Zimmerman, 2010).

Decreased flashiness on the other hand has been documented to lead to shifts in community composition and decreased species richness (Poff and Zimmerman, 2010). Increase in total baseflow (corresponding to high scores on PC1, Figure 12) is also expected to be harmful for native biota. In their literature review of the ecological effects of hydrologic alteration, Poff and Zimmerman (2010) found that native fish communities showed consistent negative response to shifts in baseflow magnitude, however they note that there are a lack of data for documented cases of responses to moderate flow alteration (cases of extreme flow alteration leading to major ecological shifts dominate the literature on the topic).

An observed ecological outcome in systems with reduced flood peaks (PC2 in Results 3.6) is impaired recruitment of indigenous riparian vegetation. This can allow invasive trees to proliferate and encroach on the river (Stromberg *et al.,* 2007; Poff and Zimmerman, 2010). Also observed is an increased abundance of non-native flood intolerant fish species and an alteration in fish assemblage composition (Meffe, 1984; Poff and Zimmerman, 2010). In their meta-analysis of 165 papers documenting ecological consequences of flow alteration, Poff and Zimmerman (2010) found that macroinvertebrate abundance and diversity declined in response to altered flow magnitudes (with increases or decreases in baseflow, and increases or decreases in peak flows). Fish food source changes have been identified as a cause for declining native-fish numbers. If minimum baseflow is reduced, limited habitat connectivity can harm certain fish species (Poff and Zimmerman, 2010).

One notable potential negative ecological impact of high winter flows (high scores on PC 3 axis of Chapter 5 Results 3.6) is that these anomalous regimes may increase mortality of eggs of fall spawning salmonid fish, caused by scouring of river bed gravel combined with infiltration into redds of unseasonal high suspended loads associated with the high flows (Montgomery *et al.,* 1999). Loss of the natural timing of flood peaks (seasonality) can also lead to the establishment of non-native fish species (Fausch *et al.,* 2001; Marchetti and Moyle, 2001; Olden *et al.,* 2006), and modified river food webs (Wooton, Parker and Power, 1996). Magnitudes of transported nutrients and suspended organic matter depend on the frequency and duration of high flows, thus these food sources are altered when seasonal flow regimes change (Doyle *et al.,* 2005). Reduced seasonal variability can increase populations of equilibrium strategists such as Smallmouth bass (Mims and Olden, 2011), but this is at the expense of the native species who suffer as spawning cues are disrupted (Poff and Zimmerman, 2010). In steep river reaches, high January velocities may also prevent ice cover formation leading to open water frazil ice formation and consequent ice jamming in low slope reaches. Ice jamming can lead to stress on riparian vegetation and in some places scour of river bed (Church, 1995). We expect the severity in ice regime change to be particularly pronounced in systems with anomalously high flashiness; especially hydropeaking systems (low score on PC1, Figure 12 (Chap. 2 Results 3.6)).

Chapter 7: General Conclusions

In Chapter 4 we classified 96 unregulated (reference) rivers selected to be of broadly similar scale and geographically proximal (mostly within 500km) to regulated HydroNet rivers across Canada into flow regime classes representative of environmental flow norms, and characterised the differences between the classes. We then assigned the regulated HydroNet rivers to flow regime classes based on geographic and physical watershed characteristics. In Chapter 5 we identified the features of the regulated flow regimes at HydroNet sites that are most anomalous compared to the appropriate regional reference (natural flow regime classes). For each regulated river, for heuristic reasons, we classified and differentiated between anomalous flow features (indices) that are related to seasonality (and thus have the a-priori potential to clash with regional fish life history strategies), flow features (indices) that are aligned with a principal axis of variation in the reference set of rivers (i.e. features that vary significantly across the unregulated flow class but are pushed to an extreme by regulation at the site) and anomalous flow features that are orthogonal to and not part of an important axis of natural variation. We also drew a general picture of the main axes of flow regime feature anomalies across all regulated HydroNet sites in Canada. We also discussed particular flow regime anomalies in the regulated HydroNet rivers that, based on theory and previous studies, may have implications for fish at the community and population levels. Our general conclusions are as follows:

1. Flow regimes and flow regime anomalies are both multidimensional vectors and are complicated to characterize.
2. Reducing the dimensionality of flow regimes and flow regime anomalies is necessary in order to move forward with flow-ecology river management efforts.
3. Even when compared to broad, and thus conservative, regional reference flow regime classes, certain regulated rivers exhibit flows that are well outside the normal range of flow behaviour; suggesting flow related stress to native biota in these systems.
4. Within and across flow classes, we observed differences in the nature of the strongest flow anomalies among regulated rivers (these differences are summarized using PCA in

Results 3.6), suggesting that dams do not simply homogenize river flows (consistent with the findings from McManamay *et al.* (2012a)). Although dams do not homogenize flows, rivers below dams with similar characteristics (e.g. storage versus ROR dams, or dams with or without hydro peaking) do exhibit broadly similar anomalies (along the same axes of anomaly variability) in all three Canadian regions studied regardless of regional flow class membership.

Efficient flow regime characterization is essential to improve our understanding of the morphological and ecological effects of discharge regimes across Canada and advances in these topics will empower dam managers to make informed operational decisions. These results suggest that despite the variability of flow regimes across Canada, flow regime anomalies seem sufficiently similar and similarly explained by dam operation regimes for us to advocate the transferability of established local flow anomaly-ecology relationships to regional management efforts. Combining these understandings of the flow conditions in regulated HydroNet systems with biotic measures of these systems that are currently being studied by other HydroNet researchers, we may be able to detect significant flow-ecology relationships within the HydroNet study region, thus contributing to a long term effort of understanding the 'ecological limits of hydrologic alteration' in Canada (Poff *et al.,* 2010).

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Appendix 1

Appendix 1 Table 1 Full list of flow indices used throughout this thesis

Code	Units	Hydrologic Index	Definition	Source
M_A3	%	Variability in daily flows 1	Mean (or median - Use Preference option) of the coefficients of variation (standard deviation/mean) for each year. Compute the coefficient of variation for each year of daily flows and then compute the mean of the annual coefficients of variation.	HIT
M_A4	%	Variability in daily flows 2	Coefficient of variation of the percentiles of the logs of the entire flow record. Standard deviation of the percentiles of the logs of the entire flow record divided by the mean of percentiles of the logs. Compute the log10 of the daily flows for the entire record. Compute the 5th, 10th, 15th, 20th, 25th, 30th, 35th, 40th, 45th, 50th, 55th, 60th, 65th, 70th, 75th, 80th, 85th, 90th, and 95th percentiles for the logs of the entire flow record. Percentiles are computed by interpolating between the ordered (ascending) logs of the flow values. Compute the standard deviation and mean for the percentile values. Divide the standard deviation by the mean.	HIT
M_A6	NA	Ratio of low flow (Q90) to high flow (Q10) quantiles	Range in daily flows is the ratio of the 90 percent to 10 percent exceedance values for the entire flow record (low flow/high flow). Compute the 90 percent and 10 percent exceedance values for the entire flow record. Exceedance is computed by interpolating between the ordered (descending) flow values. Divide the 90 percent exceedance value by the 10 percent value.	HIT
*nM_A12	$m^3 s^{-1}$	Mean monthly flow (Jan)	Means (or medians - Use Preference option) of all January flow values over the entire record.	HIT
nM_A13	$m^3 s^{-1}$	Mean monthly flow (Feb)	Means (or medians - Use Preference option) of all February flow values over the entire record.	HIT
nM_A15	$m^3 s^{-1}$	Mean monthly flow (Apr)	Means (or medians - Use Preference option) of all April flow values over the entire record.	HIT
nM_A21	$m^3 s^{-1}$	Mean monthly flow (Oct)	Means (or medians - Use Preference option) of all October flow values over the entire record.	HIT
nM_A22	$m^3 s^{-1}$	Mean monthly flow (Nov)	Means (or medians - Use Preference option) of all November flow values over the entire record.	HIT
M_A24	%	Variability in monthly flows (Jan)	Variability (coefficient of variation) of January flow values. Compute the standard deviation for January in each year over the entire flow record. Divide the standard deviation by the mean for January in each year. Average (or median - Use Preference option) these values across all years.	HIT
M_A27	%	Variability in monthly flows (Apr)	Coefficient of variation in monthly flows for April (see MA24)	HIT
M_A28	%	Variability in monthly flows (May)	Coefficient of variation in monthly flows for May (see MA24)	HIT
M_A36	NA	Variability across monthly flows 1 (0-100)	Compute the minimum, maximum, and median of the monthly means (every month in the entire flow record). MA36 is the maximum of the monthly means minus the minimum of the monthly means divided by the median of the monthly means.	HIT
M_A41	$m^3 s^{-1} km^{-2}$	Specific mean annual runoff	Compute the annual mean daily flows. MA41 is the mean of the annual means divided by the drainage area.	HIT
M_A42	NA	Variability across annual flows (0-100)	Range of annual flows divided by median annual flows. MA42 is the maximum of the annual mean flows minus the minimum of the annual mean flows divided by the median of the annual mean flows.	HIT
M_A45	NA	Skewness in annual flows	MA45 is the mean of the annual flow means minus the median of the annual means divided by the median of the annual means = (Mean annual flow - median annual flow)/median annual flow	HIT
nM_L1	$m^3 s^{-1}$	Mean minimum monthly flows (Jan)	For each year, compute the minimum flow for the month of January. ML1 is the mean (or median - Use Preference option) of these values.	HIT
nM_L3	$m^3 s^{-1}$	Mean minimum monthly flows (Mar)	For each year, compute the minimum flow for the month of March. ML3 is the mean (or median - Use Preference option) of these values.	HIT
nM_L4	$m^3 s^{-1}$	Mean minimum monthly flows (Apr)	For each year, compute the minimum flow for the month of April. ML4 is the mean (or median - Use Preference option) of these values.	HIT
nM_L6	$m^3 s^{-1}$	Mean minimum monthly flows (Jun)	For each year, compute the minimum flow for the month of June. ML6 is the mean (or median - Use Preference option) of these values.	HIT
nM_L8	$m^3 s^{-1}$	Mean minimum monthly flows (Aug)	For each year, compute the minimum flow for the month of August. ML8 is the mean (or median - Use Preference option) of these values.	HIT
nM_L11	$m^3 s^{-1}$	Mean minimum monthly flows (Nov)	For each year, compute the minimum flow for the month of November. ML11 is the mean (or median - Use Preference option) of these values.	HIT
M_L13	%	Variability across minimum monthly flows	Coefficient of variation in minimum monthly flows. Compute the mean and standard deviation for the minimum monthly flows over the entire flow record. ML13 is the standard deviation times 100 divided by the mean minimum monthly flow for all years.	HIT
M_L17	NA	7-day minimum baseflow	Compute the mean annual flows. Compute the minimum of a 7-day moving average flow for each year and divide them by the mean annual flow for that year. ML17 is the mean (or median - Use Preference option) of those ratios.	HIT

M_L18	%	Variability in Baseflow Index 1	Coefficient of variation in ML17. Compute the standard deviation for the ratios of 7-day moving average flows to mean annual flows for each year. ML18 is the standard deviation times 100 divided by the mean of the ratios.	HIT
M_L20	NA	5-day-block baseflow (inverse measure)	Divide the daily flow record into 5-day blocks. Find the minimum flow for each block. Assign the minimum flow as a base flow for that block if 90 percent of that minimum flow is less than the minimum flows for the blocks on either side. Otherwise, set it to zero. Fill in the zero values using linear interpolation. Compute the total flow for the entire record and the total base flow for the entire record. ML20 is the ratio of total flow to total base flow.	HIT
nM_H2	$m^3 s^{-1}$	Mean maximum monthly flows (Feb)	For each year, compute the maximum flow for the month of February. MH2 is the mean (or median - Use Preference option) of these values.	HIT
nM_H5	$m^3 s^{-1}$	Mean maximum monthly flows (May)	For each year, compute the maximum flow for the month of May. MH5 is the mean (or median - Use Preference option) of these values.	HIT
nM_H7	$m^3 s^{-1}$	Mean maximum monthly flows (Jul)	For each year, compute the maximum flow for the month of July. MH7 is the mean (or median - Use Preference option) of these values.	HIT
nM_H8	$m^3 s^{-1}$	Mean maximum monthly flows (Aug)	For each year, compute the maximum flow for the month of August. MH8 is the mean (or median - Use Preference option) of these values.	HIT
nM_H9	$m^3 s^{-1}$	Mean maximum monthly flows (Sep)	For each year, compute the maximum flow for the month of September. MH9 is the mean (or median - Use Preference option) of these values.	HIT
nM_H10	$m^3 s^{-1}$	Mean maximum monthly flows (Oct)	For each year, compute the maximum flow for the month of October. MH10 is the mean (or median - Use Preference option) of these values.	HIT
M_H14	NA	Median of annual maximum flows	Compute the annual maximum flows from monthly maximum flows. Compute the ratio of annual maximum flow to median annual flow for each year. MH14 is the median of these ratios.	HIT
M_H17	NA	25% exceedance value	Compute the 25 percent exceedance value for the entire data record. MH17 is the 25 percent exceedance value divided by the median flow for the entire record.	HIT
M_H18	%	Variability across annual maximum flows	Coefficient of variation of logarithmic annual maximum flows. Compute the logs (log10) of the maximum annual flows. Find the standard deviation and mean for these values. MH18 is the standard deviation times 100 divided by the mean.	HIT
M_H19	NA	Skewness in annual maximum flows	Use the equation: $M_H19 = (N^2 * sum(qm^3) - 3*N*sum(qm)*sum(qm^2) + 2*(sum(qm))^3) / (N*(N-1)*(N-2)*stddev^3)$ where: N = Number of years qm = Log10(annual maximum flows) stddev = Standard deviation of the Log10(annual maximum flows)	HIT
F_L1	events/year	Low flow frequency 1 (Low flood pulse count)	Compute for each year the number of flow events with flows below a threshold equal to the 25th percentile value for the entire flow record. FL1 is the mean (or median - Use Preference option) number of events per year.	HIT
F_L2	%	Variability in Low flow frequency 1	Coefficient of variation in F_L1. Compute the standard deviation in the annual pulse counts for FL1. FL2 is 100 times the standard deviation divided by the mean pulse count.	HIT
F_L3	events/year	Low flow frequency 2 (Frequency of low flow spells)	Compute for each year the number of flow events with flows below a threshold equal to 5 percent of the mean flow value for the entire flow record. FL3 is the mean (or median - Use Preference option) number of events per year.	HIT
F_H1	events/year	Flood frequency 1 (High flood pulse count)	Compute for each year the number of flow events with flows above a threshold equal to the 75th percentile value for the entire flow record. FH1 is the mean (or median - Use Preference option) number of events per year.	HIT
F_H2	%	Variability in Flood frequency 1	Coefficient of variation in F_H1. Compute the standard deviation in the annual pulse counts for FH1. FH2 is 100 times the standard deviation divided by the mean pulse count.	HIT
F_H3	days/year	Days per year above 3x flow median	Compute the number of days each year that the flow is above a threshold equal to three times the median flow for the entire record. FH3 is the mean (or median – Use Preference option) of the annual number of days for all years.	HIT
F_H7	events/year	Flood frequency 7x median	Compute for each year the number of flow events with flows above a threshold equal to seven times the median flow value for the entire flow record. FH7 is the mean (or median - Use Preference option) number of events per year.	HIT
F_H10	events/year	Flood frequency 4	Compute for each year the number of flow events with flows above a threshold equal to the median of the annual minimums for the entire flow record. FH10 is the mean (or median - Use Preference option) number of events per year.	HIT
D_A1	days	Longest rise period	Maximum duration of consecutive periods of rising values	Steuer
D_A2	days	Median rise period	Median duration of consecutive periods of rising values	Steuer
D_A3	days	Longest fall period	Maximum duration of consecutive periods of falling values	Steuer
D_A4	days	Median fall period	Median duration of consecutive periods of falling values	Steuer
D_A5	$days/km^2$	Specific longest rise period	Maximum duration of consecutive periods of rising values (DA1) divided by drainage area	Steuer
D_A6	$days/km^2$	Specific longest fall period	Maximum duration of consecutive periods of falling values (DA3) divided by drainage area	Steuer
nD_L5	$m^3 s^{-1}$	Annual minimum of 90-day moving average flow	Compute the minimum of a 90-day moving average flow for each year. DL5 is the mean (or median - Use Preference option) of these	HIT

