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Using regional flow classes as references to analyse flow regime anomalies across a set of regulated Canadian rivers

Fraser McLaughlin [a,*], Michel Lapointe [a,1], Guillaume Bourque [b], Daniel Boisclair [b]

[a] Department of Geography, McGill University, Burnside Hall, 805 Sherbrooke Street West, Québec H3A 0B9, Canada

[b] Département de Sciences Biologiques, Université de Montréal, Pavillon Marie-Victorin 90, Avenue Vincent-d'Indy, Québec H2V 2S9, Canada

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SUMMARY

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 be detrimental to biotic communities and even affect river ecosystem structure (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 as units of analysis to identify significant damming related flow alteration (e.g. Poff, 1996; Poff and Zimmerman, 2010; McManamay et al., 2012a). Specifically, the natural range of flow behaviour within regional classes can be used to identify clearly anomalous flow features in rivers regulated by dams. Through ordination analysis on 70 ecologically important flow indices, we isolated five distinctive regional groupings of natural flow regimes among the 96 unregulated rivers located in study regions of South Eastern and South Western Canada, selected based on watershed characteristics as possible references for the 13 hydro-regulated, NSERC-HydroNet study rivers in British Columbia, Alberta, Ontario, Quebec and New Brunswick. 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 appropriate regional flow classes through discriminant function analysis based on shared geographic location and watershed characteristics. Anomalous flow features in the regulated rivers are then characterized by type and strength, based on identification of flow indices that are significantly different from observed natural variability in the relevant regional class. The magnitude distributions and the main axes of variability in index anomalies are analysed, across regions and regulation types (storage, peaking and run-of-the-river (RoR)). We also discuss the potential biological implications of the dominant flow anomalies in this set of Canadian rivers regulated by hydro dams.

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 in channels flowing through their own alluvium is shaped by the 2–5 yr recurrence high flow levels; these high flow levels affect channel dimensions, reach scale bed material composition, substrate mobility levels and overall 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 taxa are adjusted in complex ways to mosaics of patch and reach scale depth and velocity patterns and flow timing features all dependent on the flow regime of a river (e.g. Riis and Biggs, 2003; Baranyi et al., 2002). Other key environmental factors such as water temperature and chemistry, winter ice regime and fate of invasive species are also affected by the flow regime and are important to river ecosystem structure and function (Poff et al., 1997; Baron et al., 2002; Poff et al., 2010).

After dam construction, river flows are regulated by dam operators. The type and degree of flow alteration that occurs after regulation can be highly variable as it depends, first, on the physical characteristics of the installation (i.e. dam height, reservoir volume, number of turbines and design of other release structures) all of which affect the amount of water that can be retained, the number of possible increments to releases in peaking mode and

* Corresponding author. Address: 932 Rue Gilford, Montreal, Quebec H2J 1P2, Canada. Tel.: +1 514 715 6975.

E-mail addresses: Fraser.Mclaughlin@mail.mcgill.ca (F. McLaughlin), Michel.Lapointe@mcgill.ca (M. Lapointe).

[1] Co-corresponding author. Address: 805 Sherbrooke Street West, Montreal, Québec H3A 0B9, Canada.

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the maximum release rates possible at various times. Regulation regime also depends on design hydropower mode of operation (e.g. other hydro plants on the same river, timing of grid demand, ramping rate restrictions and environmental baseflow requirements), and finally on the rivers pre-regulated flow regime and flow events that exceed possible regulation. Tools are required to quantitatively analyse the range of regulation effects that are encountered or desirable.

The variety of possible flow regime alterations complicates analysis of regulation effects. A multi-metric approach to flow regime alteration in regulated systems has emerged with the recognition that, beyond simple minimum flow requirements, a naturally variable flow regime with many distinct ecologically important features 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 a deepening understanding of the range of hydrologic features affecting ecosystem structure and function emerging from individual river studies, a scientific consensus is emerging supporting the development of multi-metric environmental flow standards, defined at the regional scale (Poff et al., 2010). Poff et al. (2010) present an empirical framework called the Ecological Limits of Hydrologic Alteration (ELOHA) to implement regional environmental flow standards protecting faunal biodiversity and evolutionary potential, based on observed trends between altered hydrologic parameters and ecological outcomes across many regional river systems. ELOHA 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).

