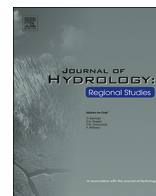


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Assessing the potential impacts of dam operation on daily flow at ungauged river reaches

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ABSTRACT

Study Region: The study region is the Southern Quebec river network. Dataset on dams as well as daily flow recorded at stations were used.

Study Focus: Dam construction and operation can have significant impacts on hydrological regimes. If dam construction induces some basic alterations to basin hydrology, dam operation can introduce dynamic alterations in streamflow. Assessing the impacts of dam operation can be crucial for many applications where recorded flow series are used as a proxy for flow at nearby ungauged basins in regional flood frequency analysis or for hydrological modelling. The potential influence of dam operation on recorded flows was assessed through statistical testing that verified the unimodality of the daily flow distribution. The Degree of Regulation (DOR) index was then used to relate the potential influences of dam operation to basic physiographic and dam characteristics.

New Hydrological Insights for the Region: Application of a unimodality test to daily flow series recorded at stations located in the study region confirms that dam operation can result in non-unimodal daily flow distribution. Estimation of DOR values for all reaches of the study region shows that regulated river reaches could be potentially influenced by dam operation when $DOR > 8$. Of the 29% regulated river reaches (i.e. with one or more upstream dams), approximately 30% could be potentially influenced ($DOR > 8$) by dam operation.

1. Introduction

The construction of dams have altered the natural flow regimes of many watersheds across the world (Graf, 1999; Nilsson et al., 2005; Grill et al., 2015) and this will become even more important as dam construction is expected to continue increasing in the future (Zarfl et al., 2015). Dams have major impacts on hydrology as they can alter low flow regime and reduce peak flows, change the interannual flow variability (FitzHugh and Vogel, 2011; Magilligan and Nislow, 2005), and alter geomorphology and aquatic ecosystems (for a description of these impacts see Poff and Hart, 2002; Poff and Schmidt, 2016).

In order to evaluate the impact of dam construction on hydrological regimes, many studies have compared hydrographic characteristics estimated from pre- and post-dam construction on flows at downstream gaging stations (e.g. Magilligan and Nislow, 2005; Graf, 2006; Poff et al., 2006; Gao et al., 2009). Hydrological indices, inspired from those initially proposed by Richter et al. (1996) and The Nature Conservancy (2006), also called Indicators of Hydrologic Alteration (IHA), are often used to assess the hydrological changes resulting from dam construction. These studies showed that globally dams tend to decrease flow peak frequency, magnitude

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and duration, while generally increasing the frequency, magnitude and duration of low flows (Magilligan and Nislow, 2005; Magilligan et al., 2003). Other impacts such as those related to downstream channel changes as a result of dams have also been analyzed (Schmidt and Wilcock, 2008).

Assessments of dam construction on streamflow by means of comparing pre- and post- dam hydrographic characteristics (e.g. annual peak flow or annual minimum flows) imply that some range of values are defined for natural flow regimes and that certain metrics are used to assess if post-dam values significantly differ from natural values (or pre-dam conditions). This type of comparison can be very challenging since many watershed characteristics (e.g. areas, altitudes, and latitudes) may influence hydrographic characteristics (e.g. low flow values, annual peak flow; Carlisle et al., 2010) and therefore the influence of dam construction cannot be unambiguously assessed in certain cases.

Assessing the specific impacts of dam operation are necessary if recorded flow series are used as a proxy for flow at nearby ungauged basins in regional flood frequency analysis or for hydrological modelling. In this sense, evaluating the specific impacts of dam operation can be important as non-operated dams can be assimilated to storage capacities. As pointed out by Villarini and Smith (2010), ‘structural’ alterations to basin hydrology, such as those induced by dams, are the norm for flood records, and analyses of flow distributions should reflect such anthropogenic changes. Dam operation however, can induced dynamic alterations to streamflow that may overlap with the more basic changes introduced by dam construction. Comparing pre- and post-dam construction flows does not allow for the separation of the impacts of dam construction from its operation.

Many studies have analyzed the influence of dam construction on flow regimes (e.g. Magilligan and Nislow, 2005; Assani et al., 2006; Lajoie et al., 2007; Gross and Moglen, 2007; Matteau et al., 2009; Peñas et al., 2016; Mei et al., 2017), but very few studies have looked at the specific impacts of dam operation on flows, i.e. how operations change flows in comparison to the situation where dams are not operated. White et al. (2005), using wavelet analysis, evaluated the impact of Glen Canyon dam (Colorado River) by comparing pre- and post-dam construction hourly flows at a downstream station. They showed that clear operating cycles related to hydroelectricity production could be detected from hourly flow series. Zimmerman et al. (2010) compared hourly flow series downstream of dams (flood control, run-of-river hydropower, and peaking hydropower) operated by the US Army Corps of Engineers on the Connecticut River basin to assess the potential impacts of dam operations on sub-daily flow regimes. These studies demonstrated that there was a distinctive signature for dam operation on sub-daily flow. Other more recent studies have also addressed this issue of dam operation on streamflows (e.g., Meile et al., 2011; Carolli et al., 2015; Chen et al., 2015; Bevelhimer et al., 2015). Collectively, these studies considered sub-daily flow series and only hydroelectric dams. The question however, remains if dam operation, other than hydroelectric dams, can also have an impact on daily flows and if other types of dams (e.g. flood control dams) may also have a ‘detectable’ impact on daily flow or a more general feature of the daily hydrogram.

The detection of characteristic signatures of dam operation on daily streamflow is difficult for many reasons. Firstly, operation records or operation rules are unknown and, in many cases, operation status (i.e. is the dam operated or not?) is even unknown. Secondly, even when operation records are available, operations have an impact on the short term flow and it remains difficult to assess their overall impact on hydrographs. Furthermore, operation frequency can vary considerably from one dam to another depending on the specific use of the dam (e.g. hydroelectricity production, flood control), thus making it even more difficult to detect the possible impacts on downstream flow. Incidentally, studies have reported the impacts of dam operation on sub-daily flow records arguing that flow variability changes induced by dam operation mainly affects sub-daily flow and that a daily time scale is too coarse to characterize the possible influence of dam operations (White et al., 2005; Zimmerman et al., 2010). Additionally, it remains difficult to specifically assess the impacts of operations on downstream recorded flow, given that stations are located at varying distances from operated dams. Finally, upstream watersheds may include many dams being operated to varying degrees with varying operation schedules, therefore increasing the difficulty of identifying distinct signatures of dam operation on recorded flows.

