Southern Quebec environmental flow assessments: spatial and temporal scales sensitivity

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ABSTRACT

Faced with increasing demands for water withdrawals and a changing climate, the Quebec Department of Environment and Fight Against Climate Change is reviewing its water withdrawal guidelines to protect riverine ecosystems. For Southern Quebec, guidelines currently limit water withdrawals to a maximum of 15% of the 7Q2 (mean 7-day low flow with a return period of two years) during low flow periods. In this context, one of the issues raised is to investigate measures that help to preserve riverine ecosystems during low flow periods by establishing cut-off flow restrictions. This study compared eight low flow metrics to investigate which can be considered useful metrics to assess environmental flow in Southern Quebec rivers. Using 98 hydrometrics stations with a minimum of 20 years of daily flow data from eight hydrological regions, those low flow metrics were compared to three thresholds based on Tennant Method for monthly and annual temporal scales. The relevance of current hydrological regions delineation was investigated by looking at results within these regions, compared to six groups of stations defined using multivariate analyses. This study emphasizes that assessing environmental flows is linked to the hydrological context of the area of interest, the temporal scale of the historical data available, and the catchment size. The results showed that (1) winter low flows were lower than summer low flows; (2) 23% to 26% of the values were under the conservative thresholds for all the metrics depending of the time scale; and (3) the 7Q2, 7Q10 (mean 7-day low flow with a return period of ten years), Q95 and Q90 (95th and 90th percentile on the flow duration curve) are the less conservative for rivers having a low regime flow. To conclude, assessing several regionally adapted environmental flow metrics is recommended rather than systematically using the 7Q2 for Southern Quebec.

KEYWORDS: Environmental flows, temporal scale, hydrological regions, riverine ecosystem sustainability, water sharing guidelines.

RÉSUMÉ

Face à la demande croissante de prélèvements d’eau et aux changements climatiques, le ministère de l’Environnement et de la Lutte contre les changements climatiques du Québec révise sa politique de partage des eaux pour protéger ses écosystèmes riverains. Au Québec méridional, les prélèvements d’eau sont actuellement limités à un maximum de 15% du 7Q2 (débit minimum d’une moyenne mobile de 7 jours et une période de retour de deux ans) durant les périodes d’étiage. Dans ce contexte, une étude hydrologique a été faite pour déterminer les débits planchers, en dessous desquels il n’est plus permis de prélever d’eau. Dans cette étude, les résultats de huit métriques ont été comparés à trois seuils issus de la méthode de Tennant, pour des temporalités mensuelles et annuelles, afin de pointer celles pouvant être considérées comme des débits environnementaux. Les débits journaliers, ayant au moins 20 ans de données, proviennent de 98 stations situées dans huit régions hydrographiques. La pertinence de celles-ci a été étudiée en considérant les résultats dans ces régions, mais aussi dans six groupes de stations définis à l’aide d’analyses multivariées. Il ressort que la détermination d’un débit environnemental est liée au contexte hydrologique de la zone d’étude, à la temporalité et à la taille du bassin versant. De plus, les résultats ont montré que (1) les débits hivernaux étaient inférieurs aux estivaux ; (2) 23 % à 26 % des métriques calculées étaient inférieures aux seuils de restriction, selon l’échelle temporelle ; et (3) le 7Q2, 7Q10 (débit minimum d’une moyenne mobile de 7 jours et une période de retour de dix ans), Q95 et Q90 (95^{e} et 90^{e} percentile des débits classés), sont déconseillés pour les rivières ayant de faibles débits. Enfin, il est recommandé de définir plusieurs débits environnementaux, au lieu d’un seul (7Q2), au Québec méridional.

MOTS-CLÉS : Débits environnementaux, échelle temporelle, régions hydrologiques, durabilité des écosystèmes riverains, politique de partage de l’eau.

1. Introduction

Environmental flows are defined as “the quantity, timing, and quality of freshwater flows and levels necessary to sustain riverine ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being” (Arthington et al. 2018). Over ten years after the Brisbane Declaration (2007), this definition asserts an economic dimension provided by the environmental flow assessments and an interdependency between human conditions and the riverine ecosystems sustainability. According to Poff et al. (1997), riverine ecosystems have adapted to their natural flow regime and their sustainability comes from the river dynamics defined by water quality, physical habitat, biotic interactions and energy sources. Floods and medium flows maintain the river structure, establish a link with floodplain habitats, ensure sediment sorting and flushing, stimulate upstream migration and spawning, while low flows may prevent invasive species spread, while protecting habitats (Acreman and Dunbar 2004). For 17 fish species of interest identified by Belzile et al. (1997), the summer period concerns mainly the feeding phase of the fish life cycle for the growth and survival of the larval and juvenile fish in the Southern Quebec rivers.