			values.	
D_L7	%	Variability of annual minimum of 3-day moving average flow	Coefficient of variation. Compute the standard deviation for the minimum 3-day moving averages. DL7 is 100 times the standard deviation divided by the mean.	HIT
D_L12	NA	Normalized 7-day annual minimum flow	Annual minimum of 7-day moving average flow divided by the median for the entire record. Compute the minimum of a 7-day moving average flow for each year. DL12 is the mean of these values divided by the median for the entire record.	HIT
D_L16	days	Low flow pulse duration	Compute the average pulse duration for each year for flow events below a threshold equal to the 25th percentile value for the entire flow record. DL16 is the median of the yearly average durations.	HIT
D_L17	%	Variability in low flow pulse duration	Coefficient of variation in D_L16. Compute the standard deviation for the yearly average low pulse durations. DL17 is 100 times the standard deviation divided by the mean of the yearly average low pulse durations.	HIT
D_L20	%	Percent of zero-flow months	Percentage of all months with zero flow. While computing the mean monthly flow values, count the number of months over the entire flow record in which there was no flow. DL20 is this number of no-flow months divided by the total number of months.	HIT
nD_H5	$m^3 s^{-1}$	Annual maximum of 90-day moving average flow	Compute the maximum of a 90-day moving average flow for each year. DH5 is the mean (or median - Use Preference option) of these values.	HIT
D_H6	%	Variability of annual maximum daily average flow	Coefficient of variation in annual maximum daily average flow. Compute the standard deviation for the maximum daily average flow. DH6 is 100 times the standard deviation divided by the mean.	HIT
D_H15	days	High flow duration 1 (High flow pulse duration)	Compute for each year the average duration for flow events with flows above a threshold equal to the 75th percentile value for the entire flow record. DH15 is the median of the yearly average durations.	HIT
D_H16	%	Variability in High flow duration 1	Coefficient of variation in D_H15. Compute the standard deviation for the yearly average high flow durations. DH16 is 100 times the standard deviation divided by the mean of the yearly average high pulse durations.	HIT
D_H17	days	High flow duration 2 (1x)	Compute for each year the average duration of flow events with flows above a threshold equal to the median flow value for the entire flow record. DH17 is the mean (or median - Use Preference option) duration of the events.	HIT
T_A1	NA	Constancy	Constancy is computed via the formulation of Colwell (see example in Colwell, 1974). A matrix of values is compiled where the rows are 11 flow categories and the columns are 365 (no February 29th) days of the year. The cell values are the number of times that a flow falls into a category on each day. The categories are (using natural logarithms): log(flow) < .1 x log(mean flow) .1 x log(mean flow) <= log(flow) < .25 x log(mean flow) .25 x log(mean flow) <= log(flow) < .5 x log(mean flow) .5 x log(mean flow) <= log(flow) < .75 x log(mean flow) .75 x log(mean flow) <= log(flow) < 1.0 x log(mean flow) 1.0 x log(mean flow) <= log(flow) < 1.25 x log(mean flow) 1.25 x log(mean flow) <= log(flow) < 1.5 x log(mean flow) 1.5 x log(mean flow) <= log(flow) < 1.75 x log(mean flow) 1.75 x log(mean flow) <= log(flow) < 2.0 x log(mean flow) 2.0 x log(mean flow) <= log(flow) < 2.25 x log(mean flow) log(flow) >= 2.25 x log(mean flow) The row totals, column totals, and grand total are computed. Using the equations for Shannon information theory parameters, constancy is computed as (using natural logarithms): 1 - ((uncertainty with respect to state) / log (number of state))	HIT
T_A2	NA	Predictability of flow	Composed of two independent, additive components: constancy (a measure of temporal invariance) and contingency (a measure of periodicity). Predictability is computed from the same matrix as constancy (see TA1; see example in Colwell, 1974). It is computed as (using natural logarithms): 1 - ((uncertainty with respect to interaction of time and state - uncertainty with respect to time) / log (number of state))	HIT
T_L1	Julian day	Julian date of annual minimum	Determine the Julian date that the minimum flow occurs for each water year. Transform the dates to relative values on a circular scale (radians or degrees). Compute the x and y components for each year and average them across all years. Compute the mean angle as the arc tangent of y-mean divided by x-mean. Transform the resultant angle back to Julian date.	HIT
T_L2	Julian days	Variability in Julian date of annual minimum	Circular variance in T_L1. Compute the sum of the cosinus of the difference between each angle (dates on a circular scale) and the circular mean (TL1 before the back-transformation). TL2 is 1 minus the ratio of the sum of cosinus divided by the sample size (number of years).	HIT (Modified by Bourque)
T_H1	Julian day	Julian date of annual maximum	Determine the Julian date that the maximum flow occurs for each year. Transform the dates to relative values on a circular scale (radians or degrees). Compute the x and y components for each year and average them across all years. Compute the mean angle as the arc tangent of y-mean divided by x-mean. Transform the resultant angle back to Julian date.	HIT

T_H2	dim	Variability in Julian date of annual maximum	Circular variance in T_H1. Compute the sum of the cosinus of the difference between each angle (dates on a circular scale) and the circular mean (TH1 before the back-transformation). TH2 is 1 minus the ratio of the sum of cosinus divided by the sample size (number of years).	HIT (Modified by Bourque)
R_A2	%	Variability in rise rate	Coefficient of variation in R_A1 (Mean rate of positive changes in flow from one day to the next. Compute the change in flow for days in which the change is positive for the entire flow record). Compute the standard deviation for the positive flow changes. RA2 is 100 times the standard deviation divided by the mean.	HIT
R_A5	NA	Proportion of rise days (Number of day rises)	Compute the number of days in which the flow is greater than the previous day. RA5 is the number of positive gain days divided by the total number of days in the flow record.	HIT
R_A8	$year^{-1}$	Number of reversals (day-to-day)	Compute the number of days in each year when the change in flow from one day to the next changes direction. RA8 is the average (or median - Use Preference option) of the yearly values.	HIT
R_A9	%	Variability in reversals	Coefficient of variation in R_A8. Compute the standard deviation for the yearly reversal values. RA9 is 100 times the standard deviation divided by the mean.	HIT
R_A15	%	Relative rise rate	Mean of the relative change in daily values for days where change is positive. SUM((value(t) - value(t-1))/value(t)), where value(t) is the daily mean value on day t.	Steuer

Sources : HIT : Calculated with R, See HIT User Manual & Olden and Poff 2003

Steuer : Calculated with R, based on suggestions by Steuer et al 2010

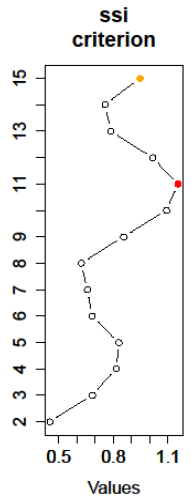
Bourque : Calculated with R, based on suggestions by Guillaume Bourque

Exceedance and percentile are used in the calculation for a number of indices. Note the difference: a 90 percent exceedance means that 90 percent of the values are equal to or greater than the 90 percent exceedance value, while a 90th percentile means that 10 percent of the values are equal to or greater than the 90th percentile value.

Preference option: Whenever there was a choice between mean and median (as of the Preference option in HIT), medians were used.

*nXXX (e.g. nMA12) means that the index has been normalized by dividing by median flow for the entire data period (units are no longer m3s).

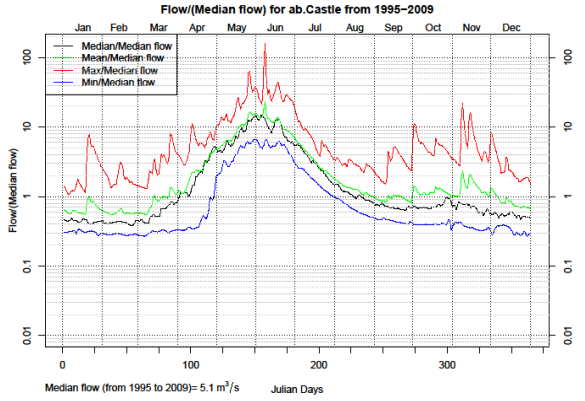
Appendix 1 Figure 1

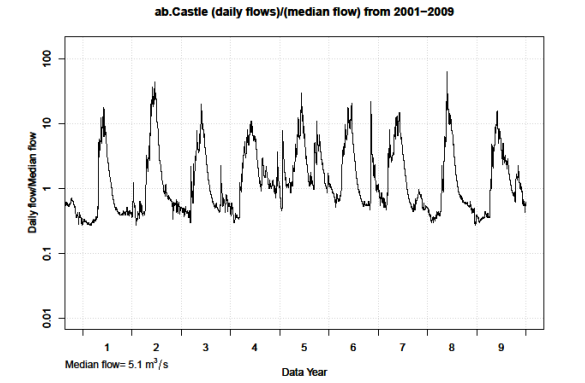


Appendix 2 The simple structure index (ssi) is an output from the vegan cascadeKM function in R that is calculated from three elements of each solution: the maximum difference of each variable between the clusters, the sizes of the most contrasting clusters and the deviation of a variable in the cluster centers compared to its overall mean. The best partition is indicated by the highest ssi value (R cclust package)**.** Although the best identified clustering solution is 11 groups, we would rather increase class sized and accept the increased flow variability by using 5 groups (second best solution).