The main goal of this study was to define an index that can be readily estimated at any ungauged river reach from the available watershed and dam characteristics, thus providing information about the potential impacts of dam operations on streamflow. This was achieved through three main sub-objectives. First, we investigated the impact of dam operation on recorded daily flow. Herein, we propose a novel hydrological indicator of dam influence based on the unimodal or multi-modal character of the daily flow distribution. This indicator was validated through a comprehensive analysis of all streamflow records available for southern Quebec. Second, we propose an index based on readily available dam and hydrographic characteristics to assess the potential influence of dam operation on ungauged river reaches. Finally, we have applied the proposed index to a river network in southern Quebec and generated a map assessing the potential influence of dam operation on each reach.

The present study is organized as follows. Section 2 describes the dam and station datasets used in this study. Section 3 describes how the various dam configurations upstream of each station were structured in order to analyze the potential influence of dam operations on recorded flow. Section 4 describes the unimodality test and presents the results for the unregulated and regulated watersheds upstream of daily flow gauging stations. Section 5 presents the index, based on readily available dam and watershed characteristics, used to assess the potential influence of dam operation at ungauged river reaches. Section 6 presents some results of the global application of this index to the hydrographic network of Southern Quebec. Finally, conclusions and perspectives for future work are presented in Section 7.

2. Datasets

2.1. Dam dataset

Dataset from the *Répertoire des barrages du Québec* (Quebec Dam Register available at <http://www.cehq.gouv.qc.ca/barrages/>) was

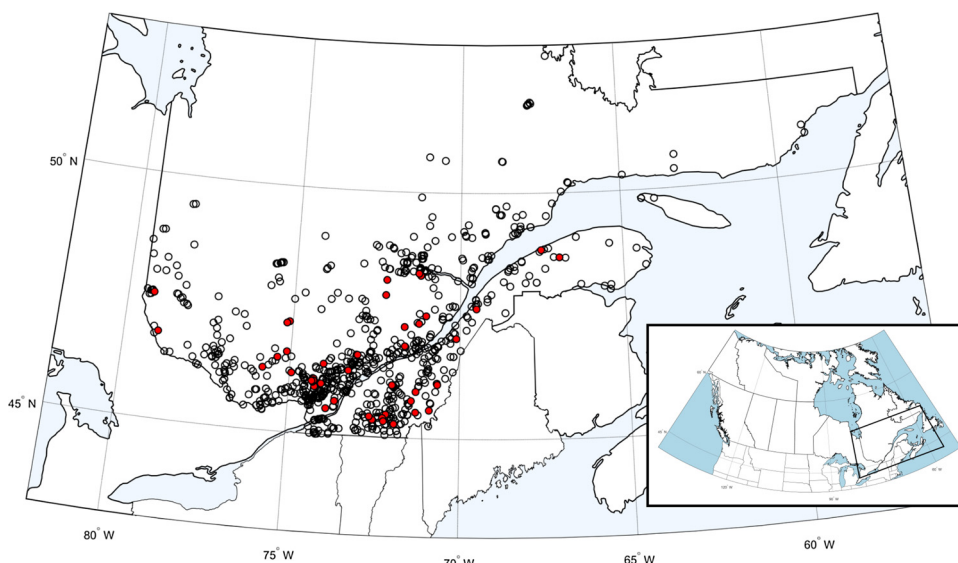


Fig. 1. Map presenting locations of dams considered in the present study (857 ‘operable’ dams with upstream watersheds larger than 15 km²). Dams operated by the MDDELCC are indicated with red dots.

used for the present study. The dataset contains information on 6,529 dams located in the Province of Quebec (Canada). The majority of the dataset focuses on dams in the southern part of the province. Available data are: a) name and identifier; b) latitude and longitude; c) altitude; d) area of upstream watershed; e) maximum reservoir capacity; f) function (e.g., hydropower production, water supply, flood control); g) construction year; h) outlet structures; i) owner (provincial or federal government, hydropower companies, municipalities, private companies, private owners, associations, etc.; a detailed description of the dam register is provided in CEHQ, 2014). The dataset does not provide information regarding dam operation or operating status (operated or not operated). The only exceptions are the dams operated by the *Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques* (MDDELCC) whose dates of operation and gate apertures are specified.

Only dams with upstream watersheds larger than 15 km² were considered in the present study reducing the number of dams to 1 889. Dams were further classified as ‘operable’ or ‘non operable’ based on outlet structures (e.g., sluice gate, spillway) leading to 857 ‘operable’ dams. The ‘operable’ subgroup therefore includes all dams that could be operated (even if their operating status is unknown) with an upstream watershed of 15 km² or more. Fig. 1 presents a map with locations of these dams and Fig. 2 presents box plots of the reservoir capacities of these dams in relation to dam function. Note that dams may have more than one function. Thus,