To characterise the hydrological regime of a river, Poff et al. (1997) developed *the natural flow paradigm*, which can be viewed as benchmark flow conditions for conserving the ecological integrity of rivers, using five main flow characteristics: magnitude, frequency, duration, timing and variability of a flow event. Over twenty years later, many jurisdictions of Canadian provinces and across the world define environmental flows using one or two metrics assessed at relatively broad regional scales, in spite of potentially important hydroclimatic variability within these regions (Linnansaari et al. 2012). However, over two hundred methodologies exist and have been classified in four categories: hydrological, hydraulic rating, habitat simulation and holistic methods (Tharme 2003; Acreman and Dunbar 2004; Arthington 2012). From hydrological to holistic methods, recent work describes environmental flow assessment as a regional to local issue, to be defined with local stakeholders (water managers, scientific experts, public and private users), and requiring sufficient financial support, knowledge and time (Poff et al. 2010; Acreman and Ferguson 2010; Pahl-Wostl et al. 2013).

In Southern Quebec, the Department of Environment and Fight Against Climate Change (DEFACC) commissioned a hydrological study to test the relevance of using only the 7Q2 flow metric (low flow with a return period of two years and seven-day duration), throughout the province to manage water withdrawals and riverine ecosystems protection during low flow periods. In the 1990s, this flow metric was used to regulate water withdrawal for golf courses and fish farming and a limitation of 70% of 7Q2 has been proposed to maintain a minimum flow in rivers (Beaudelin and Bérubé 1994). Subsequently, seasonally low flow restrictions to preserve fish habitats of identified ecohydrological regions were proposed by Belzile et al. (1997), which are used by the Department of Wildlife, Forests and Parks (MFFP 1999). Today, the 7Q2 flow metric appears three times in guidelines linked to low flow periods:

(1) To limit the cumulative effect of water withdrawals to 15% of the 7Q2 (DEFACC 2015);

(2) As a minimum flow to manage water sharing, hydraulic structure and water quality following a wastewater or a contaminant discharge (DEHAQ 2015);

(3) To minimize the risks associated with its predicted decrease during summer according to the RCP4.5 climate change scenario (GIEC 2014) for the 2050 horizon (DEFACC 2018).

Presently, no study exists to support the use of the 7Q2 as a low flow limit to sustain riverine ecosystems, on the contrary, this flow metric has been observed to result in extremely low flows in small streams in some regions of Atlantic Canada (e.g., Caissie et al. 2007).

Our first objective was to compare the 7Q2 environmental flow metric with other environmental flow methods used in other jurisdictions for different temporal scales (e.g. yearly and monthly). Through the comparisons, potential environmental flow metrics results were classified from the most to the less conservative and permissive one, using Tennant (1976) and Caissie and El-Jabi (1995) thresholds. In addition, the spatial relevance of the selected metrics was investigated. Our second objective was to compare the current hydrological regions with newly defined hydrological regions, using a multivariate analysis. Current hydrologic regions of Southern Quebec (DEHAQ 2020), a region of about 730 000 km² (DEFACC 2018) with several thousand streams and rivers, were defined using climate and geographical criteria. Finally, a third objective was to investigate the relationship between the more conservative and permissive environmental flows and catchment size.

2. Methodology

2.1 Hydrological data

Historical daily flow data come from 98 hydrometric stations spread in the eight hydrological regions of Southern Quebec: Baie des Chaleurs et Percé, Saint-Laurent sud-est, Saint-Laurent sud-ouest, Outaouais et Montréal, Saint-Laurent nord-ouest, Saguenay et lac Saint-Jean, Saint-Laurent nord-est and the Baies de Hannah et de Rupert (DEFACC 2018). Three criteria were used to select the hydrometric stations:

(1) Being located in one of the aforementioned hydrological regions;

(2) Having a natural flow regime (i.e., unimpeded by dams or reservoirs);

(3) Daily discharge time series must be $\geq$ 20 years, as required by Caissie et al. (2007).

The selected stations, with record lengths from 20 to 90 years, are located in tributaries of the Saguenay, Outaouais and St. Lawrence Rivers, in the Gaspésie region, on the north-east St-Lawrence coast and in the Baies de Hannah et de Rupert region.

Given that some of the metrics compared in the present study are used in Atlantic Canada, New England (USA) and the United Kingdom, it is important to note that their climates vary according to oceanic and continental influences. Mean annual precipitation are from 800 to more than 2000 mm, mean annual runoff from 400 to more than 2000 mm and mean annual of maximum flows from around 1600 to 12600 mm (HCAN 2013). Ouellet Dallaire et al. (2019) present maps that showed high similarities between the Southern Quebec area and regions of Atlantic Canada in terms of hydrological, geomorphic and physio-climatic characteristics.

