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Comparison of impacts of dams on the annual maximum flow characteristics in three regulated hydrologic regimes in Québec (Canada)

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Abstract:

Despite the presence of numerous dams in Québec, no study has yet been devoted to their impacts on flood levels. To compensate for this deficiency, we have compared the impacts of dams on the five characteristics (magnitude and its interannual variability, timing and its interannual variability, and asymmetry) of the maximum annual flows between natural rivers and regulated rivers by means of several statistical approaches (analysis of variance, chi-square test, nonparametric tests, etc.). In the course of this study, we analysed 88 stations on pristine rivers and 60 stations on regulated rivers. The latter group was subdivided into three regulated hydrologic regimes, i.e. inversed flow regimes (25 stations), homogenization flow regimes (15 stations) and natural-type flow regimes (20 stations). The following observations emerge from this study. (1) In inversed and homogenization flow regimes, generally associated with reservoirs, all the flow characteristics are modified. These modifications notably entrain a decrease in magnitude, a significant reduction in the frequency of the maximum annual spring flows when the snow is melting and an increase in skewness of the distribution and interannual variability of the magnitude and dates of occurrence of the annual maximum flows. We also observed the disappearance of most flows with a recurrence of over 10 years. All these changes particularly affect watersheds larger than 10 000 km^2. (2) In natural-type flow regimes, often associated with run-of-river dams, very few changes were observed compared with pristine rivers. These changes primarily affected watersheds smaller than 1000 km^2. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS maximum annual flows; magnitude; timing; interannual variability; coefficient of skewness; regulated rivers; pristine rivers; Québec

INTRODUCTION

In most studies, regulation of flows downstream from dams is exclusively concerned with minimum flows (Petts, 1995). It has been shown, however, that flood flows play just as crucial a role in the functioning and productivity of river ecosystems (Stanford *et al.*, 1996). The case of the Colorado River in the USA is an eloquent example (Schmidt *et al.*, 1998; Andrews and Pizzi, 2000; Patten *et al.*, 2001). Experimentation with the effects of a flood revealed the necessity of restoring certain strong spring floods that completely disappeared after dam construction (Patten *et al.*, 2001). In other watersheds, studies also showed the biological and morphological impacts caused by changes in the magnitude and timing of floods (Reily and Johnson, 1982; Bradley and Smith, 1985; Rood and Heinze-Milne, 1989; Rood *et al.*, 1995; Power *et al.*, 1996; Wooton *et al.*, 1996). Poff *et al.* (1997) even defined the ecological and morphological effects associated with different return periods. Some workers thus came to propose qualitative and/or quantitative criteria to define the flood

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flow thresholds necessary to rehabilitate and maintain the integrity of river ecosystems downstream from dams (Kondolf *et al*., 1987; Petts, 1995; Kondolf and Wilcock, 1996; Stanford *et al*., 1996; Galat *et al*., 1998; Schmidt *et al*., 1998; Toth *et al*., 1998; Downs and Kondolf, 2002; Sprenger *et al*., 2002).

Moreover, nearly all the studies devoted to the impacts of dams on flood flows often deal with only one river (Vivian, 1994; Church, 1995; Maheshwari *et al*., 1995; Erskine *et al*., 1999). As Friedman *et al*. (1998) had already pointed out, this approach sometimes leads to contradictory conclusions when one river is compared with another. It is important, therefore, to consider watersheds of different sizes for a better assessment of the impacts of dams in a given region. Moreover, these studies analysed only one or two flood characteristics (Maheshwari *et al*., 1995; Erskine *et al*., 1999). This makes it impossible to show all the ecological impacts likely to be triggered by changes in all characteristics of flood flow. Indeed, Richter *et al*. (1996, 1997), among others, have reported that each flow characteristic contributes to maintenance of the integrity and biodiversity of river ecosystems. Any change in one of the characteristics can rupture the natural balance of these systems.

In Québec, despite the presence of over 10 000 dams and dykes built since the 19th century (Astrade, 1998), there are still very few studies on the hydrologic impacts downstream from these structures (Assani *et al*., 2002, 2005). Thus, owing to the absence of such studies, Québec still does not have any flood flow standard for the protection and restoration of river ecosystems and their biodiversity downstream from dams. Within the perspective of development of these flood standards downstream from dams, we have analysed the impacts of dams on the maximum daily discharge (annual maximum flow) characteristics. The purpose of this study is to compare the impacts of dams on the annual maximum discharge characteristics in the three regulated hydrologic regimes observed in Québec, so that restoration measures specific to each can be developed subsequently. We will attempt to validate the assumption that the scope of the impacts of dams on annual maximum flow characteristics depends on the regulated hydrologic regime, which in turn is a function of the dam management mode and the watershed size.