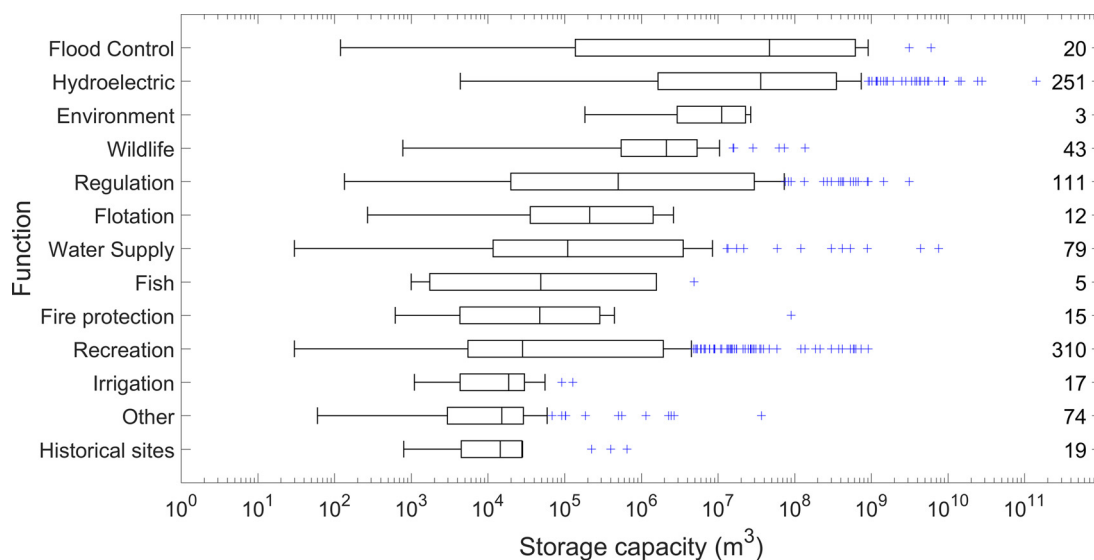


Fig. 2. Box-plots of reservoir capacities according to dam function (numbers at right correspond to the number of dams within each group). Only ‘operable’ dams with upstream watersheds larger than 15² km were considered (for a description of the various dam functions see CEHQ, 2014). Note that the functions of 5 operable dams with upstream watersheds larger than 15 km² remain unknown (not represented in the boxplots).

according to the dam register, for the selected dams, 761 (89%) dams were assigned a single function, 74 (9%) two functions, 10 (~1%) three functions, and 7 (~1%) four functions (note that the function is unknown for 5 operable dams with upstream watersheds larger than 15 km²). Therefore, a given dam may appear up to four times in Fig. 2. As presented in Fig. 2, hydroelectric and flood control dams have the largest storage capacities, while the largest number of dams are for recreation purposes (e.g., lake outlets). However, these dams have on average much smaller storage capacities. Hereafter, dams will refer to operable dams with upstream watersheds larger than 15 km².

These dams are owned, and possibly operated, by different organizations and groups (provincial government, hydropower companies, municipalities, private companies, private owners, associations, etc.).

2.2. Recorded flows

A total of 443 hydrometric stations located in the Province of Québec (Canada) and operated by the MDDLECC were initially considered for the present study. Instantaneous daily flows are archived at each station (the daily recording time may change from station to station, but is generally midnight; personal communication from William Larouche, *Chef Division de l'hydrométrie*, MDDELCC). Stations complying with the following selection criteria were targeted for further analysis: 1) stations must have a minimum of 5 valid years (a valid year is defined as a year with less than 10% missing daily values); 2) stations must not contain a sequence of more than five consecutive missing years; 3) stations must be localized south of 50°N; 4) upstream watersheds must be larger than 100 km²; 5) upstream watersheds must be completely located in the Province of Québec (this last condition is necessary as the dam repertoire only includes Québec's dams). A total of 259 stations complied with these criteria.

A comprehensive analysis of available daily flow records at the 259 stations was carried out to check for possible trends, break-points and abnormal values or sequences (e.g., series of zero values in watersheds where such a sequence is highly unlikely; stepwise series over certain periods of time that may indicate changes in resolution). Based on the comprehensive analysis, a further thirty-three (33) stations were discarded. Abnormal values were also discarded (e.g., values from early recording periods with much lower resolution than the values recorded for following periods) in many station records. Fig. 3 presents the map of the 226 stations considered in the present study.

3. Methods

3.1. Station/dam configurations

Recorded flows at stations were analyzed according to the dam configurations in the upstream watersheds which, in many cases, have changed over time with the construction of new dams (Fig. 4). In the following, recording periods at each station were partitioned into sub-periods according to the construction year of the different dams. Only sub-periods with 5 valid years or more were further considered after discarding the 2-year period preceding the construction of the dam and the year following the construction of the dam. A hypothetical scenario is presented in Fig. 4. In Fig. 4, considering that all years are valid, three stations/periods were defined, a first period with no upstream dam, a second with one upstream dam, and a third with four upstream dams. Two periods (between the construction of dam D₂ and D₃ and dams D₃ and D₄) were not considered given that these span less than 5 valid years.

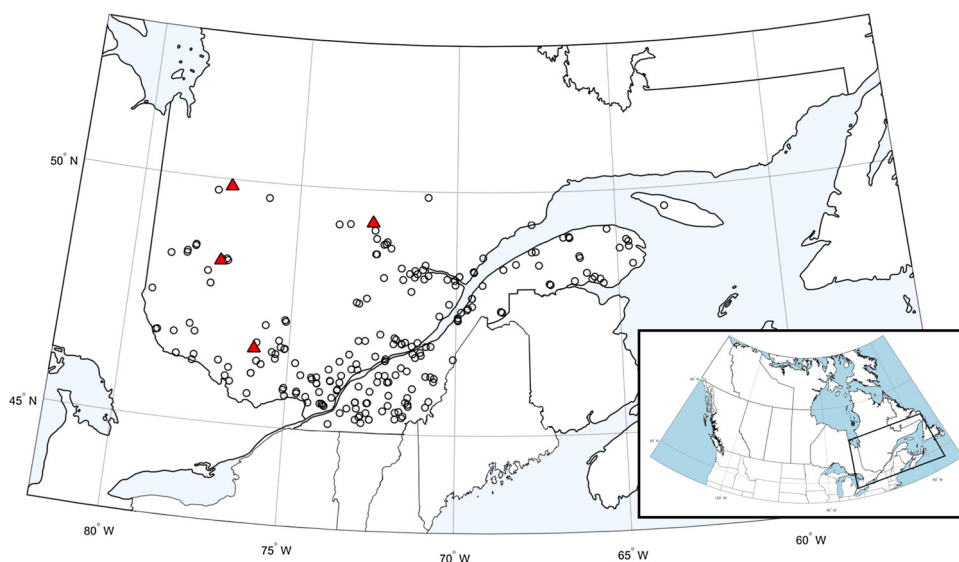


Fig. 3. Map presenting locations of the 226 stations considered in the present study. The four triangles correspond to unregulated stations with non-unimodal daily flow distributions (see Section 4 for details).