2.2 Low flow metrics

The chosen flow metrics were: the mean 7-day low flow with a return period of two and ten years (7Q2 and 7Q10), the 90th and the 95th percentiles on the flow duration curve (Q90 and Q95), derivatives from the median monthly flow (Q50), and derivatives from 70% of the median monthly flow (70%Q50). The 7Q10 flow metric was used in the United-States mainly as a minimum flow calculation to maintain water quality (for dilution purpose); however, it has been used in some cases to calculate environmental flows (Linnansaari et al. 2012). The 7Q10 was criticised in the literature because of the low flow values it provided, particularly for rivers with relatively low baseflows (Belzile et al. 1997). The 7Q10 was deemed insufficient for fisheries protection as an environmental flow method by Caissie et al. (2007) and fish habitat protection (Tennant 1976). Nevertheless, the 7Q10 was included in the present study for comparison purposes with other flow metrics. The Q90 flow metric was tested in New Brunswick, as a potential environmental flow method (Caissie and El-Jabi 1995, Caissie et al. 2007) and results showed that it most likely provided insufficient flows for fish and fisheries protection, particularly during low flow periods (similar results to the 7Q10). The Q95 flow metric was developed in the United-Kingdom (Acreman and Ferguson 2010) and the median monthly flow metric (Q50) in New England, U.S. (USFWS 1981). Both of these flow metrics have been used to calculate environmental flows in these respective regions. The Q50 flow metric for the month of August (AQ50) was also used in New England mainly through regional studies for ungauged river (Linnansaari et al. 2012). Notably, the Q50 for August is also called the Aquatic Base Flow (Linnansaari et al. 2012). The AQ50 flow metric will also be calculated in the present study, as well as the median flow for the lowest flow month (i.e., lowest Q50 or LQ50), as the lowest flow month could be different than the month of August. In Caissie et al. (2014), the LQ50 was shown to be a relevant environmental flow metric in New Brunswick (generally occurring in August and September). The 70% of Q50 which is a variant of the Q50 method has been used in the province of Prince Edward Island for environmental flow calculations (Caissie et al. 2014). This flow metric was also be calculated in the present study, including the 70%Q50 for August (70%AQ50) as well as the 70%Q50 during the lowest flow month (70%LQ50). Therefore, the above flow metrics were selected to evaluate potential environmental flow methods in Southern Quebec with a specific attention to the results of the 7Q2 flow metric.

2.3 Environmental flows in Southern Quebec

To evaluate and compare the potential environmental flow metrics, several thresholds were calculated using the mean annual flow (MAF). Tennant (1976) established environmental flow thresholds based on biological and hydrological data from a ten-year study of Montana, Wyoming and Nebraska rivers (U.S.). In addition, 17 years of USGS flow data from stations in 21 other states were also used in their study. Tennant (1976) concluded that, in general, flows lower than the 10%MAF most likely cannot conserve the riverine ecosystems and suggested a value closer to 30%MAF to maintain good habitat conditions. Also, other studies have used environmental flows based on the MAF, while this metric has to be adapted to different climatic regions (Acreman and Dunbar 2004). For example, 25% of the MAF (25%MAF) was historically used as a target environmental flow in Nova Scotia (Linnansaari et al. 2012) and in New Brunswick (Caissie and El-Jabi 1995) to preserve the ecological integrity of rivers. In the present study, three thresholds (30%, 25% and 10% of MAF) were used as potential benchmarks for comparison. In addition, recommendation of Belzile et al. (1997) related to low flow restrictions to preserve fish habitats in Southern Quebec can be considered for discussion. These are the Aquatic Base Flow (AQ50) during summer periods, to maintain rearing and feeding habitat of all species and the eel migration in localised areas, the 25%MAF during winter periods for the protection of incubating eggs, and the 50% of the MAF in the Montérégie and the Outaouais regions, respectively along the St. Lawrence River on the south coast and along the Outaouais River (Belzile et al. 1997). To compare low flow metrics, this study focuses on winter (January to March) and summer (July to September) low flow periods.

2.4 Frequency analysis, statistical non-parametric tests and multivariate analysis

The 7Q2 and 7Q10 flow metrics are calculated using low flow frequency analysis. This is a predictive statistical method to calculate the probability of reaching or exceeding a flow value for a specific river (Meylan et al. 2008) as shown in the Equation (1) for low flows:

$$t(x) = \frac{1}{1-p} \quad (1)$$

t(x): return period of a flow related to a given event x (years);

p: probability of exceedance, such as p=1-F(x, Θ), where F is the cumulative probability distribution and where x and Θ are the probability distribution parameters.