METHODOLOGY

Study sites and source of data

Québec is divided into three major watersheds (Figure 1): the St Lawrence River watershed (673 000 km^2), Ungava Bay (518 000 km^2) and Hudson Bay (492 000 km^2) watersheds. In this study, we will deal exclusively with the St Lawrence watershed, because we were unable to obtain data on the regulated river flows in the other two watersheds. It is worth noting, however, that the vast majority of hydroelectric dams are constructed in the St Lawrence River watershed. From a lithologic standpoint, this watershed consists of three major geological formations: the Canadian Shield (intrusive and metamorphic rocks) on the north shore, the Appalachians (folded sedimentary rocks) on the south shore, and the St Lawrence Lowlands (schists and carbonates). The extent of the St Lawrence Lowlands is small, covering the two shores of the river from which they take their name. The flow data are given by the *Sommaire chronologique de l'écoulement au Québec* published by Environment Canada (1992). This summary indicates the station number and name, the mean monthly and mean annual flows, the magnitude and the timing (day and month), and the annual maximum and minimum flows. It is specified whether the flow values have been corrected in order to take into account the effect of ice. Also reported in this summary are data on the watershed area upstream from the gauging station, the geographic coordinates (latitude and longitude), the name of the station manager and the watercourse status (pristine or regulated). It is appropriate to specify that the word 'regulated' has been used in its broadest sense, i.e. any alteration of the water flow caused by man-made structures. This may mean a simple spillway crest or impounding of the shores to contain the water in the main channel. Although the duration of the discharge record varies from one watershed to the next, discharge data were collected between 1920 and 1990. For some rivers on which the duration of the flow record was less than 10 years, we extended the hydrologic series with data taken from the hydrologic directories published annually by the Ministère de l'Environnement du