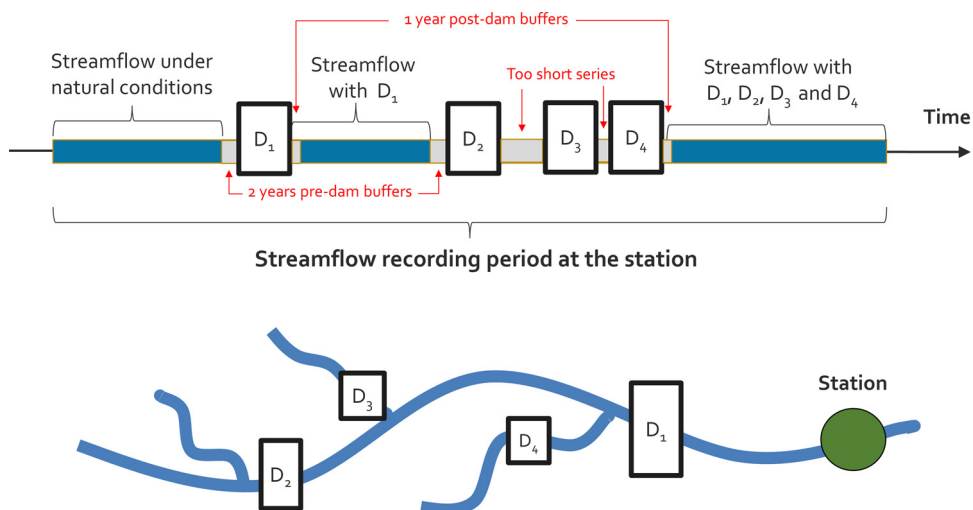


Fig. 4. Fictitious example of the evolution of dam configurations upstream of a given hydrometric station. The upper diagram illustrates the time evolution of the construction of the various dams (D_1 to D_4 correspond to the dams) and the corresponding division into stations/periods of the flow series recorded at the station. The lower diagram presents the locations of these dams in the watershed.

These periods associated with specific stations and specific upstream dam configurations are, hereafter referred to as stations/periods.

A total of 174 stations/periods were, therefore defined with 70 stations/periods (40%) having no dams in their upstream watersheds. Fig. 5 presents the histogram of the number of stations/periods with one or more dams in their upstream watersheds (104 station/period). As can be seen, 48 stations/periods (46%) have one dam in their upstream watersheds, while the remaining 56 have more than one dam upstream. Some stations/periods have a large number of dams in their upstream watersheds (up to 24 dams). To our knowledge, no dams have been removed and therefore the number of dams in the upstream watersheds has either increased or remained unchanged over time. Fig. 6 presents the histogram of the number of available valid years of records for both stations/periods with and without dams.

3.2. Detection of the influence of dam operation on daily flow distribution

A metric based on the unimodality of the daily flow distribution was analyzed to assess the potential impacts of dam operation on daily flow. The application of such a metric was motivated by the existence of dam operating rules aimed at maintaining discharges within a fixed range of flow during specific periods of the year. Such rules may result in ‘sustained’ flows over these periods and consequently, in more than one mode in the daily flow distribution downstream of the dam. In comparison, natural flows or flows downstream of non-operated dams usually leads to a unimodal distribution. Fig. 7 presents an example in which two modes can be clearly seen. These modes were associated with the two targeted flows by the dam operator, the first at $\sim 1.4 \text{ m}^3/\text{s}$ generally set during summer, and the second at $\sim 3 \text{ m}^3/\text{s}$ set during autumn and winter (personal communication Julie Lafleur, MDDELCC). The main advantage of this approach compared to the one based on hydrological indices, such as Indicators of Hydrology Alteration (IHA; Richter et al., 1996), is that the distribution unimodality can be simply and quickly assessed using a statistical test, while changes in indices can be cumbersome as one needs to compare values from operated and non-operated dams which may depend, for instance, on upstream watershed superficies (Mailhot et al., 2014). Furthermore non-unimodality can be directly linked to dam

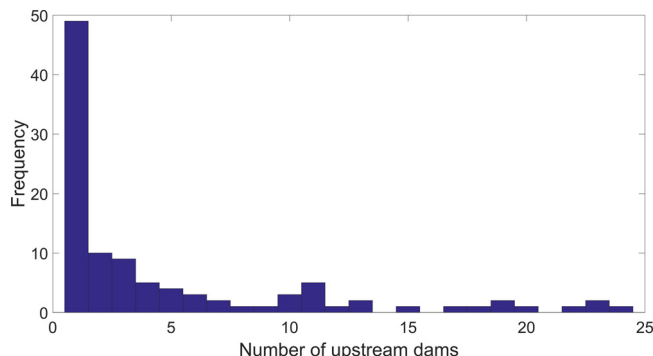


Fig. 5. Histogram of the number of stations/periods with one or more dams in their upstream watersheds (104 station/periods).

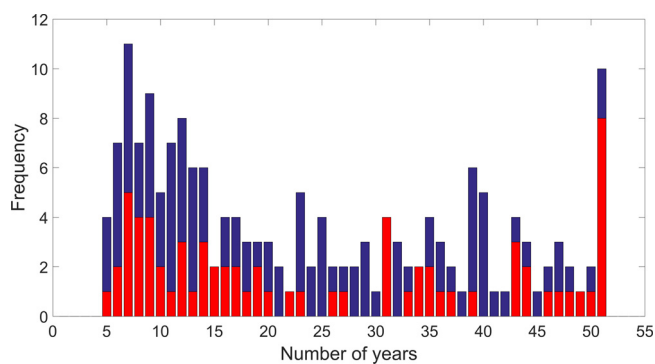


Fig. 6. Histogram of the number of years (excluding the buffer periods) with recorded flows for stations/periods with one or more dams (in blue) and without dams (in red) in their upstream watersheds.

operation while approaches based on IHA cannot disentangle the potential influences of dam operation from those due to dam construction.

Unimodality was assessed using the ‘dip test’ (hereafter called unimodality test) developed by [Hartigan and Hartigan \(1985\)](#). The non-unimodality distribution was tested at the 5% significance level and associated with the influence of dam operation on recorded flows.

Two special features of the daily flow series were considered, since they led to spurious unimodality test results. The first feature was related to the coarse flow resolution or changes in recorded flow resolution over time. The second feature was related to the presence of constant flow values over many days, in some of the records. Coarse resolution or changing resolution led to stepwise discontinuities in the cumulative function distribution of daily flow that were interpreted as a non-unimodal distribution by the unimodality test. In this circumstance, random values (uniformly distributed) were added to the recorded values to generate a continuous series.