In this study, several probabilistic distributions for low flow frequencies (WMO 2008, Smakhtin 2001) were tested, including Generalized Extreme Value (GEV), Weibull and Gumbel. A statistical distribution was fitted to annual and monthly minimum of the seven-day moving averages using the maximum likelihood method. Independence (Wilcoxon-Mann-Whitney test), stationarity (Mann-Kendall test) and homogeneity (Breusch-Pagan test) conditions were tested. The Kolmogorov-Smirnov and Chi-square tests were applied to confirm the hypothesis that the selected statistical distributions were adequate, given the fitted samples. Finally, Akaike and Bayesian information criteria were used to select the distribution that best fitted the empirical quantile values or observed flood values. As for New Brunswick environmental flows characterization (El-Jabi and Caissie 2018), the GEV distribution presented best fit while the overall second best fit was with the Weibull distribution. Therefore, following Kite (1978) advocating the type III extreme-value distribution function to assess low flows, GEV was thus selected, with cumulative probability density function defined in Equation (2):

$$F(x;\mu,\sigma,\varepsilon) = exp\left\{-\left[1+\varepsilon\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\varepsilon}\right\} \qquad (2)$$

With ε, μ and σ, which are respectively the shape, location and scale parameters of the distribution, σ and $1+\varepsilon\left(\frac{x-\mu}{\sigma}\right)>0$. When independency, stationary and/or homogeneity conditions were not accepted, standardized residuals, high-leverage points and normal Q-Q plots were made to identify outliers data and remove them.

Hydrometric stations were sorted by their low flow characteristics using a Principal Component Analysis (PCA), based on a methodology used by Daigle et al. (2011). PCA is a multivariate statistical approach computing linear combinations (principal components, or PC) of original variables to maximize the explained variance while maintaining orthogonality between PCs. As in Daigle et al. (2011), PCA was used to reduce 71 hydrological flow indices, drawn mainly from Hersh and Maidment (2006) and Olden and Poff (2003) studies, calculated and standardized for each station, while retaining at least one low flow indices per characteristic (amplitude, duration, frequency, timing, variability). Then, the selected hydrological indices were used in an agglomerative (ascendant) hierarchical clustering, often used for regional analyses (Poff and Ward 1989), to statistically group the hydrometric stations by similarities in several clusters, called PC-HC. A hierarchical clustering calculates a Euclidean distance as a measure of similarity between stations using the selected indices, and groups them using average-linkage (comparison of group average distances). After grouping station in PC-HC regions, two non-parametric ANOVA tests were used to compare groups. This analysis allowed to confirm that each PC-HC group was significantly different from the others. The Kruskal-Wallis test permits a grouping of populations with equal medians (H_0 not rejected for p-value > 0.05). Then, the Wilcoxon-Mann-Whitney test was used as a post-hoc test to confirm or infirm that group pairs were from the same population (H_0 accepted for p-value > 0.05).

3. Results

3.1 Overview of low flow results

Figure 1 represents the number of hydrometric stations (of the 98 pre-selected) having their eight associated flow metrics value below the two hypothetic conservative (30%MAF, 25%MAF) and non-conservative (10%MAF) thresholds. Results are presented for inter-annual and monthly temporal scales. March and August were selected as they typically represent the lowest flow month of the winter and summer periods. When compared to the 10%MAF threshold, the 7Q10, Q95 and 7Q2 flow metrics present the lowest flow values with respectively 43, 24 and 29 stations under this limit for inter-annual data (Figure 1a). When comparing flow metrics to the same threshold seasonally, August (Figure 1b) and March (Figure 1c) values of the 7Q10, Q95 and Q90 indicate that 20 to 27 stations are below. The AQ50 flow metric have the highest values for all the periods. Moreover, the differences of the number of stations show that the summer values are the highest, then the winter values and finally the inter-annual values. Results of the 7Q2 flow metric for August are close to the 70%AQ50, whereas higher than the 70%AQ50 for March and the inter-annual period. Considering the results for the 98 stations, it appears that (1) winter low flow metrics are lower than summer low flow metrics; (2) the AQ50 presents the highest values for the three temporal scales, and is considered as the most conservative metric, and (3) 23% (26%) of the AQ50 values results, are ≤25%MAF (and 30%MAF) conservation threshold.