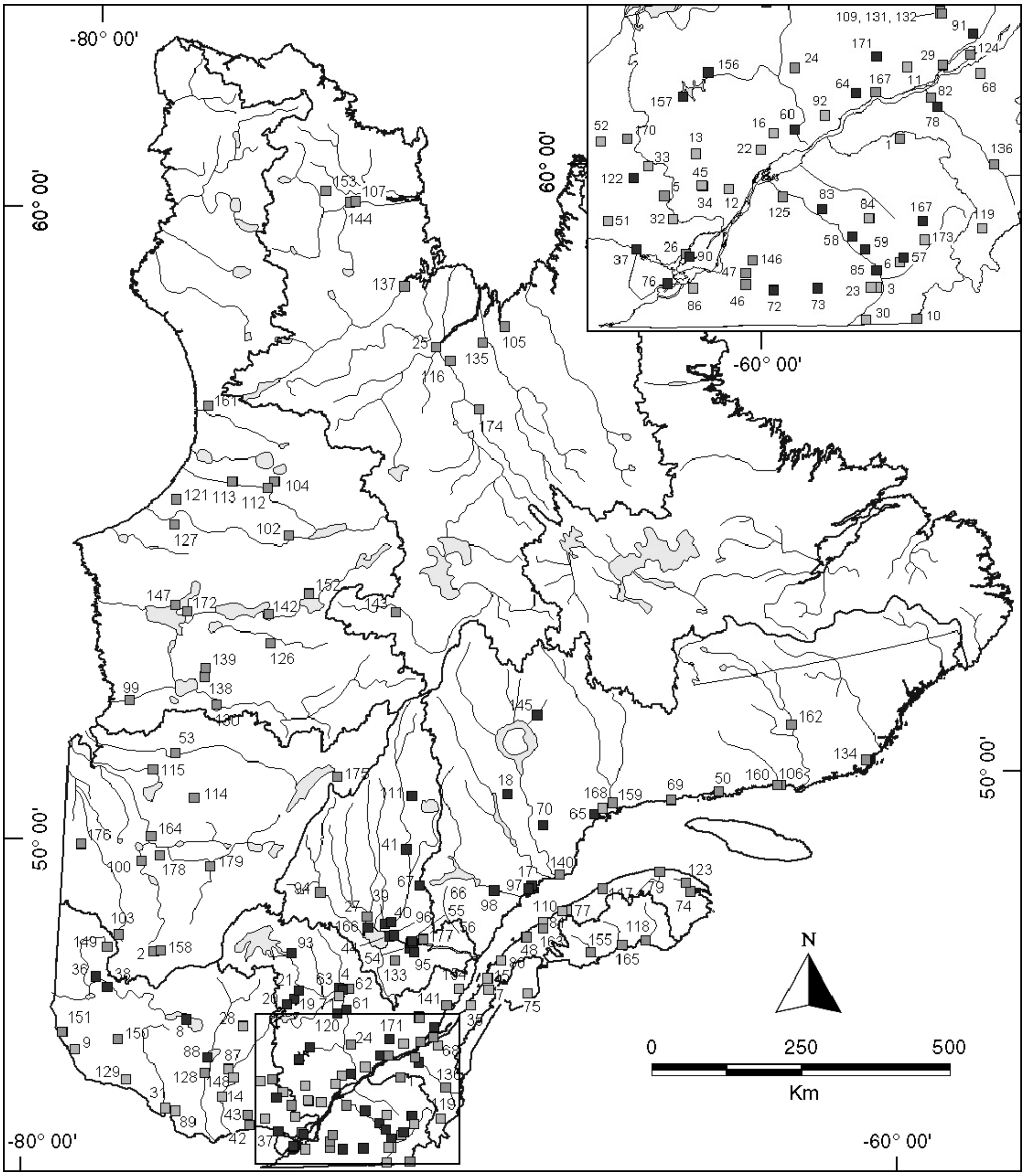

Figure 1. Locations of stations analysed. Black rectangle: regulated rivers; grey rectangle: unregulated rivers. The station numbers refer to our database

Québec between 1991 and 1993. For some pristine rivers, we also used the data published by Anctil *et al.* (1998) regarding the mean maximum annual flows.

In the case of a station directly influenced by a dam, the name of the dam is indicated. This allowed us to look up the characteristics of each dam on the Ministère de l'Environnement du Québec Website (http://barrages.menv.gouv.qc.ca, [3 March 2003]). On this site, the Ministère publishes four categories of information: identification, administrative category and type of use, and the technical characteristics of each dam.

Regarding the artificialized hydrologic regimes, i.e. the hydrologic regimes directly influenced by the dams, analysis of the monthly and seasonal flows by means of principal component analysis (PCA) revealed three types of regime (Assani *et al.*, 2004). Each type corresponds to a specific dam management mode.

- The inversed flow regime is characterized by the monthly maximum discharges in winter (December to March) and the monthly minimum discharges in the spring (April to May) when the snow is melting. The natural hydrologic cycle is, therefore, completely inversed. This type of flow regime is observed exclusively on the north shore of the St Lawrence River due to the low winter flow and high power production in the winter.
- The homogenization flow regime is characterized by a low variation in monthly discharges. This is a less contrasted regime than the previous one. In fact, the ratio between the monthly maximum and minimum discharges is close to unity, whereas under natural conditions this ratio is always greater than 10. Moreover, contrary to the previous regime, the monthly minimum discharge flows never occur in the spring when the snow is melting. On the other hand, the monthly maximum flows can be observed in winter. This regulated hydrologic regime is very frequent on the north shore.
- The natural-type flow regime is characterized by the absence of change in the periods of occurrence of the monthly maximum and/or minimum flows. It is comparable to the flow regimes of pristine rivers. Thus, the monthly maximum discharges occur in the spring when the snow is melting, and the monthly minimum flows occur in winter and/or summer. Compared with the flow regime in pristine rivers, the natural flow regime resulting from the effect of the dam is marked by a slight increase of discharges in the winter and a slight decrease in the spring. Contrary to the previous two regimes, it is found on both shores of the St Lawrence River.

Data analysis methods

Characterization of annual maximum flows. From an ecological standpoint, Richter *et al.* (1996, 1998) have shown that river flows can be described by the following five characteristics: magnitude, timing, duration, frequency and the rate of change in water conditions. These characteristics are quantitatively described by 33 hydrologic variables known as indicators of hydrologic alteration. They make it possible to detect and quantify the impacts of man-made origin, particularly dams, on the natural hydrologic regimes. Richter *et al.* (1996, 1998) emphasized the importance of these characteristics in ecology for watercourse management. Thus, they are used increasingly often in the scientific community to describe the hydrologic regimes and quantify the human impacts on river systems (Richter *et al.*, 1997, 1998; Claussen and Biggs, 2000; Olden and Poff, 2003). However, these 33 variables only apply when daily flow records are available. In our case, we only had the annual maximum flows, i.e. a single maximum daily flow value per year, because daily flow data measured at the dam are not disclosed to the public by the hydroelectric companies for industrial competition reasons. In fact, these data will show the daily hydroelectric power for each dam. For this reason, we could not consider all of the five characteristics proposed by Richter *et al.* (1996) to analyse the impacts of dams on annual maximum flows.