The second feature relates to the presence in some of the records of constant flow values over many days for the period prior to 1966–1967. Flows were manually recorded by an observer prior to 1966–1967 and constant flow values are presumably related to the observer assiduity (personal communication from William Larouche, *Chef Division de l’hydrométrie*, MDDELCC). Therefore, we decided to discard recorded flows prior to 1966 from all stations/periods.

3.3. Assessing the potential influence of dam operation on flow at ungauged river reaches

The application of the unimodality test necessitates that recorded flows are available at the reaches where potential influences of dam operation are sought. An assessment of the potential impacts of dam operation on river reaches without gauging stations requires that an index be defined, linking the potential impacts of dam operation with dam location, characteristics, and the hydrographic characteristics of the considered river reach. Two main factors may determine the potential influence of dam operation on streamflow at a given reach: 1) the capacity of the dam reservoirs compared to the reach flow (a large capacity/flow ratio suggests that the dam may induce a large relative change in flow) and 2) the relative location of the dam and the river reach (the impact of dam operation is expected to decrease for reaches further downstream of a dam).

Previous studies have defined indices to characterize the potential influences, of dam construction or operation, on downstream flow. The Impounded Runoff Index (IRI; [Singer, 2007](#)) has been defined as the ratio of reservoir capacity to median annual flood runoff volume. A slightly different index, named Impounded Runoff (IR), defined as the ratio of reservoir capacity to annual runoff, has been proposed by [Batalla et al. \(2004\)](#). In order to take into consideration the possible influence of multiple upstream dams, [Singer \(2007\)](#) also used the total upstream reservoir capacity for stations under the influence of multiple dams.

More recently, [Lehner et al. \(2011\)](#), in order to evaluate the environmental impacts of dams on biodiversity, ecosystem functioning, and fluvial geomorphology, due to hydrological alterations, introduced the Degree of Regulation (DOR) metric (see also [Grill et al., 2014](#)). DOR is defined as the ratio of total storage capacity to total annual flow volume at the considered reach:

$$DOR_j = \frac{100}{D_j} \sum_{i=1}^{n_j} s_{ij} \quad (1)$$

where s_{ij} is the storage capacity of dam i upstream of reach j , n_j is the number of dams upstream of reach j , and D_j is the annual flow volume at reach j . Water volume within the river channel corresponds to the average discharge based on an approximation of channel width and depth ([Grill et al., 2014](#)). This metric is very similar to the IRI index and both are designed to quantify hydrological alterations induced by dams. A large DOR value corresponds to a configuration allowing a significant fraction of the annual discharge volume at a given reach to be stored and released at later time. DOR was therefore used in the present study as a proxy for how streamflow at a given reach may be altered by upstream dam operations ([Grill et al., 2014](#)). Since annual flow volumes were not available for all reaches, volumes were estimated using the linear regression between median annual flow volume and the upstream watershed area (not shown for conciseness). DOR values were therefore estimated and compared to the result of the unimodality test

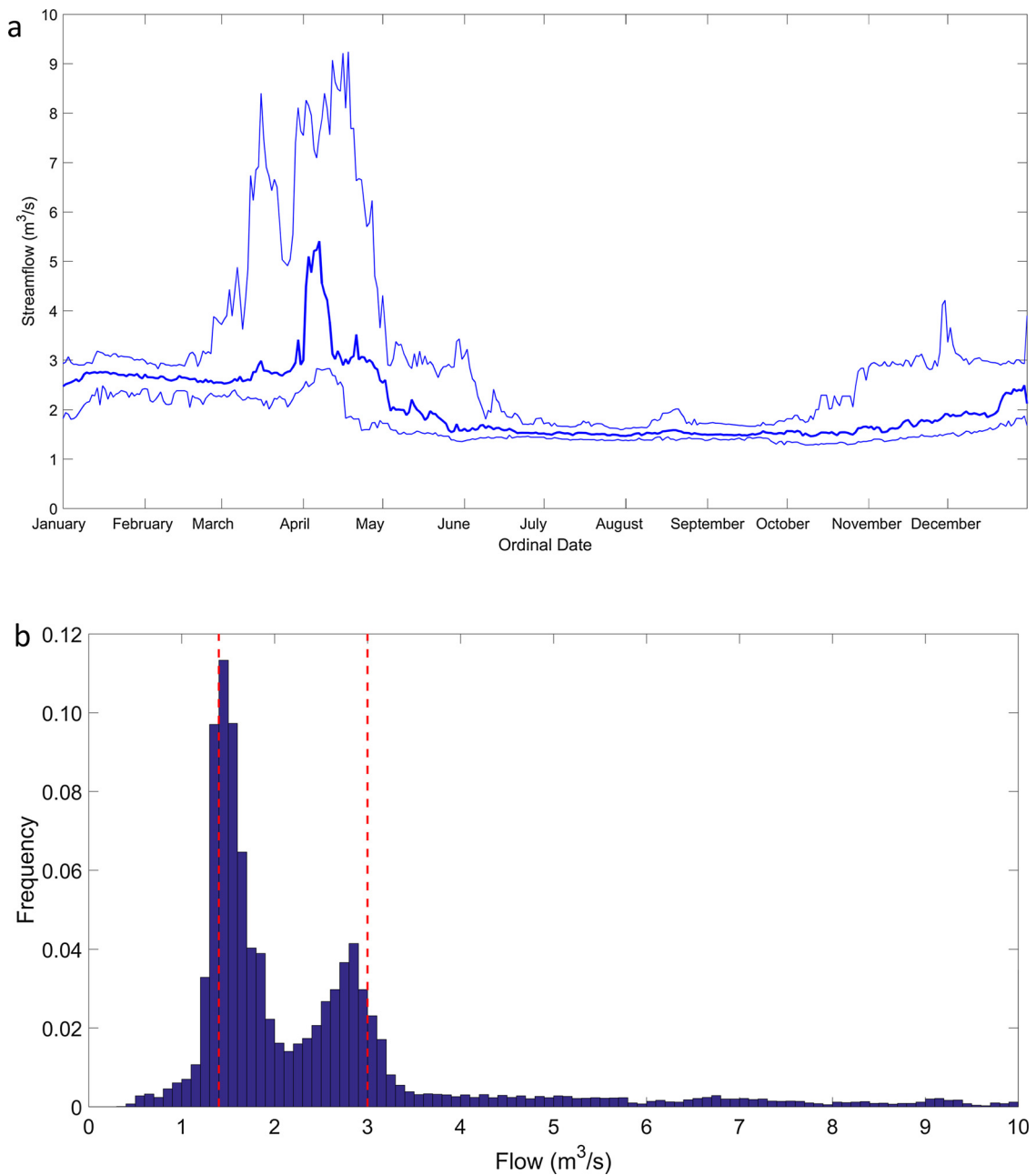


Fig. 7. (a) Mean annual hydrograph (demarcations on the X-axis correspond to the first day of each month; the thick line corresponds to the mean daily flow and the two thin lines correspond to the first and third quartiles); (b) daily flow histogram (the two vertical red lines correspond to the two flow values targeted according to operational rules) at the station located 0.4 km downstream of the Choinière dam.

for the available stations/periods. It is expected that altered flows due to dam operation, detected through non-unimodal flow distribution, is more likely to occur for reaches with high DOR values.