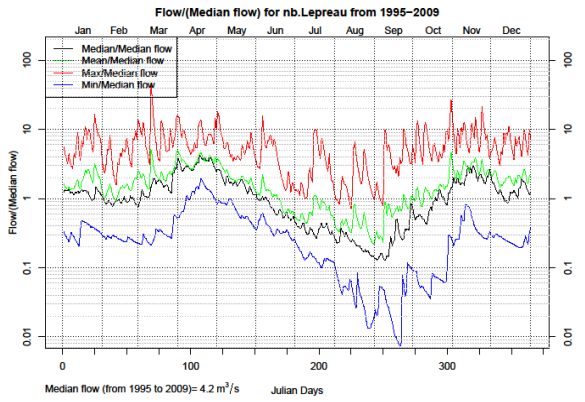
Appendix 1 Figure 2

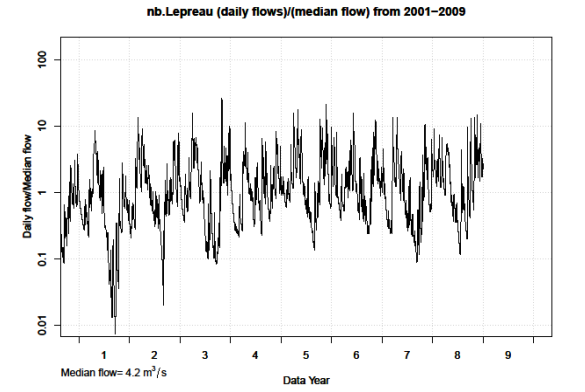
PC1 Low Score



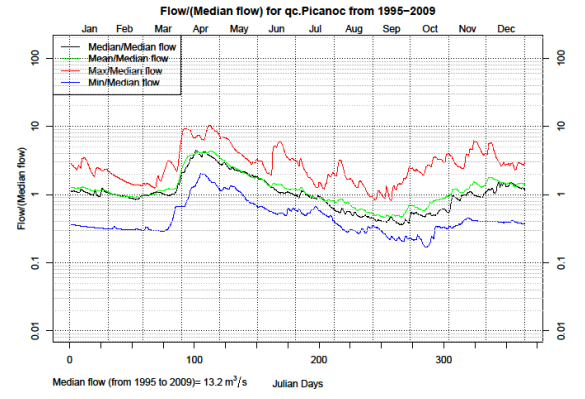


PC1 High Score

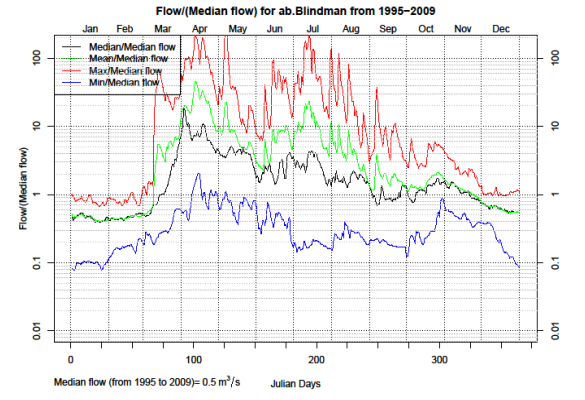


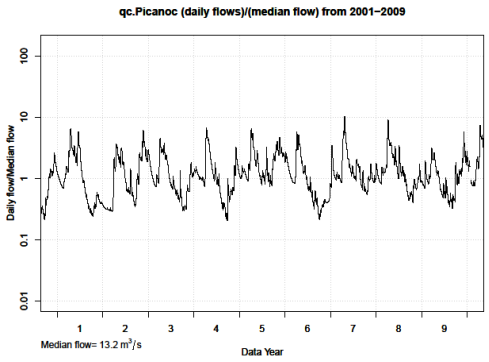


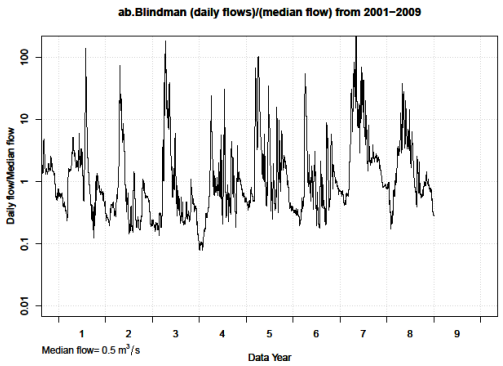
PC2 Low Score



PC2 High Score

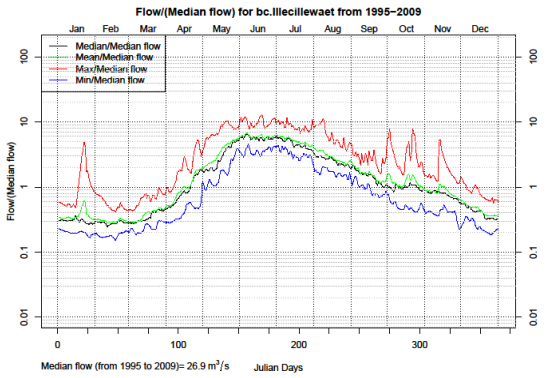


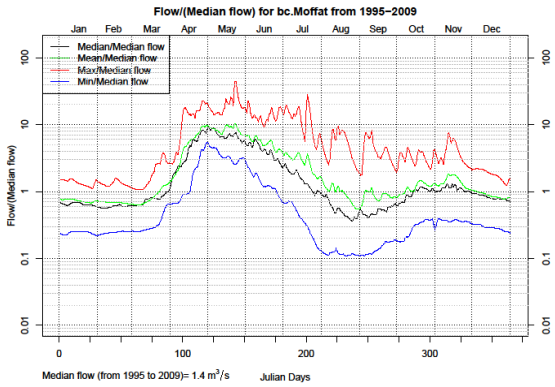


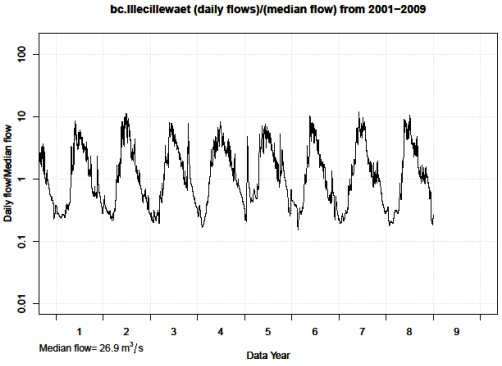


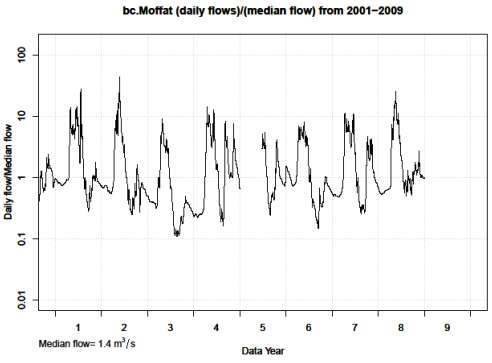
PC3 Low Score

PC3 High Score









Canada Wide Unregulated PCA Extreme Hydrographs

Appendix 1 Table 2

Flow Class E1	Distances to Class E1 Unregulated Rivers (n = 27)			
E1 Regulated Rivers	**Mean Distance (km)**	**SD (km)**	**% of class < 500km away**	**% of class < 200km away**
on.Magpie	684	498	48	33
on.Michipicoten	685	498	48	29
on.Mississagi	642	449	48	26
qc.StJean	617	430	52	26

Flow Class E2	Distances to Class E2 Unregulated Rivers (n = 18)			
E2 Regulated Rivers	**Mean Distance (km)**	**SD (km)**	**% of class < 500km away**	**% of class < 200km away**
qc.Etchemin	269	162	100	44
qc.StFrancois1	284	176	94	33
qc.StFrancois2	289	178	89	33

Flow Class E1/E2	Distances to Class E1/E2 Unregulated Rivers (n = 45)			
E1/E2 Regulated Rivers	**Mean Distance (km)**	**SD (km)**	**% of class < 500km away**	**% of class < 200km away**
nb.dee	554	494	66	31
nb.serpentine	545	487	66	33
qc.Fourchue	494	407	69	27
qc.Kiamika	563	221	40	4

Flow Class W2	Distances to Class W2 Unregulated Rivers (n = 25)			
W2 Regulated Rivers	**Mean Distance (km)**	**SD (km)**	**% of class < 500km away**	**% of class < 200km away**
ab.KananaskisBarrier	208	107	96	60
ab.KananaskisPocaterra	215	103	96	56
bc.bull	230	133	96	48

Flow Class W2/W3	Distances to Class W2/W3 Unregulated Rivers (n = 41)			
W2/W3 Regulated Rivers	**Mean Distance (km)**	**SD (km)**	**% of class < 500km away**	**% of class < 200km away**
bc.Shuswap1Sugar	188	81	100	61
bc.Shuswap2Wilsey	194	83	100	63

Appendix 2

Appendix 2 Table 1 Regulated site information: dam characteristics, dam and gauge locations

Province	River Name	Site Name	Dam Name	Dam Lat.	Dam Long.	Gauge Lat.	Gauge Long.	CEHQ ID	HYDAT ID	Completed	Height (m)
Alberta	**Kananaskis**	ab.KananaskisBarrier	Barrier	51.0328	-115.0420	50.700	-115.1181	n/a	05BF025	1947	44
		ab.KananaskisPocaterra	Pocaterra	50.6902	-115.1316	51.04167	-115.0319	n/a	05BF003	1955	29
British Columbia	**Shuswap**	bc.Shuswap1Sugar	Sugar	50.3511	-118.5423	50.345	-118.5467	n/a	08LC018	1929	13
		bc.Shuswap2Wilsey	Wilsey	50.2956	-118.8171	50.30333	-118.8167	n/a	08LC003	_	_
British Columbia	**Bull River**	bc.Bull	Aberfelbie	49.4994	-115.3509	49.49306	-115.3639	n/a	08NG002	1953	32
Ontario	**Michipicoten**	on.Michipicoten	Scott Falls	47.9083	-84.7426	47.9083	-84.7426	n/a	n/a	1952	29
Ontario	**Mississagi**	on.Mississagi	Aubrey Falls	46.9088	-83.2117	46.9088	-83.2117	n/a	n/a	1969	37
Ontario	**Magpie**	on.Magpie	Steephill Falls	48.0780	-84.7407	48.0780	-84.7407	n/a	n/a	1992	35
Québec	**Etchemin**	qc.Etchemin	Jean-Guérin	46.6354	-71.0447	46.6914	-71.068056	023303	02PH011	1911	17
Québec	**Saint-François**	qc.SaintFrancois1	Aylmer	45.7603	-71.406111	45.7603	-71.406111	030278	02OE070	_	_
		qc.SaintFrancois2	Weedon	45.6616	-71.4636	45.6583	-71.468333	030284	02OE062	1920	13.4
Québec	**Saint-Jean**	qc.SaintJean	Anse Saint-Jean	48.2086	-70.2836	46.86169	-71.870935	060202	n/a	1957	12
Québec	**Kiamika**	qc.Kiamika	Kiamika	46.6296	-75.1232	46.6503	-75.246944	040627	02LE025	1954	15.84
Québec	**Fourchue**	qc.Fourchue	Morin	47.6492	-69.5113	47.6508	-69.512222	022505	02PG003	1943	16.3
New-Brunswick	**Dee**	nb.Dee	Dee	47.0278	-66.9834	47.1218	-67.006	n/a	n/a	_	_
New-Brunswick	**Serpentine**	nb.Serpentine	Serpentine	47.1558	-66.8686	46.986	-67.268	n/a	n/a	_	_

Appendix 2 Table 2 Top loading flow indices for the top principal components in each flow class. This table supports the choices of PC axis names. Mind the sign of each loading when interpreting a site's high or low score on a given axis.

Flow Class E2 PCA

PC1: Index of Flashiness and Infrequent Low Flows (29.5% of total variance)

Code	PC Loading	Name	Description
FL1	0.94	Low flow frequency 1 (Low flood pulse count)	Compute for each year the number of flow events with flows below a threshold equal to the 25th percentile value for the entire flow record. FL1 is the mean (or median - Use Preference option) number of events per year.
DH17	-0.91	High flow duration 2 (1x)	Compute for each year the average duration of flow events with flows above a threshold equal to the median flow value for the entire flow record. DH17 is the mean (or median - Use Preference option) duration of the events.
nMH8	0.89	Mean maximum monthly flows (Aug)	For each year, compute the maximum flow for the month of August. MH8 is the mean (or median - Use Preference option) of these values.
FH1	0.89	Flood frequency 1 (High flood pulse count)	Compute for each year the number of flow events with flows above a threshold equal to the 75th percentile value for the entire flow record. FH1 is the mean (or median - Use Preference option) number of events per year.
nDL5	0.89	Annual minimum of 90-day moving average flow	Compute the minimum of a 90-day moving average flow for each year. DL5 is the mean (or median - Use Preference option) of these values.

PC2: Index of High Spring Flooding and Sustained High Flows (19.2% of total variance)

Code	PC Loading	Name	Description
nDH5	0.93	Annual maximum of 90-day moving average flow	Compute the maximum of a 90-day moving average flow for each year. DH5 is the mean (or median - Use Preference option) of these values.
nMA15	0.92	Mean monthly flow (Apr)	Means (or medians - Use Preference option) of all April flow values over the entire record.
MA3	0.9	Annual variability in daily flows 1	Mean (or median - Use Preference option) of the coefficients of variation (standard deviation/mean) for each year. Compute the coefficient of variation for each year of daily flows and then compute the mean of the annual coefficients of variation.
nMH5	0.87	Mean maximum monthly flows (May)	For each year, compute the maximum flow for the month of May. MH5 is the mean (or median - Use Preference option) of these values.
ML13	0.83	Variability across minimum monthly flows	Coefficient of variation in minimum monthly flows. Compute the mean and standard deviation for the minimum monthly flows over the entire flow record. ML13 is the standard deviation times 100 divided by the mean minimum monthly flow for all years.

Flow Class E1/E2 PCA

PC1: Index of Flashiness, Low Baseflow, and Variability (28.6% of total variance)

Code	PC Loading	Name	Description
RA15	0.96	Relative rise rate	Mean of the relative change in daily values for days where change is positive. SUM((value(t) - value(t-1))/value(t)), where value(t) is the daily mean value on day t.
ML20	0.95	5-day-block baseflow (inverse measure)	Divide the daily flow record into 5-day blocks. Find the minimum flow for each block. Assign the minimum flow as a base flow for that block if 90 percent of that minimum flow is less than the minimum flows for the blocks on either side. Otherwise, set it to zero. Fill in the zero values using linear interpolation. Compute the total flow for the entire record and the total base flow for the entire record. ML20 is the ratio of total flow to total base flow.
MA28	0.93	Variability in monthly flows (May)	Coefficient of variation in monthly flows for May (see MA24)
MA24	0.9	Variability in monthly flows (Jan)	Variability (coefficient of variation) of January flow values. Compute the standard deviation for January in each year over the entire flow record. Divide the standard deviation by the mean for January in each year. Average (or median - Use Preference option) these values across all years.
FH7	0.88	Flood frequency 7x median	Compute for each year the number of flow events with flows above a threshold equal to seven times the median flow value for the entire flow record. FH7 is the mean (or median - Use Preference option) number of events per year.

PC2: Index of Duration and Intensity of High Flows (16.1% of total variance)

Code	PC Loading	Name	Description
nDH5	0.84	Annual maximum of 90-day moving average flow	Compute the maximum of a 90-day moving average flow for each year. DH5 is the mean (or median - Use Preference option) of these values.
nMH5	0.8	Mean maximum monthly flows (May)	For each year, compute the maximum flow for the month of May. MH5 is the mean (or median - Use Preference option) of these values.
MH17	0.79	25% exceedance value	Compute the 25 percent exceedance value for the entire data record. MH17 is the 25 percent exceedance value divided by the median flow for the entire record.
FH3	0.77	Days per year above 3x flow median	Compute the number of days each year that the flow is above a threshold equal to three times the median flow for the entire record. FH3 is the mean (or median – Use Preference option) of the annual number of days for all years.
ML13	0.75	Variability across minimum monthly flows	Coefficient of variation in minimum monthly flows. Compute the mean and standard deviation for the minimum monthly flows over the entire flow record. ML13 is the standard deviation times 100 divided by the mean minimum monthly flow for all years.

Flow Class W2/W3

PC1: Index of Inter-Annual Variability and Occasional Secondary Fall/Winter Flooding (27% of total variance)

Code	PC Loading	Name	Description
TH1	-0.85	Julian date of annual maximum	Determine the Julian date that the maximum flow occurs for each year. Transform the dates to relative values on a circular scale (radians or degrees). Compute the x and y components for each year and average them across all years. Compute the mean angle as the arc tangent of y-mean divided by x-mean. Transform the resultant angle back to Julian date.
MA42	0.85	Variability across annual flows (0-100)	Range of annual flows divided by median annual flows. MA42 is the maximum of the annual mean flows minus the minimum of the annual mean flows divided by the median of the annual mean flows.
nMA21	-0.83	Mean monthly flow (Oct)	Means (or medians - Use Preference option) of all October flow values over the entire record.
nMH9	-0.83	Mean maximum monthly flows (Sep)	For each year, compute the maximum flow for the month of September. MH9 is the mean (or median - Use Preference option) of these values.
nML8	-0.81	Mean minimum monthly flows (Aug)	For each year, compute the minimum flow for the month of August. ML8 is the mean (or median - Use Preference option) of these values.