However, Assani (unpublished results, 2003) has shown that any hydrologic series can be defined by at least three characteristics. Thus, an annual (maximum or minimum) discharge series can be defined by the following six characteristics (Table I): magnitude, timing, interannual variability (the rate of change) of magnitude and timing, duration, frequency and the shape of the distribution curve (skewness and kurtosis). Interannual variability of the magnitude and of the period (date) of occurrence have been defined by means of coefficients of variation. To calculate the coefficients of variation of the dates of occurrence of the maximum annual flows (timing), we have converted the calendar dates into the corresponding Julian days. The shape of the distribution curve was assessed using the coefficient of skewness (Pearson coefficient).

Justification of the choice of dam impact analysis methods. Three methods are commonly used in the literature to analyse the impacts of dams:

Table I. The characteristics defining the series of annual maximum flows

Hydrologic characteristics	Hydrologic variables used	Examples of ecosystem influences[a]
Magnitude	Mean maximum annual flow	Balance of competitive, ruderal, and stress-tolerant organisms
Interannual variability of magnitude	Coefficient of variation (%)	Variation of balance
Timing	Monthly frequency of dates of occurrence	Compatibility with life cycles of organisms Predictability/avoidability of stress for organisms
Interannual variability of timing	Coefficient of variation of dates (Julian days) of occurrence	Variation of compatibility
Frequency	10-year recurrence flows	Influence population dynamics (reproduction or mortality events for various species)
Shape of the curve	Pearson's coefficent of skewness	?
Duration	No variable	Balance of competitive, ruderal, and stress-tolerant organisms

[a] Poff *et al*. (1997), Richter *et al*. (1998), Nilsson and Svedmark (2002).

- *The monitoring station method*. This consists of comparing the data measured at the same station before and after dam construction (e.g. Richter *et al*., 1998).
- *The control station method*. This is based on comparison of the flows measured upstream and downstream from a dam (e.g. Assani *et al*., 2002). The control station may also be located on another river not influenced by a dam, but which has physiographic and climatic characteristics comparable to those of the regulated river (e.g. Benn and Erskine, 1994).
- *The reconstitution method*. A way of estimating the flows under natural conditions and then comparing them with the flows released downstream from a dam is developed. This reconstitution can be based on daily power production (Assani *et al*., 1999), or a hydrologic model can be used (e.g. Maheshwari *et al*., 1995; Peters and Prowse, 2001).

Within the framework of this study, we could not apply any of these three methods for the following reasons:

- Flow data from before the construction of the dams or from stations located upstream from the dams were not available.
- It is not possible to simulate the natural flows by means of a single hydrologic model for all of the stations analysed (60 stations). Moreover, development of a hydrologic model is a long and tedious process beyond the scope of this study. This is a method generally used when working on a single station or on several stations within a single watershed.

As a result of these limitations, we had to rely on a different method for assessing the impact of dams. This method is based on the comparison of the characteristics of flows according to drainage areas for both pristine and regulated rivers. This approach is justified by the fact that, in Québec, there is a strong relationship between discharges (annual, monthly and daily scales) and drainage areas for natural flows (e.g. Belzile *et al*., 1997; Assani *et al*., 2005). This comparison has been done by means of several statistical tests (variance analysis, chi-square test, Student's t-test, etc.), depending on the nature of the data. The level of significance for the various statistical tests that we have applied in this research is 95%. However, when it was impossible to apply the statistical tests, we settled for a graphic comparison of the data. This approach simply consists of comparing a hydrologic variable measured in natural rivers and in rivers influenced by dams on a graph representing the variable studied as the ordinate and the watershed size as the abscissa.