In order to assess the potential influences of dams operated by the MDELCC, the relative DOR index was also defined. Relative DOR corresponds to the fraction of the total reservoir capacity upstream from a given reach that is associated with MDELCC-operated dams. A relative DOR value equal to zero therefore indicates that the stations/periods do not include a MDELCC dam in its upstream watershed while a value of one means that all upstream dams are MDELCC-operated dams.

Table 1
Summary of the unimodal test over all stations/periods.

Modality of daily flow distribution	No dam in upstream watershed	One or more MDDELCC-operated dams in upstream watershed	No MDDELCC-operated dam in upstream watershed	TOTAL
Unimodal	66	33	55	154
Non-unimodal	4	13	3	20
TOTAL	70	46	58	174

4. Results

4.1. Application of the unimodality test to available stations/periods

Table 1 summarizes the results of the unimodality test for all stations/periods. It was first applied to the 70 unregulated stations/periods (i.e. with no upstream dam). When applying the unimodality test to these 70 stations/periods, we obviously expected a unimodal daily flow distribution given the absence of upstream dams. The results of this application indicate that all distributions were effectively unimodal except for four stations/periods. These four stations/periods are located downstream of unregulated watersheds over their entire recording periods: Mistassini (49.32 °N, -72.64 °E; 4,194 km²; 7-year record), Bell (48.32 °N, -77.30 °E; 1,902 km²; 7-year record), Waswanipi (49.86 °N, -77.19 °E; 31,272 km²; 51-year record), and Désert (46.59 °N, -76.04 °E; 1,644 km²; 12-year record). The four non-unimodal stations are indicated by triangles in Fig. 3. The first three stations are located in the northern part of the study region (north of 48 °N) while the remaining station is located further south.

Fig. 8 presents an example of daily flow distribution and its corresponding mean annual hydrograph for the Waswanipi station (northernmost station with the longest record and the largest upstream watershed among the four unregulated stations/periods with non-unimodal daily flow distribution). As can be seen in Fig. 8, the annual hydrograph is characterized by a recession following the spring peak that extends to September and October after which flows increase in November and finally decrease for another extended period during winter. The two modes of the distribution were therefore associated with a low flow period from February to mid-April (first peak at 200 m³/sec), and the second mode (extended plateau in the distribution from 300 to 800 m³/sec) was associated with the August to December period. This example is representative of the three northernmost stations, and also of some other watersheds located north of 50° latitude (not shown for conciseness). This demonstrates that seasonal hydrological regimes for some northern watersheds may lead to non-unimodal daily flow distributions. The unimodality test should therefore be applied with caution when assessing the impacts of dam operation in northern watersheds.

The fourth case, Désert station, presents a different feature, which is characterized by very low flow and very low variability of daily flow series from September to November over a 10-year period (not shown for conciseness). This explains the non-unimodality of the daily flow distribution. No other reason (e.g., watershed characteristics or some problems with recording set-up) was found that could explain this result. This situation demonstrates that, in some very specific cases, non-unimodal daily flow distributions can

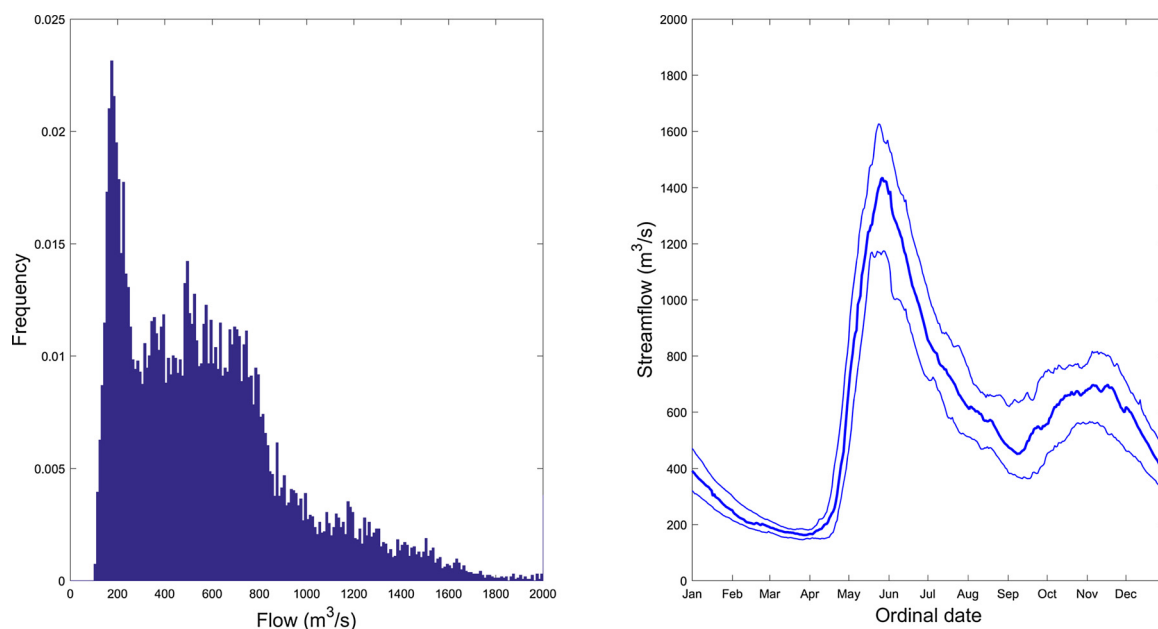


Fig. 8. (a) Distribution of daily flow and (b) mean annual hydrograph (the thick line corresponds to the mean daily flow and the two thin lines correspond to the first and third quartiles) at station Waswanipi (demarcations on the X-axis correspond to the first day of each month).