3.2 New hydrological regions

PCA was used to select explanatory hydrological indices (HI) used to generate new regions among 71 listed by Daigle et al. (2011) to explain low flow characteristics of the hydrometric stations as defined by Poff et al. 1997: amplitude (A), duration (D), frequency (F), timing (T), variability (V). Factorial loadings allowed the removal of redundant (i.e. highly correlated) variables and to select six HI that explained 79% of the variance. Table 1 lists the HI retained to make the ascendant hierarchical clustering. The original abbreviation of the HI are also provided for cross-reference with Daigle et al. (2011). Figure 2 presents the hydrometric stations grouped by PC-HC and the eight hydrological regions limits. PCA and the hierarchical clustering permitted a grouping of the Saguenay and Gaspésie stations (PC-HC1; areas south and north shores of St-Lawrence River). PC-HC2 stations are located along the St-Lawrence River whereas the PC-HC3 and PC-HC5 stations are in the southwestern area. The PC-HC6 stations are in the north-western area with four stations located on the Quebec north shore. The PC-HC4 stations are mainly in the western part of the province (both southern and northern part of the province). Figure 3 shows new PC-HC groups of stations resulting from hierarchical clustering. The groups PC-HC1, PC-HC2 and PC-HC5 have a mean catchment size of approximately 1600km² but different number of stations (30; 15; 7) and mean of MAF (25.7; 21.2; 17.2 $L.s^{-1}.km^{-2}$). The groups PC-HC4 and PC-HC6 have different mean catchment size (18 087; 8 509 km²), number of stations (19; 16) and similar mean of MAF (19.1; 19.3 $L.s^{-1}.km^{-2}$). The PC-HC3, a region of eleven stations, has the smallest mean catchment size (628 km²) and the lowest mean of MAF (16.6 $L.s^{-1}.km^{-2}$). Non-parametric ANOVA tests were used to investigate inter-region differences in environmental flow metrics for the original regions (R0s) as well as for the PC-HC groups. Hydrological regions and PC-HC groups were significantly different, as were metric results.

3.3 Comparison of low flow metrics within historical and new hydrological regions

In Figures 4 and 5, the box plots present the range of mean values of the inter-annual flow metrics divided by the MAF for hydrological regions and PC-HC groups. Each time, the flow metrics were ordered from the less to the more conservative, with the latter implying the lower risk of impacts on the ecosystem. Results were compared to the three %MAF thresholds (dotted lines). The classification of flow metrics is the same for R01 and PC-HC, R02 and PC-HC2, and R04 and PC-HC5, taken in pairs, and for R05, R06, PC-HC4 and PC-HC6. The R03, R07, R08 and PC-HC3 regions have metric orders that are different than all other regions. Using Tennant's (1976) threshold (≥ 30%MAF), in ascending order, the 70%AQ50, LQ50 and AQ50 flow metrics can be considered as adequate within hydrological regions (Figure 4), and the 70%AQ50 and Q90 flow metrics meet this criterion for PC-HC (Figure 5). They are the 7Q2, Q90, 70%AQ50, AQ50 and LQ50 flow metrics for hydrological regions and the 7Q2, LQ50, 70%AQ50 and 70%LQ50 flow metrics for PC-HC, according to Caissie and El-Jabi (1995) threshold (≥ 25%MAF). Metric orders seem to be independent from the mean catchment sizes and the number of hydrometric stations. More precisely, the AQ50 flow metric is the most conservative environmental flow approach with 80% to 100% of flows higher than the 30%MAF threshold for six R0s and four PC-HC. The 7Q10 flow metric is the less conservative approach with 50% to 100% of values above 10%MAF for three R0s and three PC-HC. Considering the 7Q2 flow metric, more than half of the results were between 10%MAF and 25%MAF thresholds for six R0s and four PC-HC. In the PC-HC2 and PC-HC3 groups, none of the metrics can be considered as protective as the environmental flow guidelines suggested by Tennant (1976) and Caissie and El-Jabi (1995).

The inter-quartile range (IQR differences between 75th and 25th percentiles) of the boxes in Figures 4 and 5 portrays the variability as a percentage of MAF of each flow metrics by regions of PC-HC groups. By R0 and by flow metric, the minimum of the differences varied from 1.8% (R06; 7Q2) to 6.8% (R05; 7Q10) and the maximum from 4.2% (R01; AQ50) to 28.7% (R08; AQ50). For PC-HC groups, IQR represented a minimum of 0.6% (PC-HC2; 7Q2) to 5.2% (PC-HC4; 70%LQ50) and a maximum from 7.5% (PC-HC2; LQ50) to 35.1% (PC-HC6; AQ50). Looking at the mean of those percentages by flow metrics through R0 and PC-HC groups, the mean differences is lower for the 7Q10, 7Q2, 70%LQ50, Q95, Q90 and LQ50 flow metrics of the PC-HC comparing to the R0, whereas for the 70%AQ50 and the AQ50 flow metrics, IQR are smaller in R0 compared to PC-HC. This indicates that PC-HC groups are generally more homogeneous than the historic hydrological regions in the context of environmental flow metrics selection.

3.4 Monthly low flow metrics within PC-HC

Figure 6 presents radial plots of the eight metrics applied to monthly flows, standardized by dividing their value by the MAF, for each PC-HC group. The y-axis has been limited to 100% of the MAF and presented on a logarithmic scale thus truncating higher monthly results. The plots show the four periods for each PC-HC, which are from the higher to the lower flow values, from March to July, September to January, July to September and from January to March. The lowest monthly flow values have been found for August and September during summer, for all PC-HC. During winter, the lowest flow month for PC-HC1, PC-HC4 and PC-HC6 is March, and February for the rest of the PC-HC.