Method of estimating natural 10-year recurring flows downstream from dams. The 10-year flow separates major flows of rare frequency (recurrence greater than 10 years) from major flows that are less rare. Therefore, we sought to assess whether the impacts of the dams indirectly affect the magnitude of rare and less rare major flows. We compared the highest flows observed downstream from the dams (Q_{max}, maximum maximorum) with the 10-year recurring flows Q_{10} estimated downstream from the dams. The latter flows were estimated by the regional analysis method developed by Anctil *et al.* (1998) for the Province of Québec. This estimate was produced as follows:

- First, for regulated stations, we estimated the mean of annual maximum flows Q_{m} from the area A of the watersheds by means of the formula proposed by Anctil *et al.* (1998):

$$Q_{\mathrm{m}} = 1{\cdot}61A^{0{\cdot}70} \tag{1}$$

  This estimate is justified by the fact that it must be posited as an initial assumption that the flows downstream from the dams are altered. Consequently, they cannot be used to estimate the quantiles corresponding to the 10-year recurrence.
- Then we calculated the quantiles Q_{R} corresponding to the 10-year recurrence by means of the formulas developed by Anctil *et al.* (1998) in the natural homogeneous hydrologic regions. These have been defined in Québec by means of the Hosking and Wallis method. The following equations were used:

$$Q_{\mathrm{R}} = \xi + (\alpha B/\kappa) \tag{2}$$

$$B = 1 - \{-\ln[(T-1)/T]\}^{\kappa} \tag{3}$$

  where T is the return period and κ, α and ξ are respectively the shape, location and scale parameters of the standardized parameters of the regional generalized extreme value (GEV) distribution. These parameters are estimated by means of the L-moments method, for which the values were calculated by Anctil *et al.* (1998) in the natural homogeneous hydrologic regions defined in Québec.
- Finally, we estimated the 10-year recurrence quantile Q_{10} downstream from the dams:

$$Q_{10} = Q_{\mathrm{R}}Q_{\mathrm{m}} \tag{4}$$

  In fact, Q_{10} corresponds to the 10-year recurring flow that should be observed under natural conditions at a station without the presence of a dam.

RESULTS

Impacts of dams on the timing and its interannual variability

Figure 2 presents the monthly frequencies of the maximum annual flow occurrence periods in the three regulated hydrologic regimes in the St Lawrence River watershed. The following observations emerge from this figure:

- A significant increase in the frequency of the timing of the annual maximum discharges in summer, fall and winter flows downstream from the dams compared with the pristine rivers. This increase is especially marked in the inversed and homogenization flow regimes. In the natural-type flow regime, the increase is mainly observed during the first half of the cold season (October to January). Whatever the case may be, this increase is negligible compared with the other two regimes.