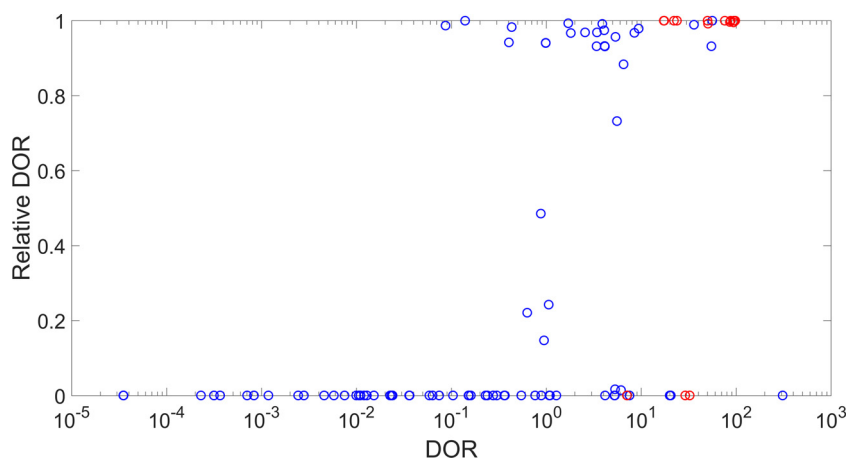


Fig. 9. Relative DOR values (y-axis) as a function of DOR values (x-axis) for all available stations/periods with upstream dams. Influenced stations/periods, according to the unimodality test (5% significance level), are indicated by red circles and non-influenced stations/periods correspond to blue circles.

be observed. Further research is needed to investigate this point.

The unimodality test was then applied to stations/periods with one or more dams in their upstream watersheds (Table 1). Of the 104 stations/periods belonging to this category, 88 (85%) were classified as unimodal. Of the 46 stations/periods with at least one dam operated by the MDDELCC-operated dam (regardless of their locations in the upstream watershed or their capacities), 13 (28%) were classified as influenced by upstream dam operation (since their daily flow distributions were non-unimodal), while for the 58 remaining stations/periods (with no upstream dams operated by the MDDELCC-operated dam), only 3 were classified as being influenced by dam operation (non-unimodal daily flow distribution).

4.2. Potential influence of dam operation on flow at ungauged river reaches

Fig. 9 presents the relative DOR and DOR values for all stations/periods with upstream dams and the results of the unimodality test (5% significance level). This figure reveals some interesting features. The first is that the available stations/periods with upstream MDDELCC dams have DOR values close or larger than 10^{-1} . The second is that no station/period was classified as influenced (non-unimodal daily flow distribution according to the unimodality test) for $\text{DOR} > 8$ (i.e. reaches where the total upstream dam capacity represents 8% or more of the median annual volume transiting this reach). This result therefore supports the hypothesis that impacts of dam operation on daily streamflow is more easily detected for larger DOR values. It also suggests that DOR values may be used as a proxy to assess the potential modification of streamflow due to dam operation for river reaches where no recorded streamflow are available. It however does not imply that a reach with $\text{DOR} > 8$ is necessarily influenced by dam operation. River reaches with DOR values larger than 8 may be, in fact, non-influenced by upstream dam operations simply because these dams are not operated or that their operations have negligible impact on daily streamflow. River reaches with $\text{DOR} > 8$ are therefore designated as ‘potentially influenced’ by dam operation.

4.3. Application to southern Quebec river network

The intent of the proposed approach is to provide an indicator identifying the river reaches that are potentially influenced by operation at upstream dams. Such information can be crucial for many applications where recorded flow series at specific reaches are used as proxies for flow at nearby ungauged basins in regional flood frequency analysis or for hydrological modelling. A large scale application of the proposed approach to the southern Quebec river network using readily available data was therefore realized.

DOR values were estimated for reaches with upstream watersheds completely located within Quebec boundaries for a total of 4,200 reaches with an average reach length of 16 km. Of these river reaches, 3,384 reaches (81%) were unregulated (no upstream dams and DOR values of zero). Fig. 10 presents the cumulative distribution of DOR values for all regulated reaches. It is interesting to note that approximately 30% of the regulated river reaches could be potentially influenced ($\text{DOR} > 8$) by dam operation according to our previous analysis.

Fig. 11 presents two examples of DOR values for the Rivière St-François watershed (Fig. 11a) and Saguenay watershed (Fig. 11b). These examples show that some classification of the reaches according to the potential influence of dam operation on flows can be made. For instance, river reaches with $\text{DOR} \geq 8$ could be associated with ‘potentially influenced’ reaches.

5. Conclusion

Some applications need to assess the potential influence of dam operation on flow at given river reaches, for example when

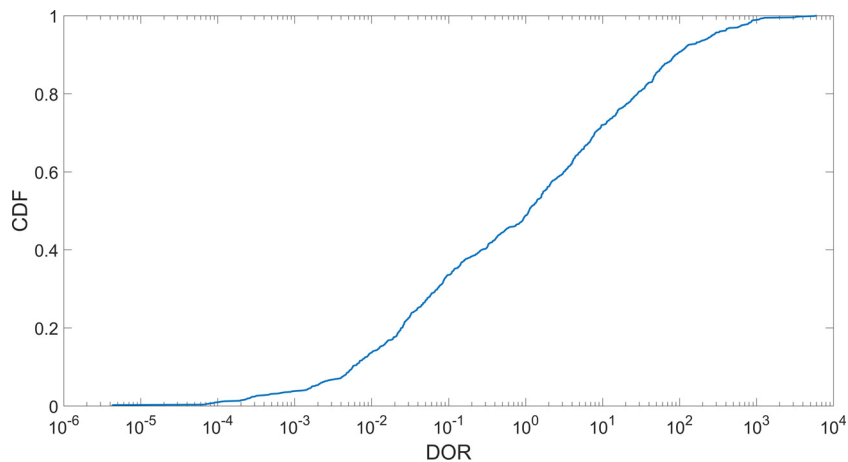


Fig. 10. Cumulative distribution function (CDF) of DOR values for all reaches with one or more dams in their upstream watersheds.