For August and September, the classification of the flow metrics, in ascending order from the less to the more conservative, is: 7Q10, Q95, Q90, 7Q2, 70%LQ50 / 70%AQ50 and the LQ50 / AQ50 for all PC-HC except the PC-HC4 having the 7Q2 flow metric on the second to last. The metrics order for the summer is quite similar to the inter-annual PC-HC2 and PC-HC3 metric orders (Figure 5), excepting that the 7Q2 is more conservative than the Q95 and Q90 flow metrics for summer results. For monthly results, it appeared that the 7Q10 and Q95, the 70%LQ50 and 70%AQ50 and the LQ50 and AQ50 values were pairs of very similar values for all PC-HC, as for the 7Q2 and 70%LQ50 values for PC-HC5 and PC-HC6. Differences were found when comparing monthly metrics to the 10%MAF, 25%MAF and 30%MAF thresholds. PC-HC2 and PC-HC3 summer results were similar to inter-annual results (Figure 5). All the flow metrics are under the 25%MAF limit, with the 7Q10, Q95, Q90 under the 10%MAF, with the addition of the 7Q2 for PC-HC3. For PC-HC1 and PC-HC5, the 7Q2, 70%LQ50 / 70%AQ50 and LQ50 / AQ50 flow metrics are above the 30%MAF threshold. At last, PC-HC4 and PC-HC6 presented all flow metrics above the 30%MAF.

In February and March, the classification of the flow metrics is different for each group. However, the winter metric orders of PC-HC1, PC-HC4, PC-HC5 and PC-HC6 are quite similar to their inter-annual classifications respectively (Figure 5), with, as for summer results, the 7Q2 that is more conservative than the Q95 and Q90. The 7Q10, Q95 and Q90 are the less conservative, with the 7Q10 and the Q95 having similar values for all PC-HC. As for summer values, the winter Q90 and 70%LQ50 are substantially similar for PC-HC1, PC-HC4, PC-HC5 and PC-HC6, as the 7Q2, 70%LQ50 and 70%AQ50 for PC-HC2, and the 7Q2, 70%LQ50 and AQ50 for PC-HC3. The AQ50 is the more conservative flow metric except for PC-HC2 and PC-HC5 where LQ50 is similar and for PC-HC3 where LQ50 is more conservative. When compared to the 30%MAF threshold, the 70%AQ50 and AQ50 flow metrics are above it for PC-HC1 and PC-HC6, as the 7Q2, LQ50, 70%AQ50 and AQ50 for PC-HC4 and PC-HC5, with the 70%LQ50 in addition to the latter.

For monthly results, it appears that:

(1) Winter low flow values are lower than summer flows;

(2) Summer values influenced inter-annual values for the PC-HC2 and PC-HC3 and winter values influenced inter-annual values for the rest of PC-HC;

(3) None of the flow metric methods are conservative enough to protect the aquatic ecosystems, in PC-HC2 and PC-HC3, when using Tennant (1976) and Caissie and El-Jabi (1995) recommendations during both of low flow periods. These two groups represent 25% of the hydrometric stations considered in this study, generally located along the St-Lawrence River on the south shore.

3.5 Environmental flow values and catchment size

Figure 7 presents the more conservative and restrictive inter-annual flow metrics (in m^3/s) above the 30%MAF threshold, as a function of catchment sizes for each PC-HC and for all Southern Quebec (Inter-annual, August and March data as in Figure 1). As expected, Figure 7 shows that low flow metrics of rivers and catchment size are correlated (Daigle et al. 2011). The equation and the R^2 values of the power functions of each environmental flow plotted were shown. The R^2 value is 0.89 for Southern Quebec results, and from 0.92 to 0.99 for the PC-HC, with the coefficients of the power functions close to 1. In Figure 7, for Southern Quebec, PC-HC3 and PC-HC4 graphs, a high outlier value of catchment size is presented albeit excluded from the model. The largest drainage area (146 000km²), is that of the Mille-Iles River. Also, when none of the calculated flow metric was conservative enough, the 30%MAF was proposed as an environmental flow. Compared to the 30%MAF threshold, the 70%AQ50 flow metric was the more conservative and restrictive for the Southern Quebec inter-annual values. The AQ50 is the most conservative flow metric for the Southern Quebec, August and March monthly results. For PC-HC, the results are the same as in Figure 5, regarding the selection of the more conservative and restrictive flow metric, using the power functions. Thus, using PC-HC groups lead to the selection of different sufficiently conservative flow metrics for these hydrological regions, but the correlation with catchment size remains strong ($R^2 > 0.9$) in each case.