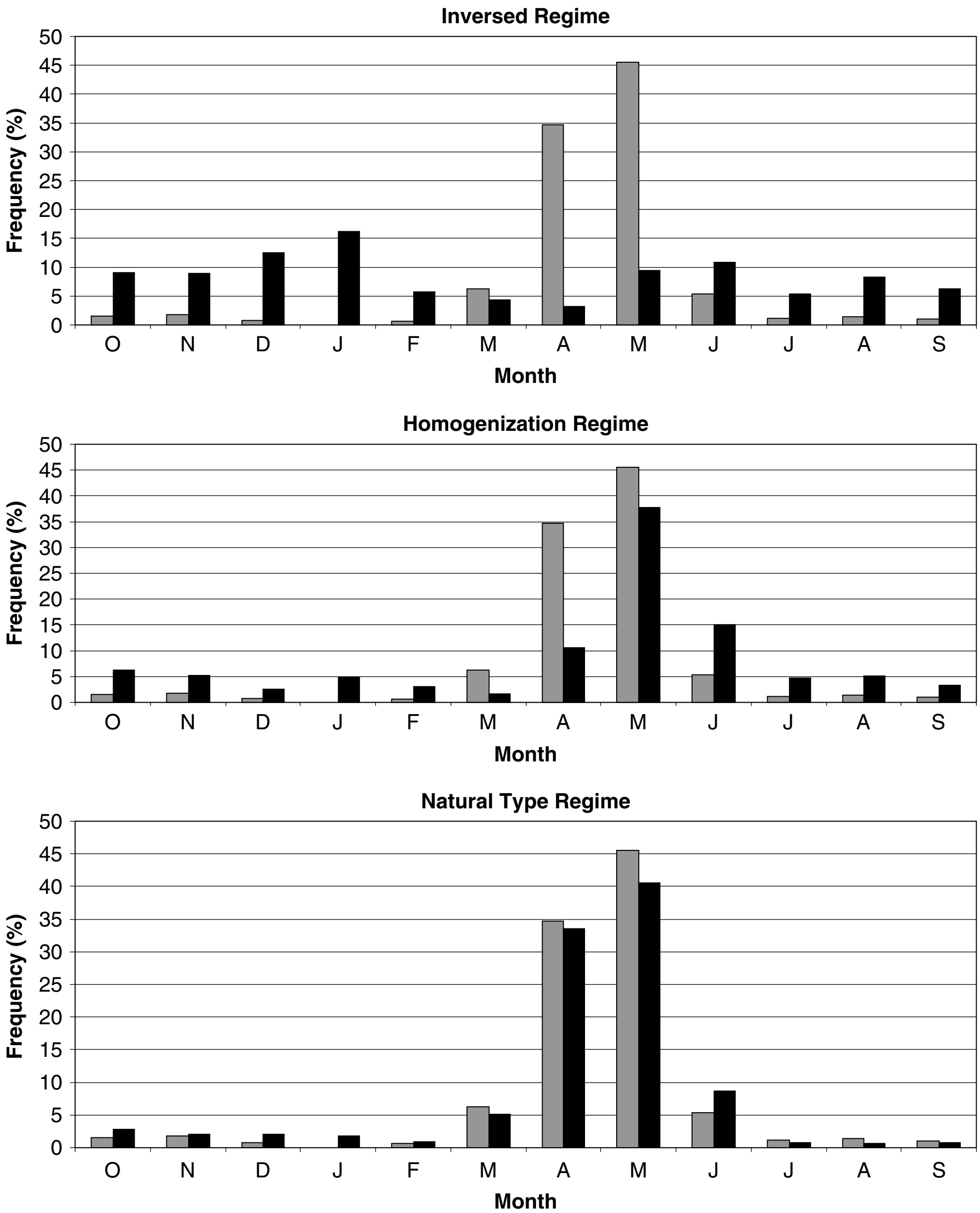

Figure 2. Comparison of the average of monthly frequency of timing of annual maximum discharges in unregulated rivers (grey bars) and regulated rivers (black bars)

- A significant decrease in the frequency of occurrence of annual maximum flows in the spring (April and May) downstream from the dams in the inversed and homogenization flow regimes. We should remember that it is during this period that at least 80% of the maximum annual flows in pristine rivers are recorded, due to snowmelt.

Figure 3 compares the values of the coefficients of variation of the Julian days (interannual variability) of regulated rivers with those of pristine rivers. In unregulated rivers, a strong interannual variation of the