PC2: Index of Range of Magnitude (17% of total variance)

Code	PC Loading	Name	Description
ML17	-0.86	7-day minimum baseflow	Compute the mean annual flows. Compute the minimum of a 7-day moving average flow for each year and divide them by the mean annual flow for that year. ML17 is the mean (or median - Use Preference option) of those ratios.
FH3	0.84	Days per year above 3x flow median	Compute the number of days each year that the flow is above a threshold equal to three times the median flow for the entire record. FH3 is the mean (or median – Use Preference option) of the annual number of days for all years.
MH17	0.81	25% exceedance value	Compute the 25 percent exceedance value for the entire data record. MH17 is the 25 percent exceedance value divided by the median flow for the entire record.
MA6	-0.81	Ratio of low flow (Q90) to high flow (Q10) quantiles	Range in daily flows is the ratio of the 90 percent to 10 percent exceedance values for the entire flow record (low flow/high flow). Compute the 90 percent and 10 percent exceedance values for the entire flow record. Exceedance is computed by interpolating between the ordered (descending) flow values. Divide the 90 percent exceedance value by the 10 percent value.
DL12	-0.79	Normalized 7-day annual minimum flow	Annual minimum of 7-day moving average flow divided by the median for the entire record. Compute the minimum of a 7-day moving average flow for each year. DL12 is the mean of these values divided by

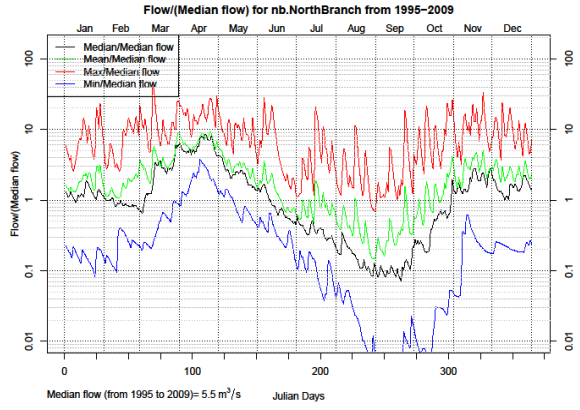
			the median for the entire record.
Flow Class W2			
PC1: Index of Brevity of Annual Flood and High Baseflow (30.1% of total variance)			
Code	PC Loading	Name	Description
nMH7	-0.92	Mean maximum monthly flows (Jul)	For each year, compute the maximum flow for the month of July. MH7 is the mean (or median - Use Preference option) of these values.
FH3	-0.91	Days per year above 3x flow median	Compute the number of days each year that the flow is above a threshold equal to three times the median flow for the entire record. FH3 is the mean (or median – Use Preference option) of the annual number of days for all years.
ML17	0.91	7-day minimum baseflow	Compute the mean annual flows. Compute the minimum of a 7-day moving average flow for each year and divide them by the mean annual flow for that year. ML17 is the mean (or median - Use Preference option) of those ratios.
nML3	0.91	Mean minimum monthly flows (Mar)	For each year, compute the minimum flow for the month of March. ML3 is the mean (or median - Use Preference option) of these values.
nDL5	0.9	Annual minimum of 90-day moving average flow	Compute the minimum of a 90-day moving average flow for each year. DL5 is the mean (or median - Use Preference option) of these values.
PC2: Index of Predictable Late and Long Lasting Annual Flood (13.9% of total variance)			
Code	PC Loading	Name	Description
DH17	0.81	High flow duration 2 (1x)	Compute for each year the average duration of flow events with flows above a threshold equal to the median flow value for the entire flow record. DH17 is the mean (or median - Use Preference option) duration of the events.
nMA15	-0.79	Mean monthly flow (Apr)	Means (or medians - Use Preference option) of all April flow values over the entire record.
RA15	-0.67	Relative rise rate	Mean of the relative change in daily values for days where change is positive. SUM((value(t) - value(t-1))/value(t)), where value(t) is the daily mean value on day t.
nML8	0.62	Mean minimum monthly flows (Aug)	For each year, compute the minimum flow for the month of August. ML8 is the mean (or median - Use Preference option) of these values.
TA2	0.6	Predictability of flow	Composed of two independent, additive components: constancy (a measure of temporal invariance) and contingency (a measure of periodicity). Predictability is computed from the same matrix as constancy (see TA1; see example in Colwell, 1974). It is computed as (using natural logarithms): 1 - ((uncertainty with respect to interaction of time and state - uncertainty with respect to time) / log (number of state))
PC3: Index of Seasonal Flow Variability (13.1% of total variance)			
Code	PC Loading	Name	Description
nML6	0.82	Mean minimum monthly flows (Jun)	For each year, compute the minimum flow for the month of June. ML6 is the mean (or median - Use Preference option) of these values.
MA36	0.77	Variability across monthly flows 1 (0-100)	Compute the minimum, maximum, and median of the monthly means (every month in the entire flow record). MA36 is the maximum of the monthly means minus the minimum of the monthly means divided by the median of the monthly means.
MA3	0.75	Annual variability in daily flows 1	Mean (or median - Use Preference option) of the coefficients of variation (standard deviation/mean) for each year. Compute the coefficient of variation for each year of daily flows and then compute the mean of the annual coefficients of variation.
nMH5	0.71	Mean maximum monthly flows (May)	For each year, compute the maximum flow for the month of May. MH5 is the mean (or median - Use Preference option) of these values.
ML13	0.68	Variability across minimum monthly flows	Coefficient of variation in minimum monthly flows. Compute the mean and standard deviation for the minimum monthly flows over the entire flow record. ML13 is the standard deviation times 100 divided by the mean minimum monthly flow for all years.
Flow Class E1			
PC1: Index of Range of Magnitude (25.4% of total variance)			
Code	PC Loading	Name	Description
FH3	0.93	Days per year above 3x flow median	Compute the number of days each year that the flow is above a threshold equal to three times the median flow for the entire record. FH3 is the mean (or median – Use Preference option) of the annual number of days for all years.
MH17	0.92	25% exceedance value	Compute the 25 percent exceedance value for the entire data record. MH17 is the 25 percent exceedance value divided by the median flow for the entire record.
MA6	-0.92	Ratio of low flow (Q90) to high flow (Q10) quantiles	Range in daily flows is the ratio of the 90 percent to 10 percent exceedance values for the entire flow record (low flow/high flow). Compute the 90 percent and 10 percent exceedance values for the entire flow record. Exceedance is computed by interpolating between the ordered (descending) flow values. Divide the 90 percent exceedance value by the 10 percent value.
ML13	0.87	Variability across minimum monthly flows	Coefficient of variation in minimum monthly flows. Compute the mean and standard deviation for the minimum monthly flows over the entire flow record. ML13 is the standard deviation times 100 divided by the mean minimum monthly flow for all years.
nDH5	0.87	Annual maximum of 90-day	Compute the maximum of a 90-day moving average flow for each year. DH5 is the mean (or median - Use

		moving average flow	Preference option) of these values.
PC2: Index of Spring Flood Brevity and Intensity and Low Summer Flow (16.1% of total variance)			
Code	PC Loading	Name	Description
nML8	-0.71	Mean minimum monthly flows (Aug)	For each year, compute the minimum flow for the month of August. ML8 is the mean (or median - Use Preference option) of these values.
nML6	-0.7	Mean minimum monthly flows (Jun)	For each year, compute the minimum flow for the month of June. ML6 is the mean (or median - Use Preference option) of these values.
nMH7	-0.66	Mean maximum monthly flows (Jul)	For each year, compute the maximum flow for the month of July. MH7 is the mean (or median - Use Preference option) of these values.
MA28	0.66	Variability in monthly flows (May)	Coefficient of variation in monthly flows for May (see MA24)
nMA15	0.65	Mean monthly flow (Apr)	Means (or medians - Use Preference option) of all April flow values over the entire record.

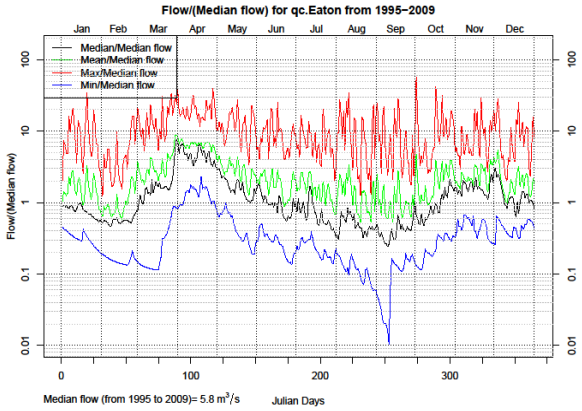
Appendix 2 Table 3 Hydrographs of sites with extreme PC scores on each PC axis defined in Appendix Table 2

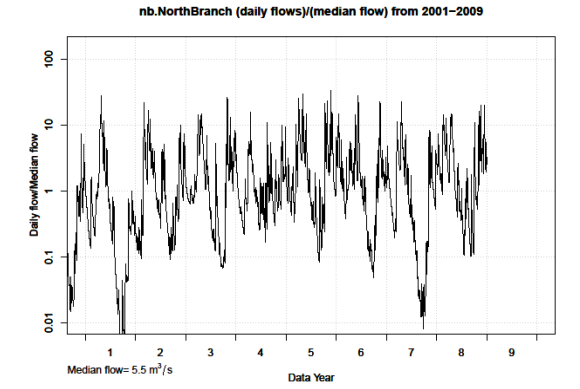
E2 Unregulated PCA

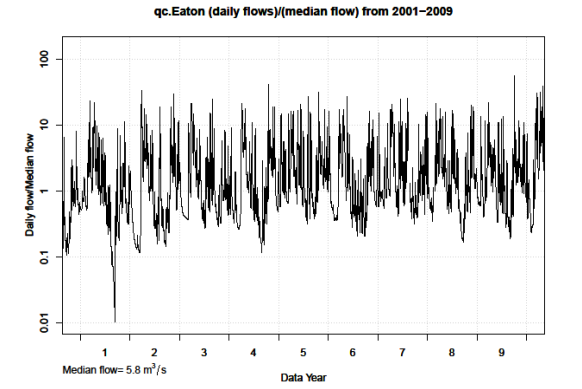
PC1 Low Score



PC1 High Score

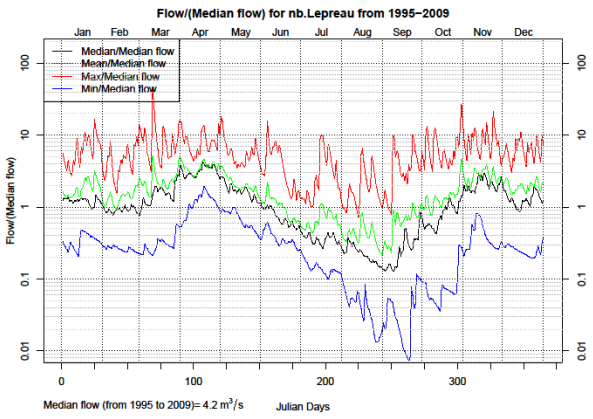


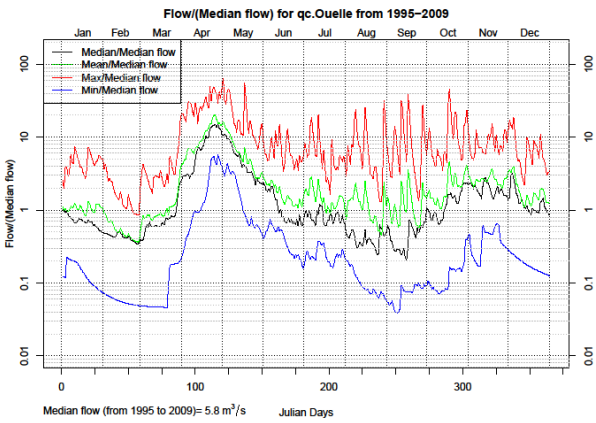


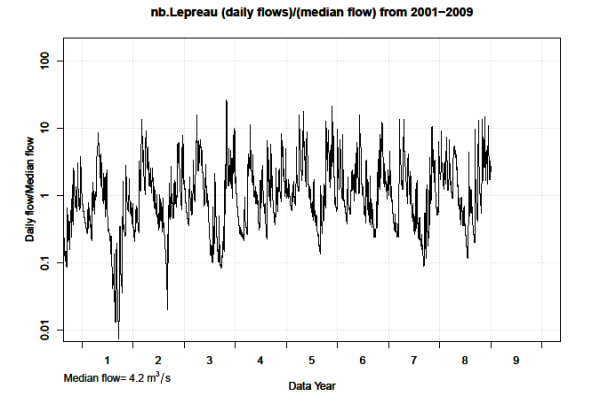


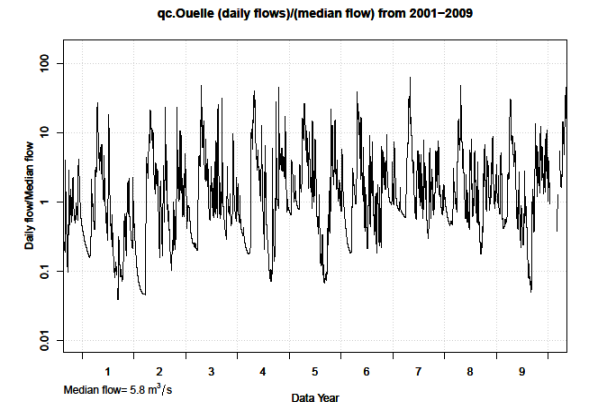
PC2 Low Score (also slightly negative on PC1)

PC2 High Score (also slightly negative on PC1)