Flow alterations by any given dam can be quantified using historical flow records by contrasting the values of large sets of flow 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 vs post-dam flow records (e.g. Richter et al., 1996). Here, we distinguish such estimates of flow regime 'alteration' (quantifying regime changes from historic conditions on the same river using either pre-dam measured or synthetic data) from flow regime 'anomalies' (which are defined in reference to regional flow regime norms over a common time period). These are distinct concepts, as regulation may in some cases quantifiably alter certain flow regime characteristics on a dammed system, but the new regime may still fail to be regionally anomalous in the above sense, i.e. it may remain within the range of natural flow behaviour in the region that is seen to support productive and species rich ecosystems in the region. Various authors argue that analyses of flow regime anomalies at regulated rivers, as defined here, may be used to support management decisions at broad, regional scales while avoiding unnecessary expense and effort at individual sites (Acreman and Dunbar, 2004; Poff et al., 2010). Following the logic of the ELOHA framework and of other authors who have been influenced by this approach (e.g. McManamay et al., 2012a), we assume here that the degree of 'anomaly' that exists at a regulated site with respect to the natural range of flow regimes for the given river type in the region may be, for management purposes, very useful to predict possible faunal impacts, irrespective of site specific flow 'alteration' estimates based on the pre-impacted regime of that particular system.

A secondary benefit to a regional comparative approach defining regulated regime anomalies is that on many rivers in Canada that have been regulated for multiple decades (the object of this study), there are insufficiently long pre-dam flow records from which before-after indices can be compared with confidence. Moreover, it is costly and data intensive to develop reliable synthetic pre-regulation hydrographs incorporating historical data on both climate and land use changes at watershed scales, as a basis for quantifying site specific, regime alteration (as done by Black et al., 2005), especially when analysing a multitude of systems across climate zones as is the case here.

McManamay et al. (2012a) found regional flow classes (groups of unregulated rivers that share hydrologic (flow regime) properties) to be effective units of analysis in their study of flow regime anomalies associated to dam regulation across the Eastern U.S.A. Such regional flow classes 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, 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 as highly unusual deviations in regulated systems within their regional reference context. The granularity and complexity of flow regime and river types/classes will depend on the purpose of the classification. Poff et al. (2010) advocate using a small number of broad river class (types) as reference sets 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 natural 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) reference flow classes.

In general, flow alteration is not a single scalar quantity, but rather a vector; this fact poses deep challenges for both science and management. In a regulated river, flow anomalies can be apparent in one or many dimensions of the flow time series, as captured by a suite of ecologically relevant indices (e.g. Olden and Poff, 2003), compared to the reference class norm. Various flow alteration studies find that predictable components of the natural flow regime tend to be altered by dams. Most notably decreases in maximum flow magnitudes and increases in minimum flow magnitudes are frequent (Magilligan and Nislow, 2005), leading to a view that dams dominantly tend to "homogenize" flows with associated loss of river habitat variability (Poff et al. 2007). However, McManamay et al. (2012a) qualified this picture, and concluded that, measured by deviations from regional flow class normals, flow regulation across studied dammed systems in the south east USA have variable flow regime outcomes.

Our specific objectives of this analysis are:

(1) To identify and characterize the various types of statistically significant flow regime 'anomalies' observed across a set of 16 gauging sites on 13 hydro regulated rivers across Canada, where 'anomalies' are defined with respect to the range of variability observed in unregulated regimes in the region (the reference flow class for each site).
(2) To expand on the well-known 'regime homogenisation' effects of dams (Poff et al., 2007; McManamay et al., 2012a) by describing other independent axes of regime anomalies across this Canadian set and relate these to hydropower regulation type (storage, peaking or RoR).
(3) Finally we discuss some potential impacts on fish fauna of each of the main observed PC axes of flow regime anomaly at hydro-regulated rivers across study regions, by summarizing possible pathways of effects that may lead to negative impacts at population levels in systems exhibiting particular types of flow anomalies.

2. Data and study sites

This analysis was conducted as one component of NSERC's HydroNet, a collaborative scientific network formed in 2010 to apply science based management to hydro-damming regulation