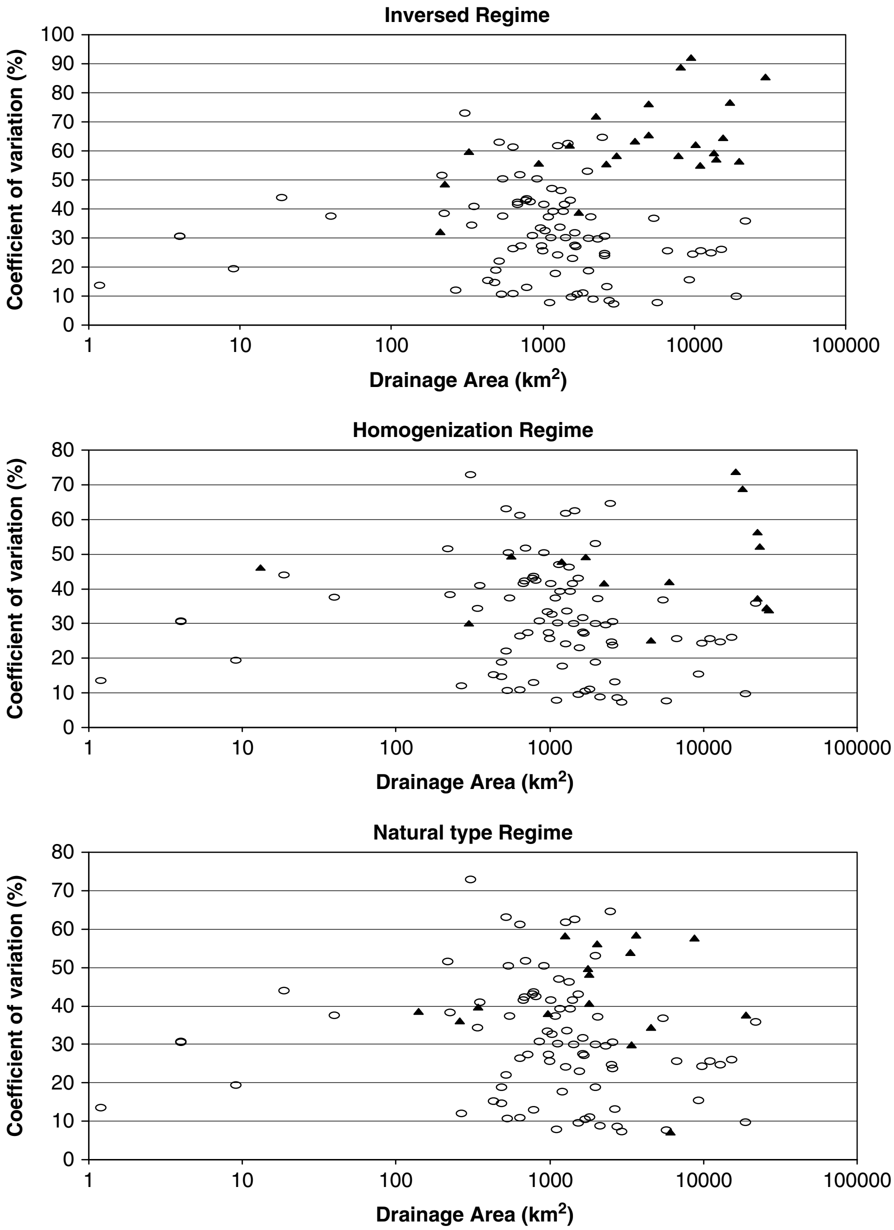

Figure 3. Comparison of the coefficients of variation of dates (Julian days) of occurrence of annual maximum flows between unregulated rivers (circles) and regulated rivers (triangles)

date of occurrence of the maximum annual flows is observed. The value of the coefficients of variation ranges between 10 and 80%. No statistically significant relationship seems to exist between these coefficients of variation and the size of the watersheds. The difference between regulated and pristine rivers is mainly observed in the inversed flow regime, which is characterized by relatively strong interannual variability of timing of the maximum annual flows. This difference particularly affects watersheds greater than 5000 km^2. On the other hand, the values of the highest coefficients of variation exceeded the 80% threshold.

Changes in the monthly frequencies and the interannual fluctuations of the dates of occurrence of the annual maximum discharges induced by the dams primarily affect the stations belonging to the inversed flow regime and, to a lesser extent, those of the homogenization flow regime. These changes are associated with a very significant reduction in the monthly frequencies in April and May, when the snow is melting, and strong variability in the dates of occurrence of the annual maximum discharges.

Impacts of the dams on magnitude and its interannual variability

Figure 4 compares the maximum annual flows of natural rivers with those of unregulated rivers based on the drainage areas. We estimated the regression lines (after logarithmic transformation of the data) using an ordinary least-squares procedure and then compared their slopes and their intercept. Figure 4 shows that the difference in flows is mainly observed in the inversed and homogenization flow regimes. The analysis of variance showed that both the slope and the intercept of the regressions are significantly different for the two artificialized hydrologic regimes. The estimates for the flows measured downstream from the dams are less than those of the pristine river flows. Thus, downstream from these dams, the mean annual maximum discharge is lower than the value estimated in a pristine river. The annual maximum flows, therefore, diminish significantly downstream from these dams.

However, the comparison of the regression parameters does not allow each station to be tested individually. In fact, the analysis of the graphic suggests that the deviation between the maximum annual flows of certain stations downstream from the dams and those of pristine rivers seems to be low. The points representing the flows at these stations downstream from the dams are sometimes confused with the clouds of points representing pristine river flows. It can thus be assumed that, for some stations, there have been no significant changes in the flow before and after dams construction. To test this hypothesis, we proceeded with the following three steps:

- We compared the annual maximum flows observed at each station influenced by the dams with the values of the estimated annual maximum flows (ED), based on the drainage areas, by the regression curve established between flow and watershed size in pristine rivers. The estimated maximum flow is assumed to correspond to the flow that should be observed at a station without the presence of a dam.
- We then estimate the ED confidence intervals at a 95% threshold.
- Finally, we compared the observed annual maximum flow (OD) downstream from a station influenced by a dam with the corresponding ED, taking into account the ED interval of confidence. When the flow measured downstream from a dam fell within this interval of confidence, we therefore considered that the two flows were not significantly different. This approach revealed that, for 72% of stations in the inversed flow regime, the observed maximum flows (OD) downstream from the dams fell outside the intervals of confidence of the estimated pristine flows (ED) (Figure 5). For the homogenization and natural-type flow regimes, this proportion is 53% and 5% respectively.