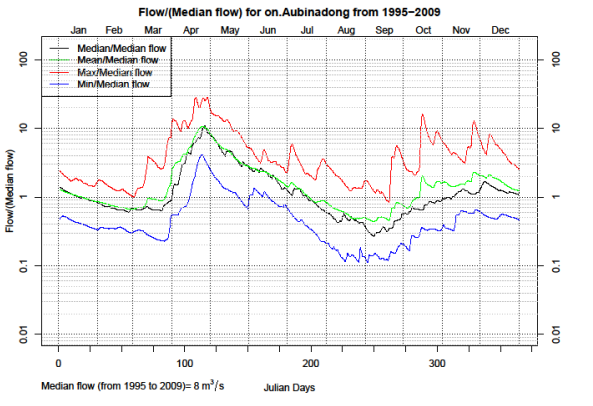




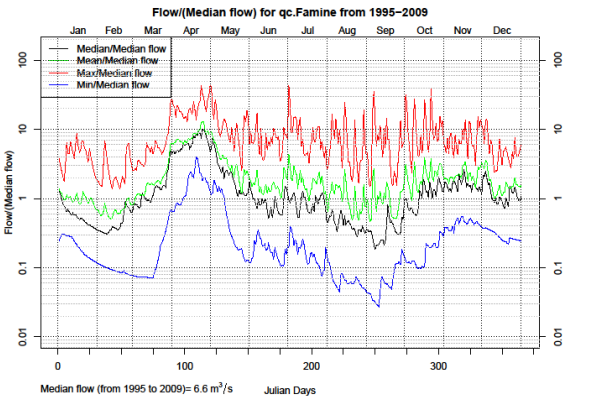


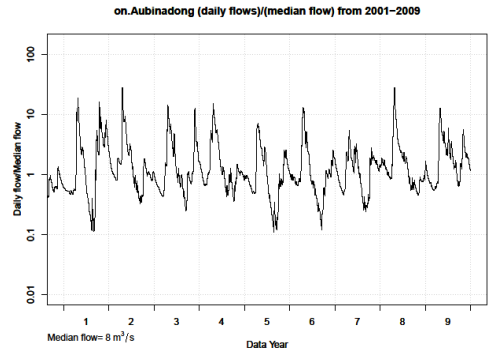
E1/E2 Unregulated PCA

PC1 Low Score

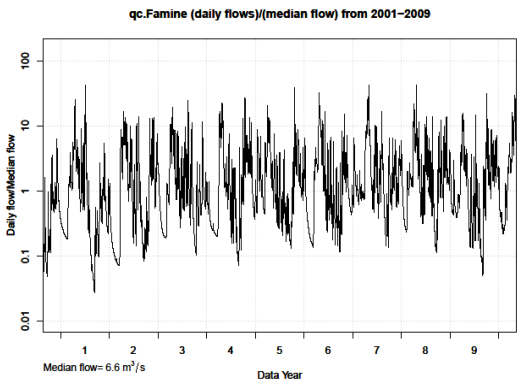


PC1 High Score

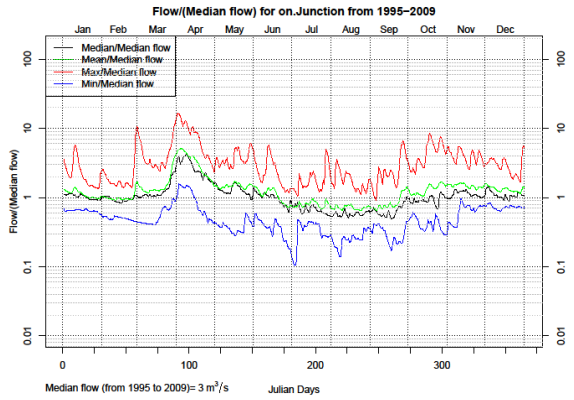


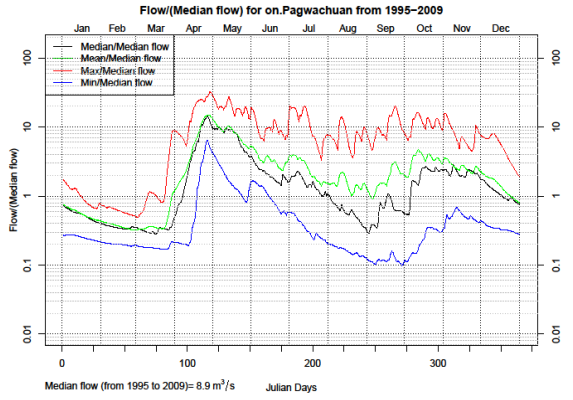


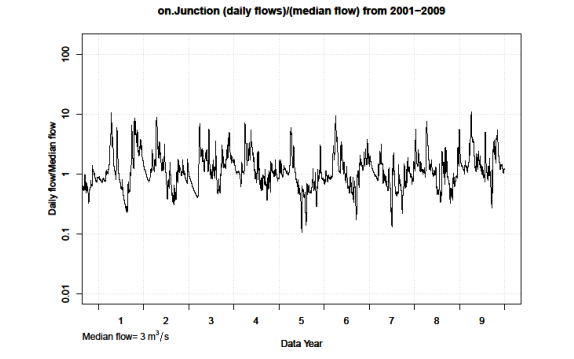
PC2 Low Score

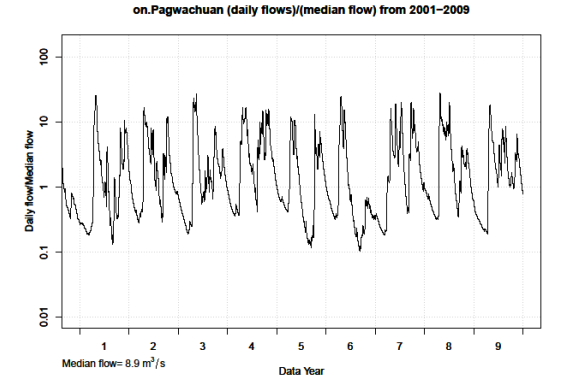


PC2 High Score





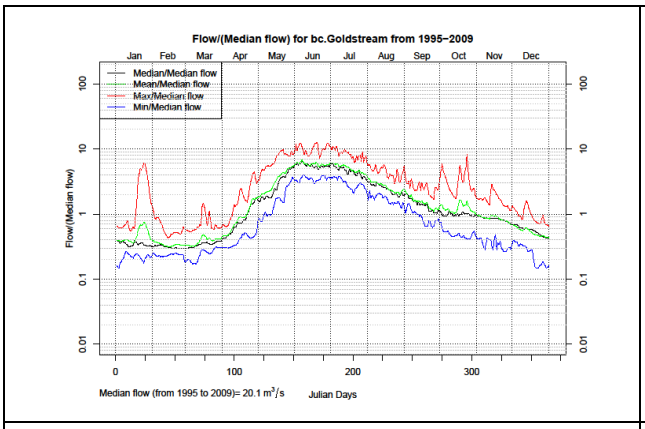


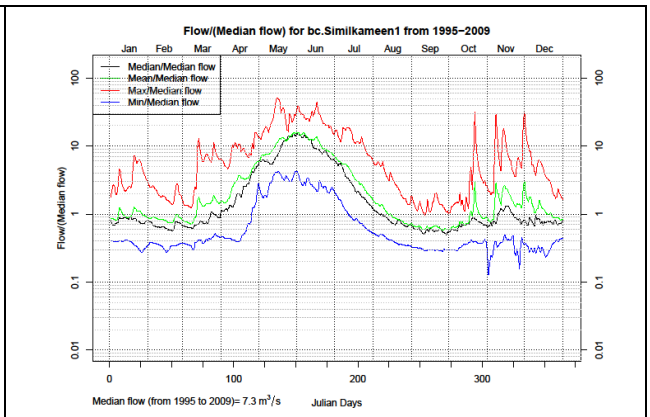


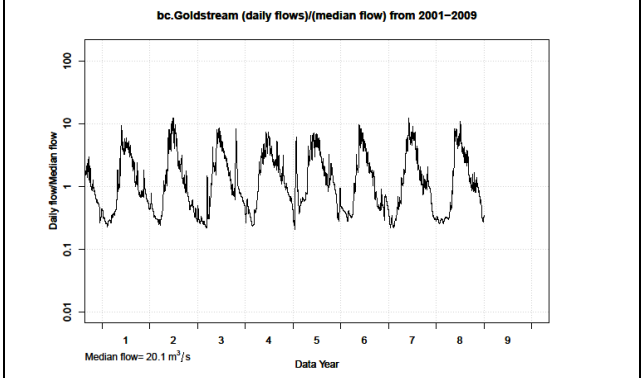
W2/W3 Unregulated PCA

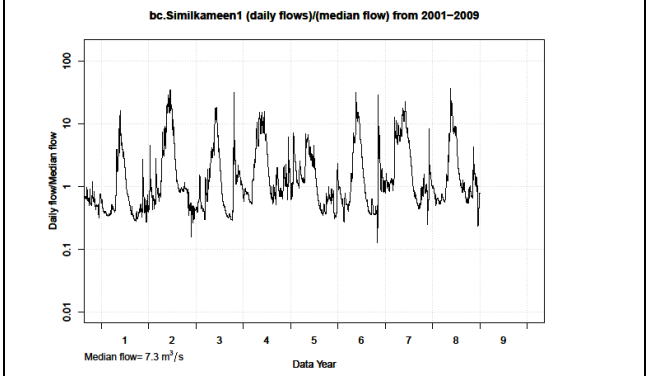
PC1 Low Score

PC1 High Score



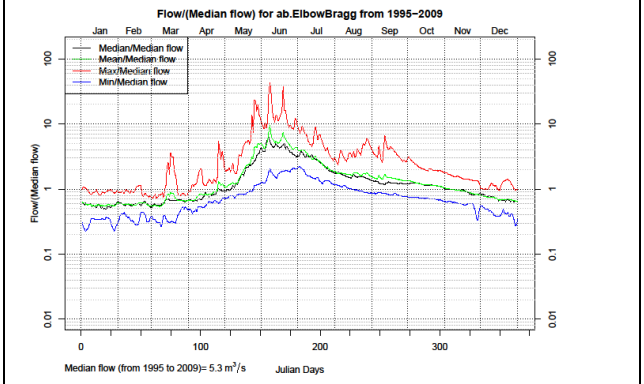


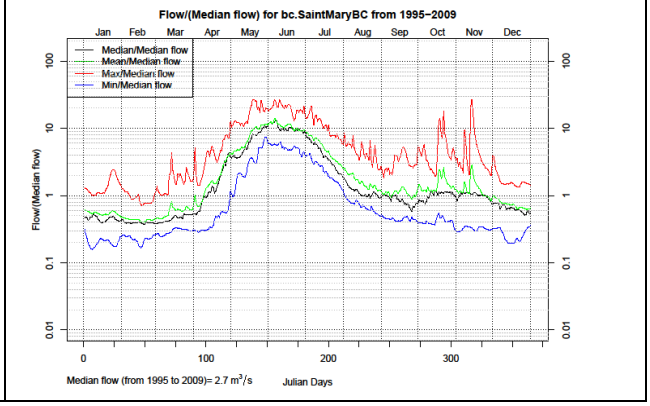


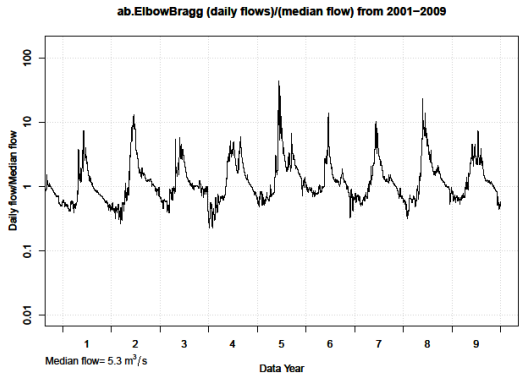


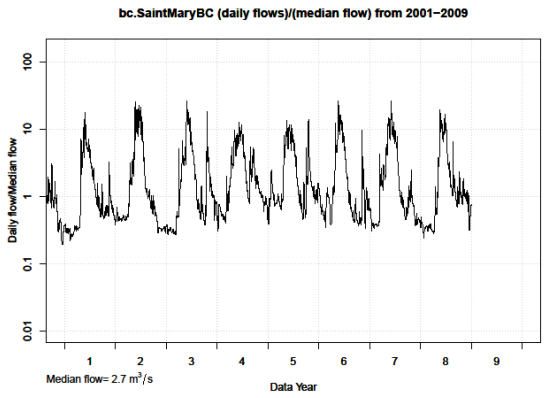
PC2 Low Score

PC2 High Score



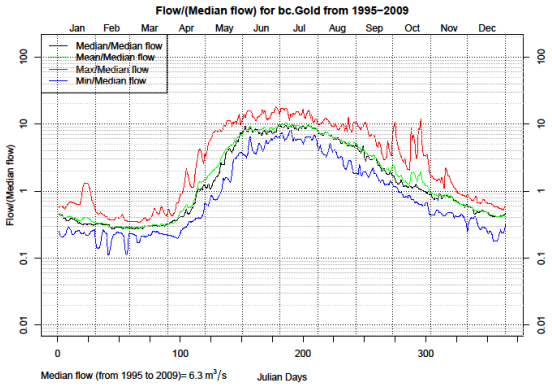


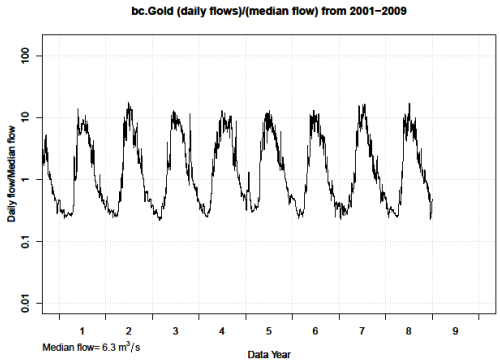




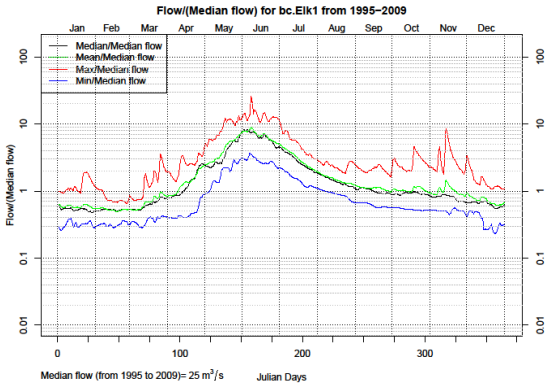
W2 Unregulated PCA

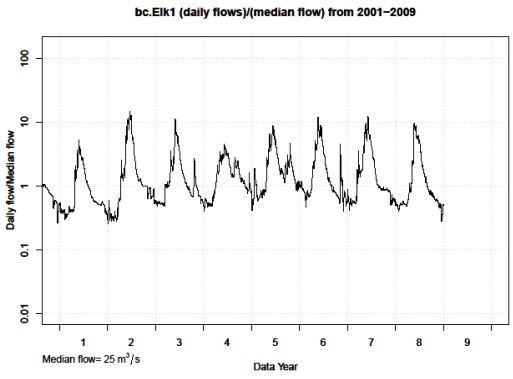
PC1 Low Score (slightly elevated on PC2)





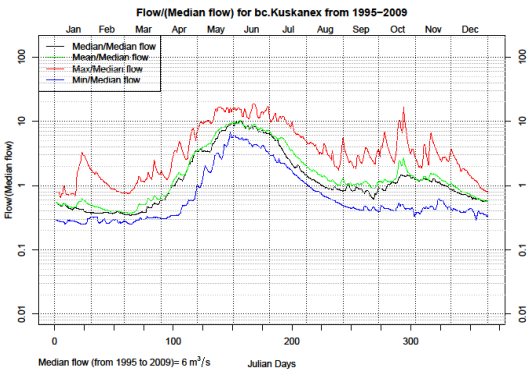
PC1 High Score (not the highest, but close to 0 on PC2 & PC3)

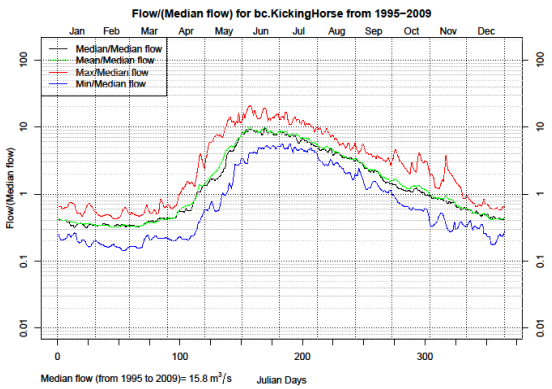


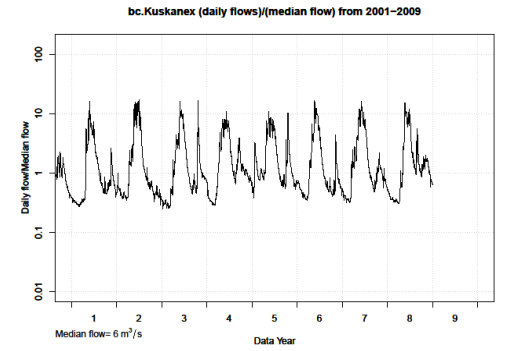


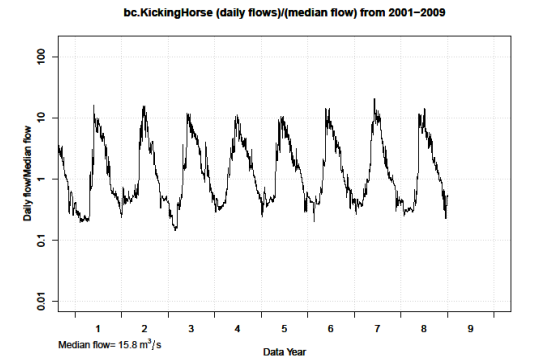
PC2 Low Score (also slightly elevated on PC3)

PC2 High Score (not the highest, also slightly low on PC1)