Table 2 is a review of the results for 21 different contexts: for inter-annual, summer and winter periods, by PC-HC and for the whole of Southern Quebec. Table 2 gives also the number of hydrometric stations and their location, the mean catchment size, the summer and winter low flow months, and characteristics of rivers for each PC-HC. The 10%MAF, 30%MAF (Tennant 1976) and the 25%MAF (Caissie and El-Jabi 1995) are used as potential thresholds to discuss the risk of using some flow metrics for riverine ecosystems in contrast with human's benefits. For the whole Southern Quebec, the LQ50 (> 25%MAF) and the 70%AQ50 (> 30%MAF) flows metrics are the less risky and pose greater restrictions on water withdrawal. It is respectively the same for PC-HC5 and PC-HC6 groups with the 70%LQ50 and the LQ50 flow metrics and the Q90 and the 70%AQ50 flow metrics. Because all of their values were superior to the 30%MAF, the 70%AQ50 and the Q90 flow metrics are the less risky and more restrictive metrics for PC-HC1 and PC-HC4 respectively. In groups PC-HC2 and PC-HC3, flow metrics considered were $\leq$25%MAF, hence the latter (or 30%MAF) was proposed as possible environmental flow metrics. These two groups include approximately 25% of the hydrometric stations.

Obviously, the selected, less risky flow metric to protect the aquatic ecosystems of the rivers changes depending of the hydrological context, for the whole of Southern Quebec or for each PC-HC groups. The selected metric changes also depending on the temporal scale (annual or monthly). Chosen flow metrics for inter-annual results are mainly based on descriptive statistics (70%AQ50, LQ50, 70%LQ50, 30%MAF, 25%MAF, Q90). For the summer periods, presenting the highest flow values, and for winter periods, frequency analyses flow metrics (7Q10, 7Q2) can be chosen for PC-HC1, PC-HC4, PC-HC5 and PC-HC6 and for PC-HC4 and PC-HC5 groups. Frequency analyses flow metrics are interested to consider extreme flow events related to the climate change.

4. Discussion and conclusion

A total of 98 natural flow regime gauged rivers with discharge time series ≥20 years were pre-selected for this study. Indeed, gauged rivers with shorter time series and ungauged rivers for which regional statistical analyses would be required were not taken into account. Those limits are discussed in Caissie and El-Jabi (1995), Richter (2010), as well as their adaptation to altered flow regimes (Richter et al. 1996; Poff and Zimmerman 2010).

The main questions that triggered this hydrological study were: should environmental flow guidelines vary temporally and spatially to improve the management of water withdrawals in Southern Quebec rivers? More precisely: are the historical hydrological regions adequately defined for the low flow characteristics of Southern Quebec rivers? Which thresholds can be fixed to protect fish habitat and preserve the river`s ecological integrity during low flow periods? Is the single use of the 7Q2 flow metric relevant across all Southern Quebec rivers? Finally, is there a link between environmental flow and catchment size?

First, a principal component analysis and an ascendant hierarchical clustering were used to group hydrometric stations in six PC-HC clusters. Using this method, rivers in the same group need not to be geographically close (e.g. PC-HC1), but can be (i.e. along the St-Lawrence River in PC-HC2). The new PC-HC groups show less inter-station variance for the lowest flow metrics (7Q10, 7Q2, Q95, Q90), when compared to inter-station variance in historical hydrological regions. Hence, the PC-HC groups can be a useful alternative to define environmental flow guidelines by regions that have more similar low flow metrics than the historical regions.

To discuss the relevance of the 7Q2 flow metric, results were compared to those of the 7Q10, Q90, Q95, 70%LQ50, LQ50, 70%LQ50 and AQ50 at different temporal scales (monthly and annually).. In summary:

- PC-HC grouped hydrometric stations according to homogenous low flow values, in contrast with contiguous geographical regions. In addition, the relationship between key low flow metric and catchment size is often slightly to significantly better in PC-HC regions than for the whole of Southern Quebec;
- The 7Q10, Q95, Q90 and 7Q2 flow metrics are potentially more risky for the riverine ecosystems compared to the 70%LQ50, LQ50, 70%AQ50, AQ50, 70%Q50 flow metrics, depending of the time scale;
- 7Q10 and Q90 flow metrics could be proposed as environmental flow metrics for rivers having the highest flow regime;

- Accounting for different temporal scale is essential to assess environmental flows for specific study areas and seasonal metrics may be more adequate than those based on inter-annual means;
- Around 25% of the hydrometric stations located along the south shore of the St Lawrence River have very low winter and summer flows with all of the metrics resulted in flows lower than 25%MAF and 30%MAF. Those rivers are near to the Montérégie region, where Belzile et al. (1997) proposed the use of 50% of the MAF;
- The percentage of the mean annual flow, as 30%MAF (Tennant 1976) or the 25MAF (Caissie and El-Jabi 1995), can be a relevant flow metrics;
- Inter-annual flow metrics can be greatly influenced by summer (PC-HC2 and PC-HC3) and winter low flow variability (PC-HC1, PC-HC4, PC-HC5 and PC-HC6);

The AQ50 flow metric is potentially the less risky as an environmental flow during summer, as stated by Belzile et al.(1997), to protect fish habitats. The main recommendation is the need of using several adapted flow metrics to assess environmental flows and protect riverine ecosystems in opposition of using only one flow metric such as the 7Q2 to manage water withdrawals for the entire region.