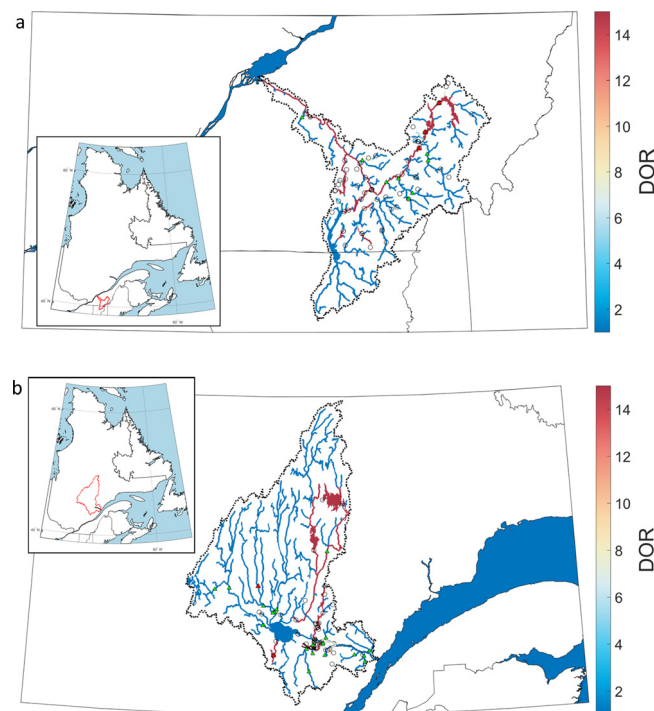


Fig. 11. Maps of the DOR values for the river reaches of: a) the St-François watershed; and b) the Saguenay watershed. Black circles correspond to dams, green triangles identify stations that are not influenced by dam operation, and red triangles identify stations influenced by dam operation (unimodality test at the 5% significance level).

recorded flows at a gauged watershed are used as a proxy for a neighbouring ungauged watershed or downstream reaches, or when using recorded flows for modelling purpose (e.g., calibration or validation of hydrological models). Non-operated dams can be assimilated to storage facilities and corresponding large scale alterations to basin hydrology could be considered as the norm for flood records. Flow distribution analysis should therefore reflect such anthropogenic changes (Villarini and Smith, 2010). Dam operation however, introduces a dynamic component to flow alterations that can be more difficult to detect and take into consideration in regional flood analysis. In this context, it is important to assess potential changes to natural flows due to dam operation and to identify stations and river reaches that may be influenced by dam operation. Generally dam operating status is unknown. When the operating status is known, dam operating records may still not be available, very vaguely described or even confidential.

The non-unimodality of daily flow distributions was examined as a possible signature of dam operation on daily recorded flow. The main hypothesis underlying the use of this metric is that many dams are operated according to some specific rules aiming at targeting specific ranges of flow values for certain flow conditions or periods of the year. Recorded flows at 226 stations across southern Quebec were analyzed. Records at these stations were partitioned into sub-periods according to the upstream dam

configuration. Each of these sub-periods, called station/period, therefore corresponds to a daily flow series with a given upstream dam configuration.

A unimodality test, aiming at verifying the hypothesis that the daily flow distribution was unimodal, was first applied to the 174 available station/periods. Results demonstrated that, for the 70 unregulated stations/periods (i.e. with no upstream dams), four were classified as non-unimodal. A close examination of these four cases showed that three correspond to watersheds located in the northern part of the study region. In these cases, the slow decrease of the spring flood and persistence of the spring flow regime over a large part of the summer months explains the non-unimodality of the daily flow distribution. Non-unimodality of the fourth watershed remains, at this point, unexplained.

Application of the unimodality test to the 104 stations/periods with one or more upstream dams suggested that the impacts of dam operation can be detected in some cases. Many stations downstream of watersheds with one or more large capacity dams with known operation status (MDDELCC-operated dams) displayed non-unimodal daily flow distributions. Consistency of results for unregulated stations/periods (unimodal distributions) and regulated stations/periods downstream of the dams operated by the MDDELCC-operated dams (some displaying non-unimodal distributions) supports the hypothesis that non-unimodality can be attributed to dam operation.

In order to be able to extend the analysis to ungauged river reaches, the ratio of the total reservoir capacity to the median annual volume transiting through a given river reach was defined. This ratio, called Degree of Regulation (DOR), initially proposed by Lehner et al. (2011), is conceptually similar to the IRI used by Singer (2007). It is based on the idea that the potential influence of dam operation will likely be more important when the upstream reservoir capacity stocks a large fraction of the median annual flow transiting in the downstream river reach. Estimation of the DOR values for all stations/periods with one or more upstream dams showed that station/period influenced by dam operation, according to the unimodality test, have DOR values larger than 8. A threshold value for DOR values could therefore be defined as a proxy for the potential influence of dam operation on flows.

Note that DOR values were designed to identify the ‘potential’ influence of dam operation, that is, an influence that could be detected if the dam is operated. A river reach with a large DOR value may not, in fact, be influenced by dam operation (for instance if the dam is not actually operated). Small DOR values are as well interpreted as indicative that possible dam operations will not influence river reach flows.

Many factors may determine the magnitude of the impacts of dam operation on downstream flows, such as the dam’s function (hydroelectricity production, water supply, flood protection, etc.), operation rules, operation frequency (daily, weekly, seasonal, annual), reservoir capacity, dam outlets (gates, spillway, etc.), etc. Unimodality test measures one specific type of influence (modality of daily flow distribution). Other indices (e.g., IHA indices) may therefore be needed to detect other possible impacts of dam operation on flows. Using ‘standard’ indices (such as IHA indices) however, imply that some reference range of index values be defined for non-influenced or natural configurations and that some metric be defined to measure possible departure from these values. Unimodality test, in contrast, provides interesting ways to assess the potential influence of dam operation on daily flow and is easy to implement and interpret. Furthermore, this index is more directly linked to dam operation. Note that non-unimodal daily flow distributions can also be observed (rarely according to our results) for unregulated watersheds.

Future work should extend the study to other regions in order to verify how dam operations affect the daily flow distributions as reported in this study. Additionally, results based on unimodality test should be compared with those produced from approaches based on indicators of hydrologic alteration (Peñas et al., 2016).

Conflict of interest

None.

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