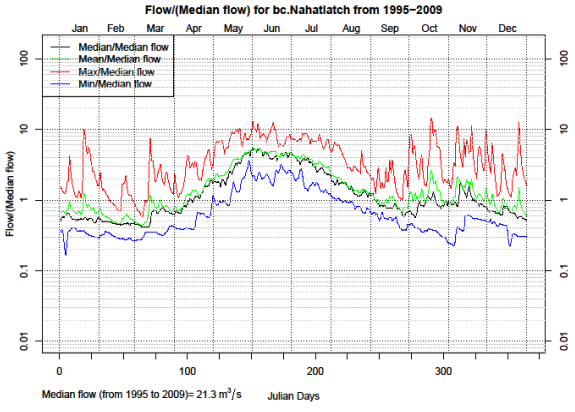




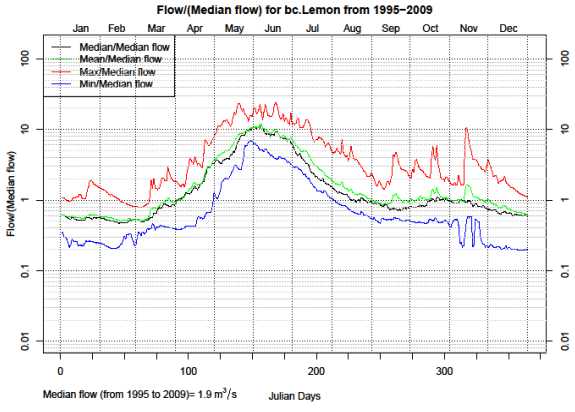


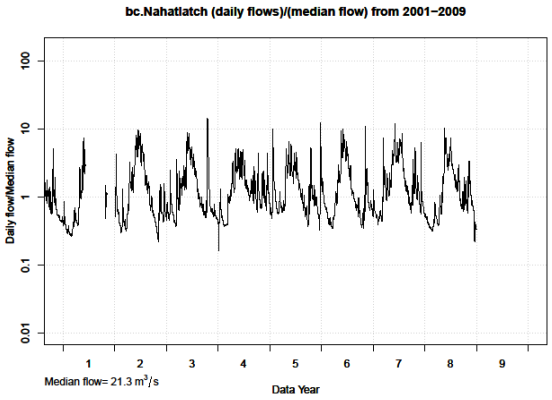


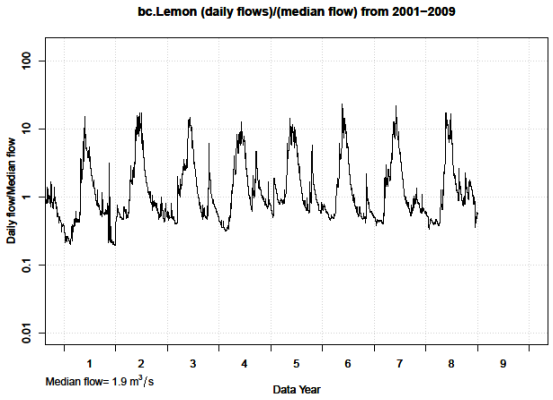
PC3 Low Score (also very low on PC2)



PC3 High Score (also very low on PC2)

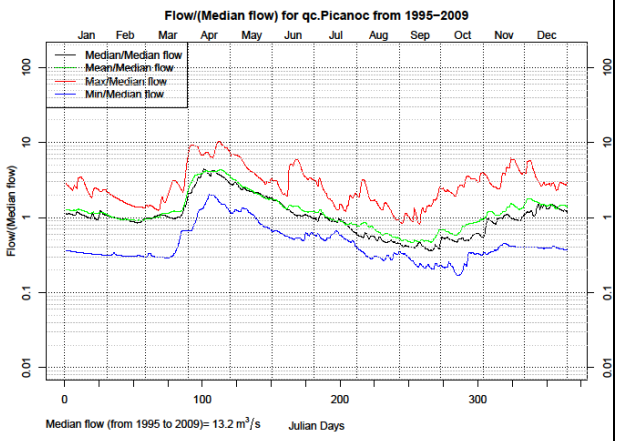




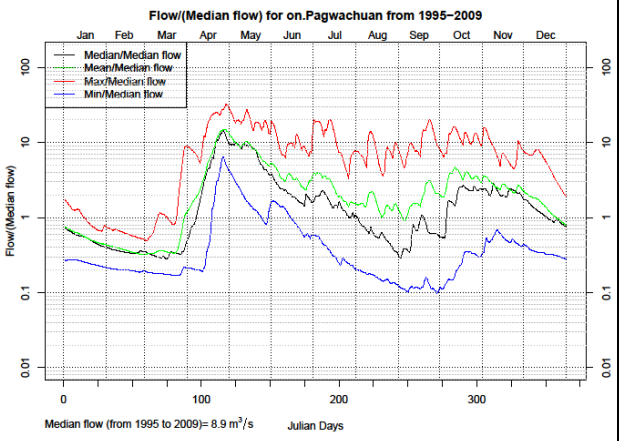


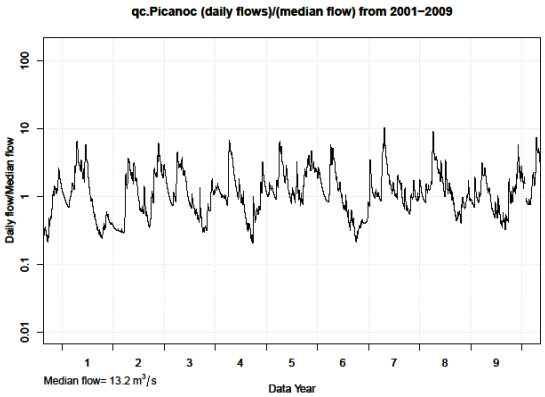
E1 Unregulated PCA

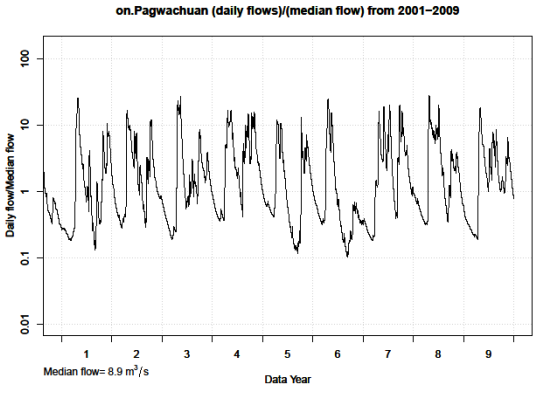
PC1 Low Score (also slightly negative on PC2)



PC1 High Score (also slightly negative on PC2)

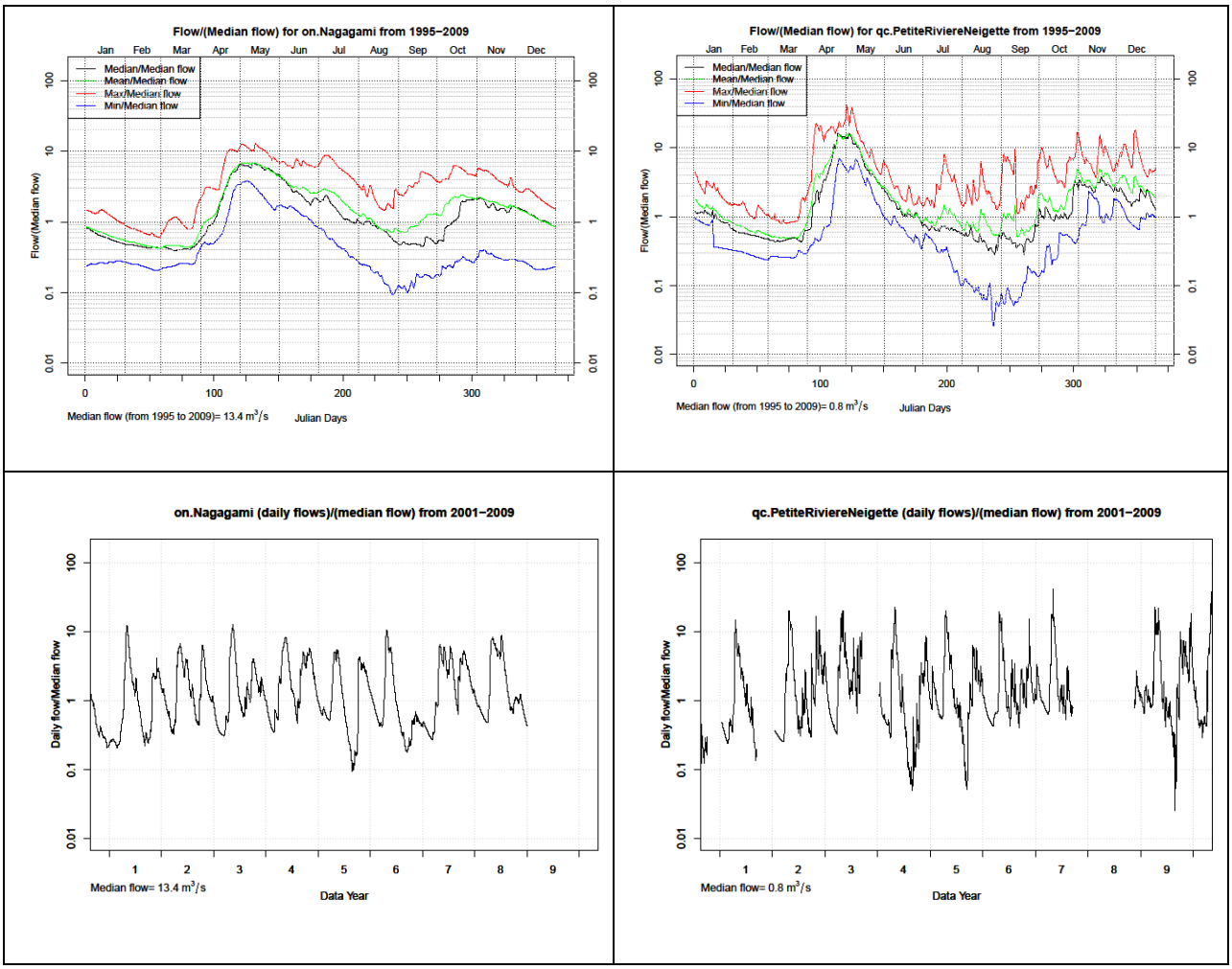






PC2 Low Score (also slightly positive on PC1)

PC2 High Score (also slightly positive on PC1)



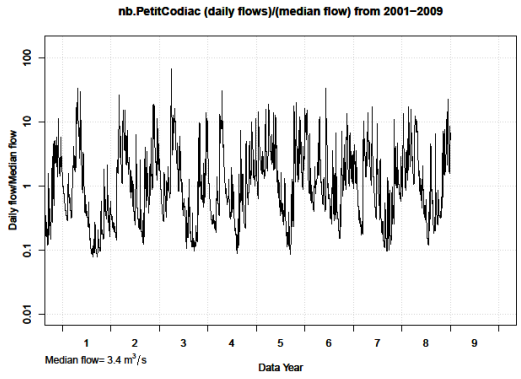
Appendix 2 Table 4

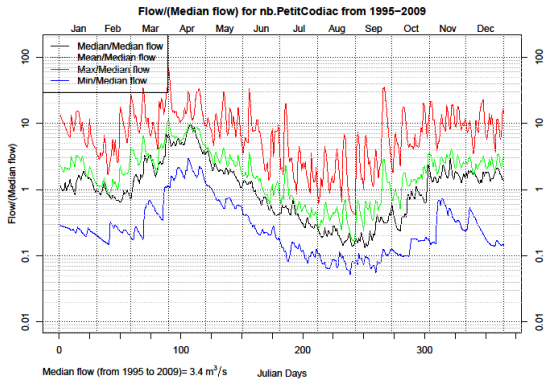
Hydrographs for the reference site closest to the class centroid (for each class) followed by each* regulated hydrograph.

* Note: Hydrographs are not shown for regulated systems where our sole source of data was private flow records were obtained by HydroNet (on.Magpie, on.Michipicoten, on.Mississagi, nb.Dee and nb.Serpentine). In some instances where HydroNet did obtain private records but a HYDAT/CEHQ gauge also exists/existed, the following hydrographs were generated using the publically available data.

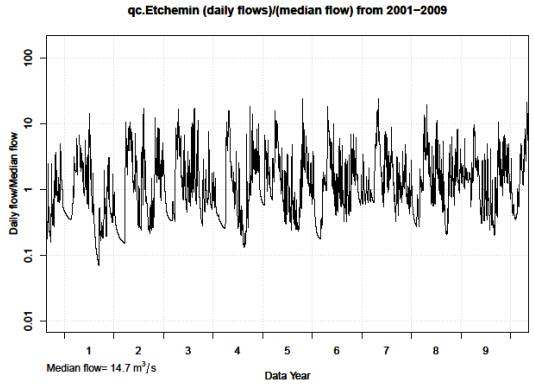
Flow Class E2

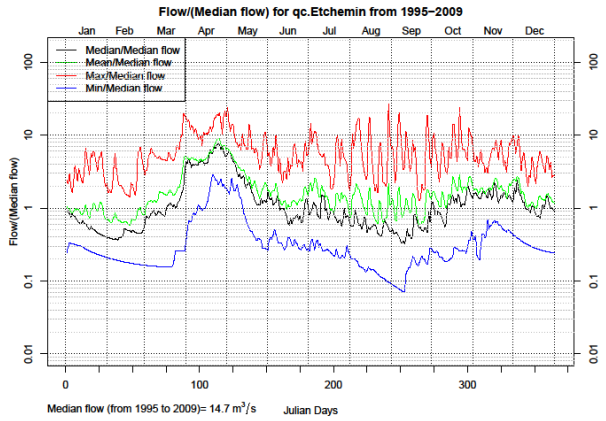
Central Unregulated Hydrograph (based on PC1 and PC2)