Table 1. Hydrological indices retained to be used in the ascendant hierarchical clustering

HI	Definition
A7	Mean of the minimums of all May flow values over the entire record ($L.s^{-1}.km^{-2}$)
A27	5-year annual minimum daily discharge ($L.s^{-1}.km^{-2}$)
D16	3-day minimum divided by the median of the entire record (unitless)
F2	Average number of flow events with flows below a threshold equal to 5% of the mean flow value for the entire flow record (unitless)
T3	Average Julian date of the seven annual 1-day minimum discharges (Julian date)
V8	Coefficient of variation of annual 7-day minimum flow (unitless)

Table 2. Review of the results and the more conservative and restrictive flow metrics. For inter-annual, summer and winter periods, by PC-HC, for 25%MAF and 35%MAF thresholds, and depending of the MAF or catchment size.*Quoting hydrological sub-classification from Ouellet Dallaire, Lehner and Creed (2019)

		Southern Quebec	PC-HC1	PC-HC2	PC-HC3	PC-HC4	PC-HC5	PC-HC6
Hydrometric stations		98	30	15	11	19	7	16
Location of stations in the southern Quebec		-	Along the Saguenay river, Gaspésie area	Along the St-Lawrence river	Along the St-Lawrence river and in the south-western	Western	South-western	North-western and Quebec north shore
Mean of catchment size		-	1 687 km²	1 545 km²	628 km²	18 087 km²	1 602 km²	8 509 km²
Lower summer monthly flow		August	September	August	August	September	September	September
Lower winter monthly flow		March	March	February	February	March	March	March
Rivers sizes, regime flow, variability between summer and winter periods, spring melt*		-	Medium rivers and regime flows, high variability, late melt	Medium rivers and regime flows, low variability, early melt	Small rivers, low regime flows and variability, early melt	Large rivers, high regime flows and variability, late melt	Medium rivers and regime flows, low variability, early to late melt	Large rivers, low to high regime flows, high variability, late melt
Inter-annual	**> 30%MAF**	AQ50	70%AQ50	30%MAF	30%MAF	Q90	LQ50	70%AQ50
	> 25%MAF	70%AQ50	70%AQ50	25%MAF	25%MAF	Q90	70%LQ50	Q90
	≤ 10%MAF	-	-	7Q10, 7Q2, Q95	7Q10, 7Q2, Q95, Q90, 70%AQ50, 70%LQ50	-	-	-

Summer period	**> 30%MAF**	AQ50	70%AQ50 / 7Q2 / 70%LQ50	30%MAF	30%MAF	7Q10 / Q95	70%AQ50 / 7Q2 / 70%LQ50	Q95 / 7Q10
	> 25%MAF	LQ50 / AQ50	Q95	25%MAF	25%MAF	7Q10 / Q95	25%MAF	Q95 / 7Q10
	≤ 10%MAF	-	-	7Q10, Q95, Q90	7Q10, Q95, Q90, 7Q2	-	-	-
Winter period	**> 30%MAF**	AQ50	70%AQ50	30%MAF	30%MAF	7Q2	70%LQ50 / 70%AQ50	70%AQ50
	> 25%MAF	LQ50 / AQ50	70%AQ50	25%MAF	25%MAF	7Q10	Q95 / 7Q10	25%MAF
	≤ 10%MAF	-	-	-	7Q10, Q95, Q90	-	-	-

Figure 1. Number of stations with metrics under the 30%MAF, 20%MAF and 10%MAF thresholds for inter-annual (a), March (b) and August (c) flow metrics

Figure 2. Hydrometric stations by PC-HC groups compared to original hydrological regions showed by numbers (Quebec map from DEHAQ 2020)

Figure 3. Ascendant hierarchical clustering of hydrometric stations by PC-HC groups: Number of hydrometric stations; Mean catchment sizes; Mean of the MAF in specific flows.

Figure 4. Inter-annual metrics results divided by MAF for hydrological regions, (#: number of stations, MCS: Mean Catchment Size, horizontal lines: 10%MAF, 25%MAF and 30%MAF)

Figure 5. Inter-annual metrics results divided by MAF for PC-HC groups, (#: number of stations, MCS: Mean Catchment Size, horizontal lines: 10%MAF, 25%MAF and 30%MAF)

Figure 6. Mean of monthly metric results divided by MAF for PC-HC groups. Solid black lines and dotted grey lines with round markers, from inside to outside, are respectively the 10%MAF, 25%MAF, 30%MAF, 70%AQ50 and the AQ50 flow metrics.

Figure 7. Most conservative and restrictive inter-annual flow metrics above the 30%MAF threshold, depending on catchment sizes for each PC-HC and Southern Quebec (SQ)

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