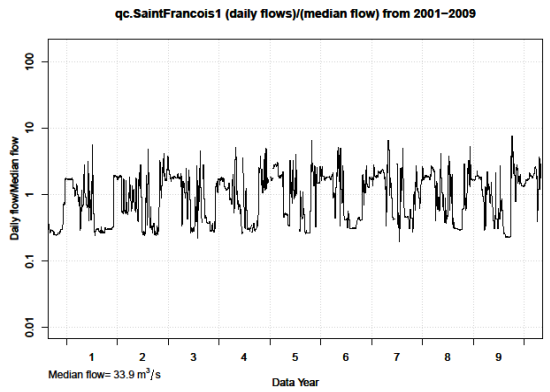


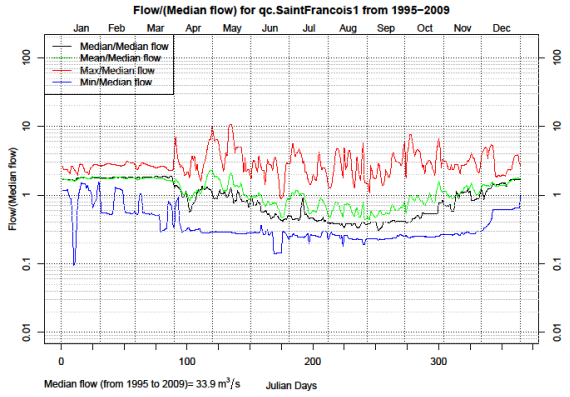
Regulated qc.Etchemin



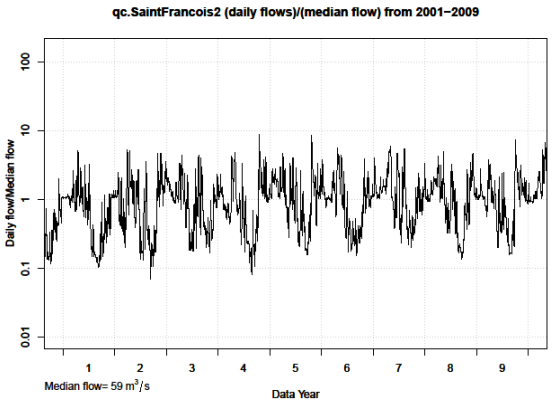


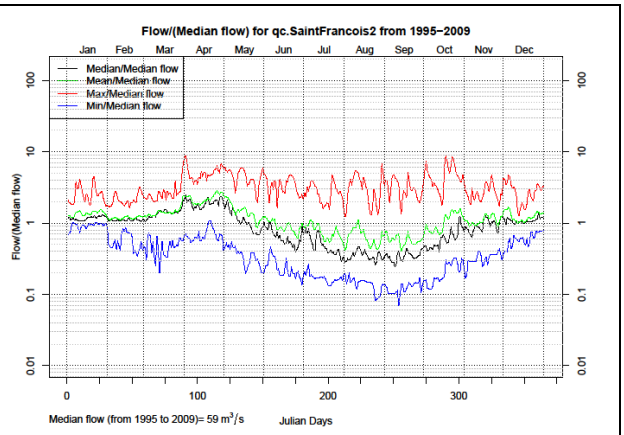
Regulated qc.SaintFrancois1





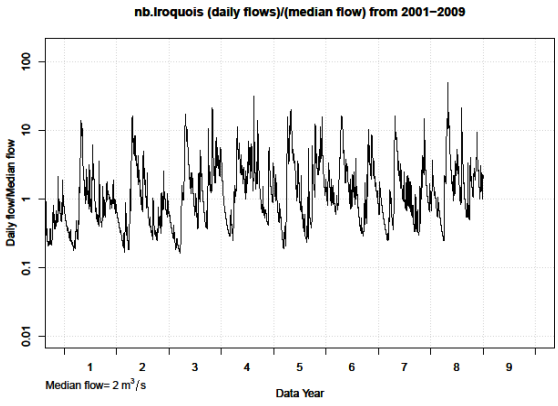
Regulated qc.SaintFrancois2

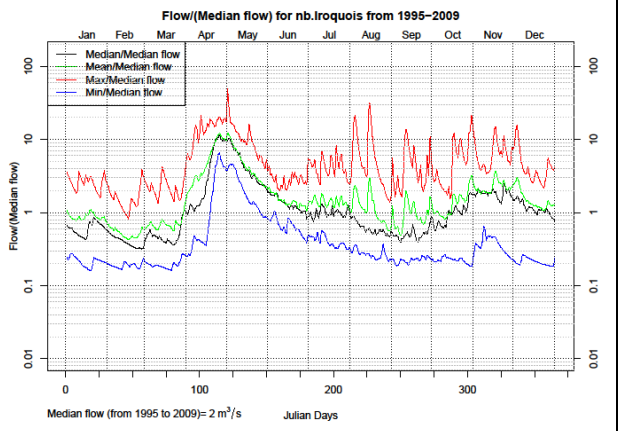




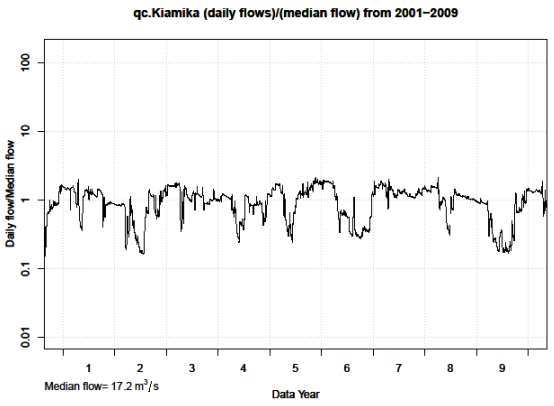
Flow Class E1/E2

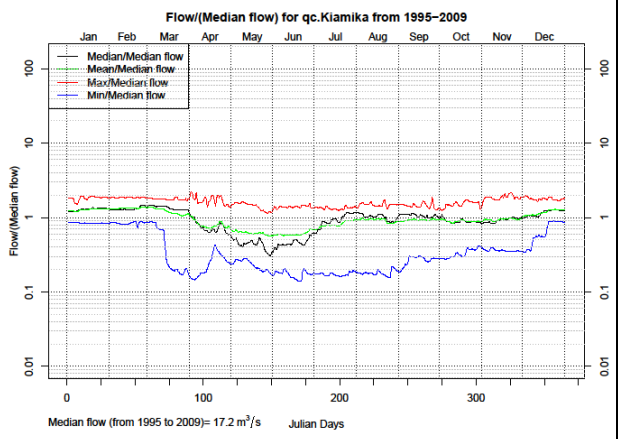
Central Unregulated Hydrograph (based on PC1 and PC2)



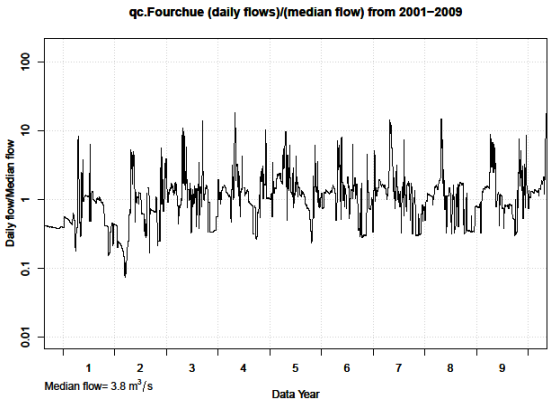


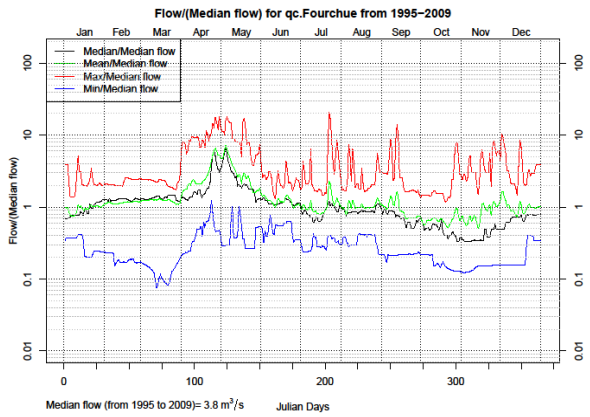
Regulated qc.Kiamika





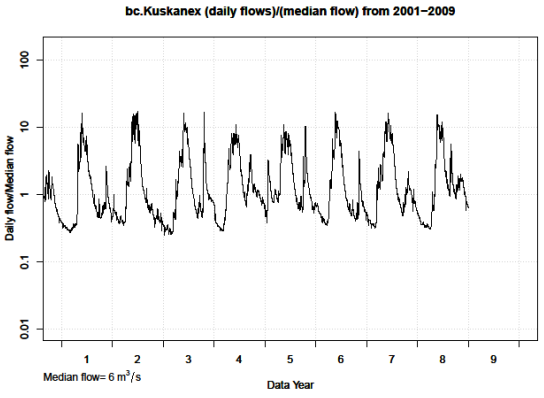
Regulated qc.Fourchue

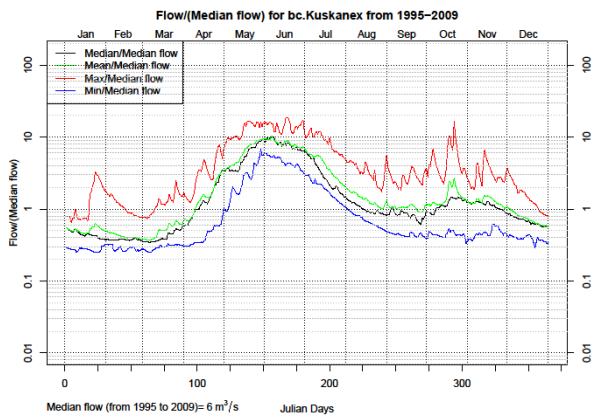




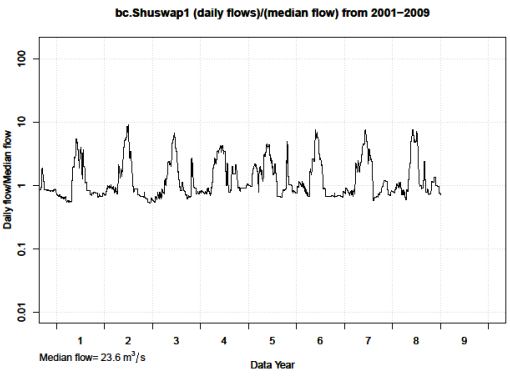
Flow Class W2/W3

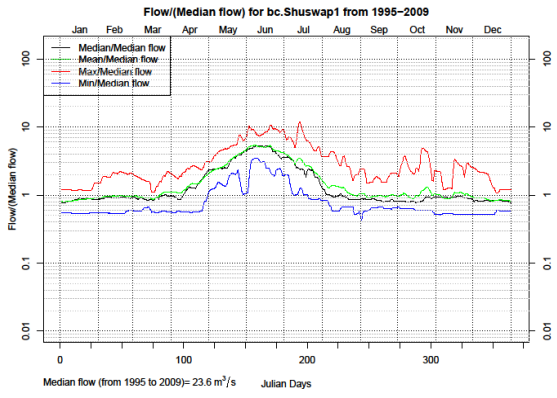
Central Unregulated Hydrograph (based on PC1 and PC2)



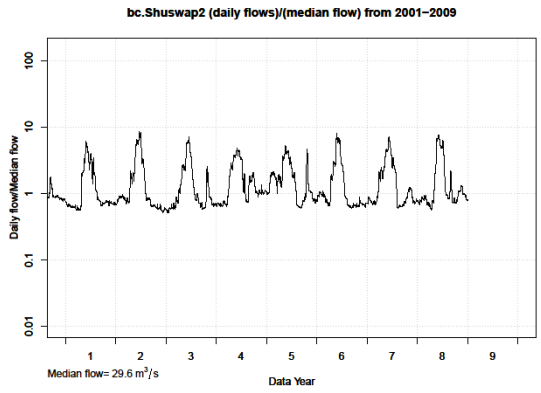


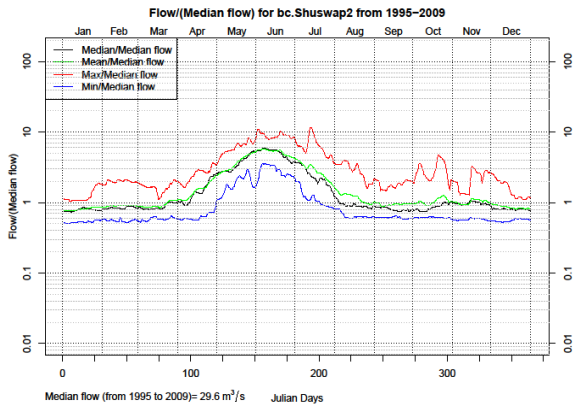
Regulated bc.Shuswap1Sugar





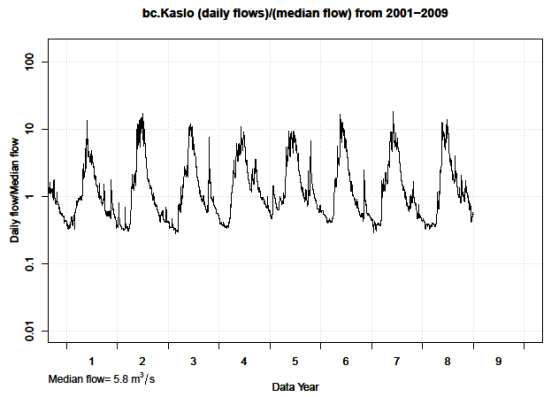
Regulated bc.Shuswap2Wilsey

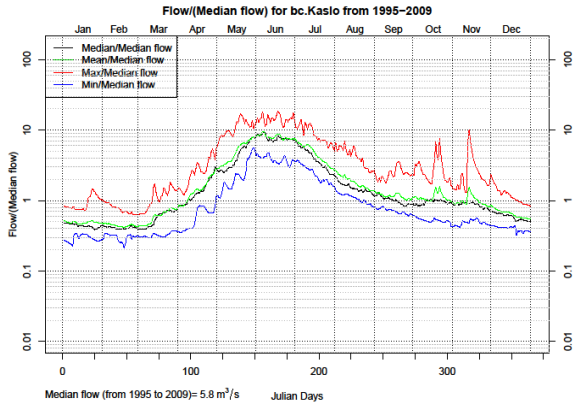




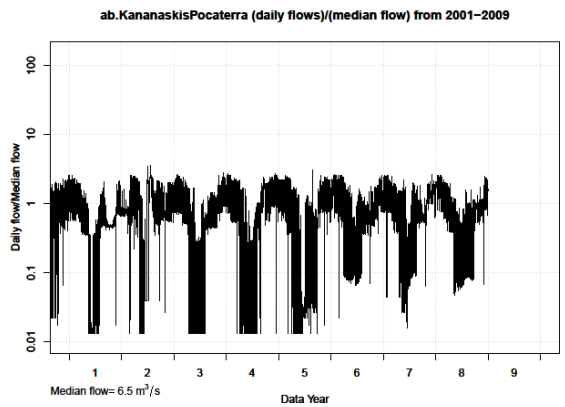
Flow Class W2

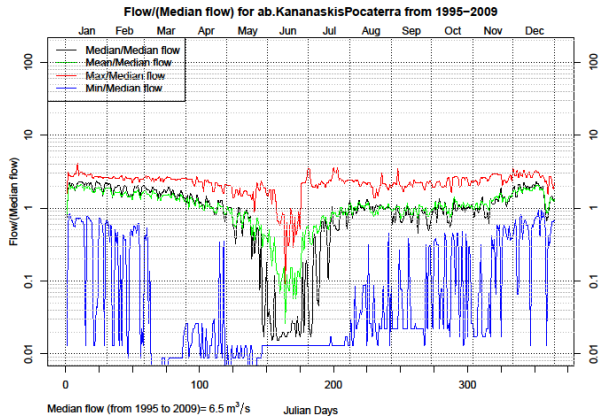
Central Unregulated Hydrograph (based on PC1 and PC3) – because regulated rivers are less divergent in PC1 vs. PC2 plot



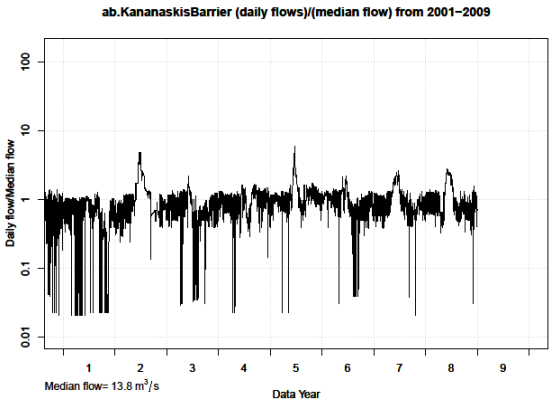


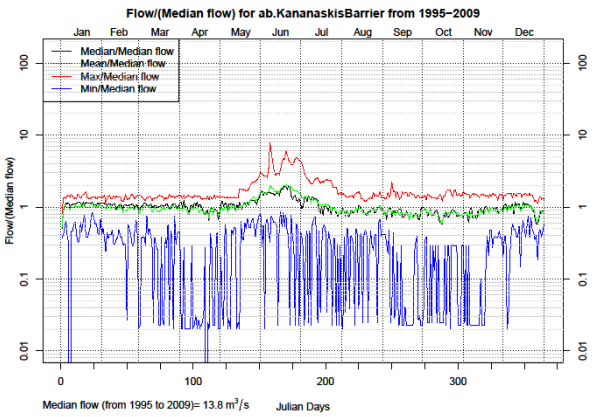
Regulated ab.KananaskisPocaterra



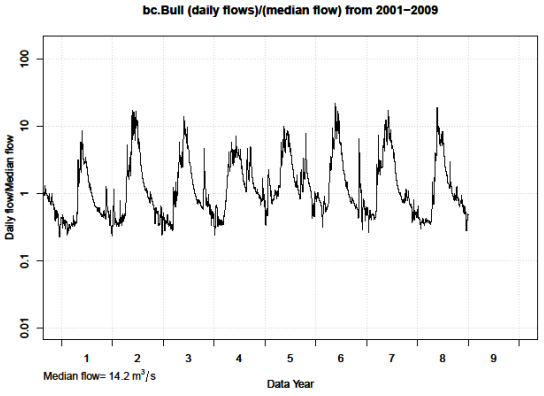


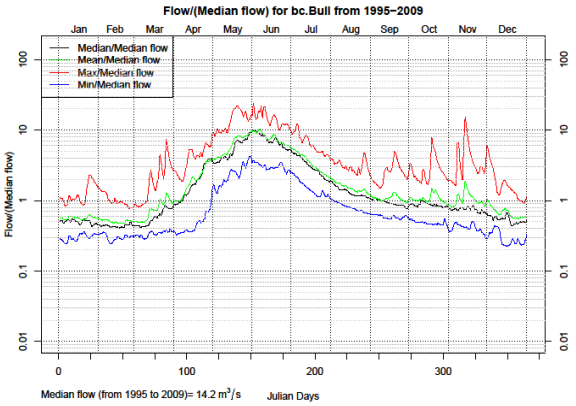
Regulated ab.KananaskisBarrier





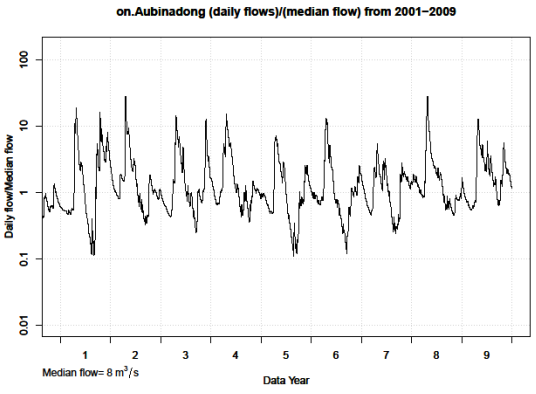
Regulated bc.Bull

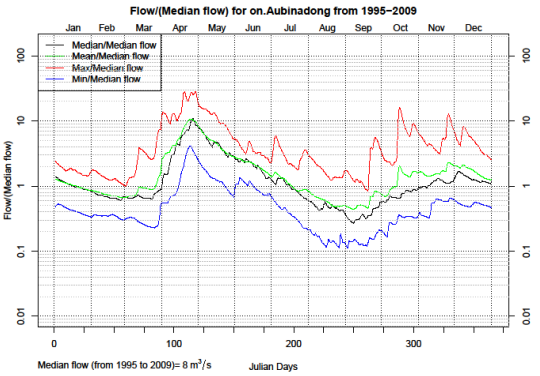




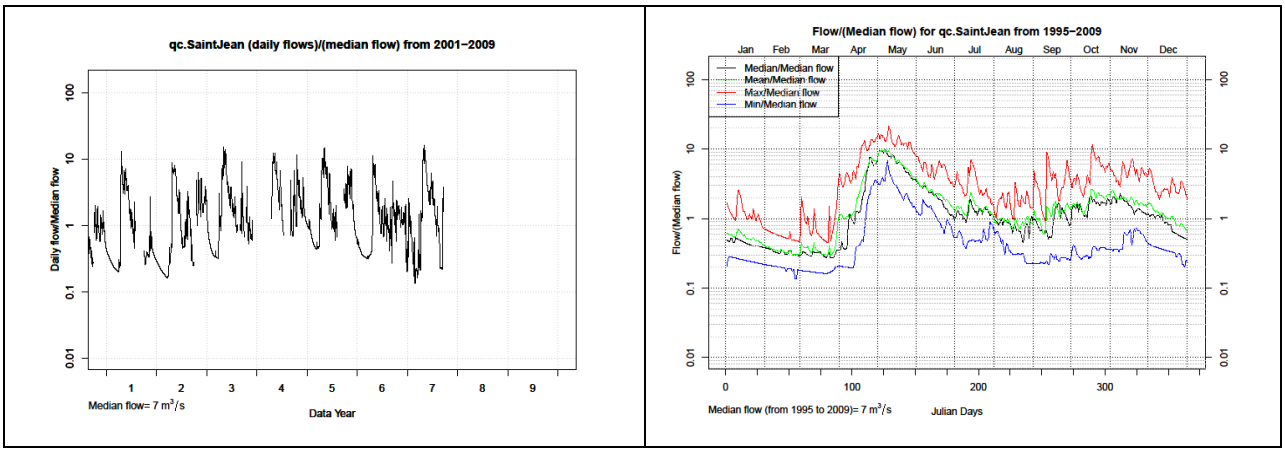
Flow Class E1

Central Unregulated Hydrograph (based on PC1 and PC2)



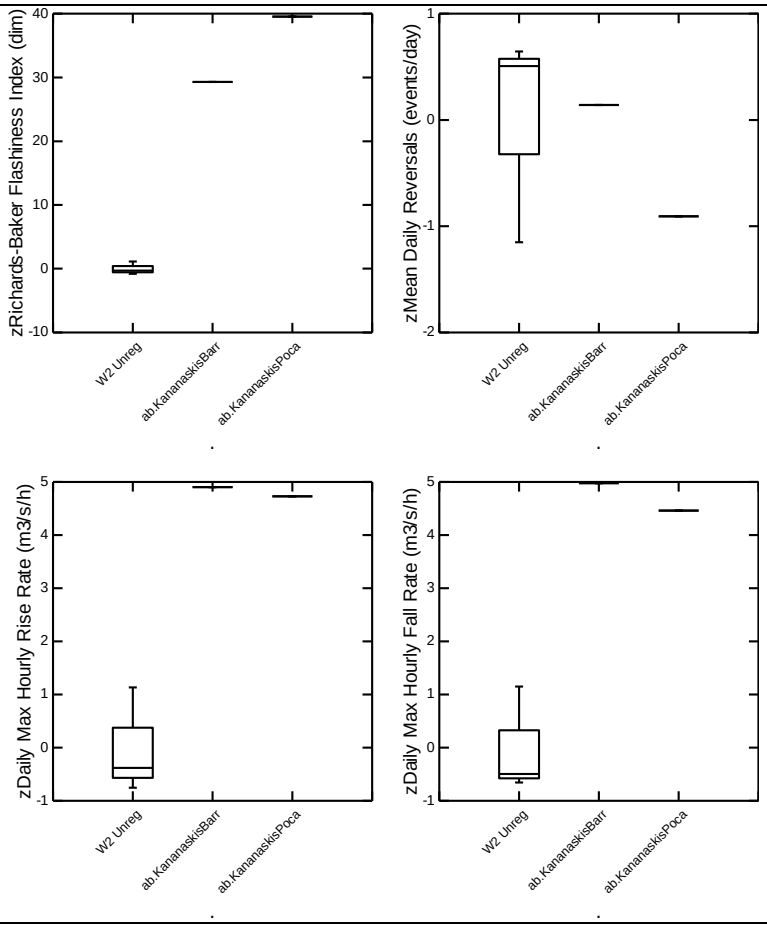


Regulated qc.SaintJean



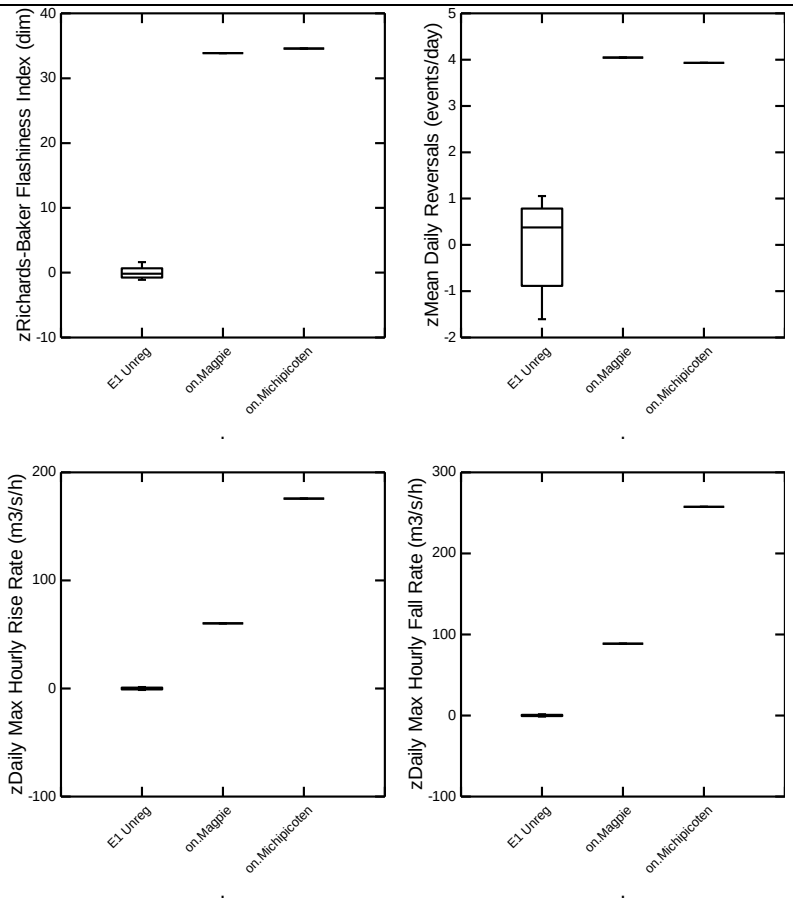
Appendix 2 Table 5 Flow indices generated from hourly discharge data for regulated sites in flow classes containing sites below hydropeaking dams compared to regional references with available hourly data.

Flow Class W2



Z-scores for unregulated **W2** rivers (n=3) beside regulated W2 hydropeaking rivers' index scores for selected hourly indices (using the same data period as the daily analysis). For the details about the Richards-Baker flashiness index, see Zimmerman *et al.* (2010).

Flow Class E1



Z-scores for unregulated **E1** rivers (n=8) beside regulated E1 hydropeaking rivers' index scores for selected hourly indices (using the same data period as the daily analysis). For the details about the Richards-Baker flashiness index, see Zimmerman *et al.* (2010). The Mississagi river is not included in this analysis because the hourly flow data at the hydro dam does not adequately reflect the flows in the river.

Appendix 2 Table 6 Top loading for the top two principal components of flow anomalies (z-scores of regulated river flow indices compared to particular reference class norms) in all regulated HydroNet rivers. This table supports the choices of PC axis names.

PCA of all regulated standardized flow indices

PC1: Index of low flashiness and high total baseflow (27.1% of total variance)

Code	PC Loading	Name	Description
RA15	-0.95	Relative rise rate	Mean of the relative change in daily values for days where change is positive. SUM((value(t) - value(t-1))/value(t)), where value(t) is the daily mean value on day t.
ML20	-0.92	5-day-block baseflow (inverse measure)	Divide the daily flow record into 5-day blocks. Find the minimum flow for each block. Assign the minimum flow as a base flow for that block if 90 percent of that minimum flow is less than the minimum flows for the blocks on either side. Otherwise, set it to zero. Fill in the zero values using linear interpolation. Compute the total flow for the entire record and the total base flow for the entire record. ML20 is the ratio of total flow to total base flow.
FH1	-0.92	Flood frequency 1 (High flood pulse count)	Compute for each year the number of flow events with flows above a threshold equal to the 75th percentile value for the entire flow record. FH1 is the mean (or median - Use Preference option) number of events per year.
DL16	0.92	Low flow pulse duration	Compute the average pulse duration for each year for flow events below a threshold equal to the 25th percentile value for the entire flow record. DL16 is the median of the yearly average durations.
FL1	-0.86	Low flow frequency 1 (Low flood pulse count)	Compute for each year the number of flow events with flows below a threshold equal to the 25th percentile value for the entire flow record. FL1 is the mean (or median - Use Preference option) number of events per year.

PC2: Index of range of magnitude and low minimum baseflow (21% of total variance)

Code	PC Loading	Name	Description
ML17	-0.85	7-day minimum baseflow	Compute the mean annual flows. Compute the minimum of a 7-day moving average flow for each year and divide them by the mean annual flow for that year. ML17 is the mean (or median - Use Preference option) of those ratios.
MA6	-0.83	Ratio of low flow (Q90) to high flow (Q10) quantiles	Range in daily flows is the ratio of the 90 percent to 10 percent exceedance values for the entire flow record (low flow/high flow). Compute the 90 percent and 10 percent exceedance values for the entire flow record. Exceedance is computed by interpolating between the ordered (descending) flow values. Divide the 90 percent exceedance value by the 10 percent value.
MH17	0.81	25% exceedance value	Compute the 25 percent exceedance value for the entire data record. MH17 is the 25 percent exceedance value divided by the median flow for the entire record.
FH3	0.8	Days per year above 3x flow median	Compute the number of days each year that the flow is above a threshold equal to three times the median flow for the entire record. FH3 is the mean (or median – Use Preference option) of the annual number of days for all years.
nMH2	0.79	Mean maximum monthly flows (Feb)	For each year, compute the maximum flow for the month of February. MH2 is the mean (or median - Use Preference option) of these values.

PC3: Index of low seasonal variability and high January flow (12.5% of total variance)

Code	PC Loading	Name	Description
MA36	-0.75	Variability across monthly flows 1 (0-100)	Compute the minimum, maximum, and median of the monthly means (every month in the entire flow record). MA36 is the maximum of the monthly means minus the minimum of the monthly means divided by the median of the monthly means.
nML1	0.72	Mean minimum monthly flows (Jan)	For each year, compute the minimum flow for the month of January. ML1 is the mean (or median - Use Preference option) of these values.
MA3	-0.68	Annual Variability in daily flows 1	Mean (or median - Use Preference option) of the coefficients of variation (standard deviation/mean) for each year. Compute the coefficient of variation for each year of daily flows and then compute the mean of the annual coefficients of variation.
nMA12	0.67	Mean monthly flow (Jan)	Means (or medians - Use Preference option) of all January flow values over the entire record.
MA27	-0.66	Variability in monthly flows (Apr)	Coefficient of variation in monthly flows for April (see MA24)
TA1	0.66	Constancy	Constancy is computed via the formulation of Colwell (see example in Colwell, 1974). Full description in Appendix 1.