Regarding the interannual variability of the magnitude of flows, Figure 6 shows that over 90% of pristine rivers are characterized by coefficients of variation between 20 and 50%. The highest value does not exceed 70%. These values tend to diminish in relation to watershed size. The coefficients of variation of regulated rivers also fall within this range. However, an increase in the coefficient of variation values is observed for watersheds larger than 10 000 km^2 in the inversed and homogenization flow regimes. Moreover, in an inversed flow regime, the value of the coefficient of variation exceeds 70%. It follows that dams result in a strong interannual variability of the magnitude of annual maximum discharges.

Impacts of dams on the frequency of rare floods

To study these impacts, we compared the 10-year recurrence flows estimated by means of Equation (4) with the highest maximum annual flows $Q_{\max}$ measured downstream from the dams. The latter flows in fact

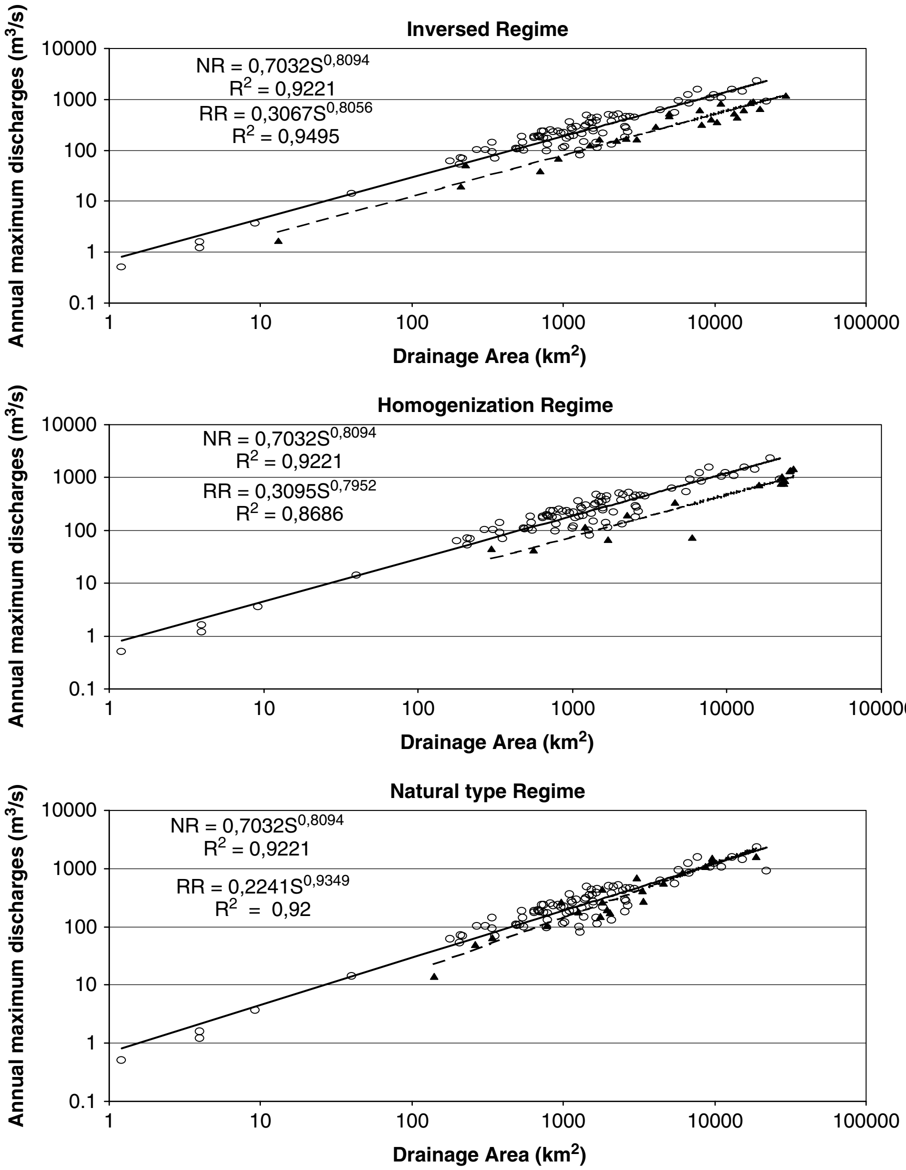

Figure 4. Comparison of relationship between the magnitude of the annual maximum flows and the drainage areas in unregulated rivers (NR, circles) and regulated rivers (RR, triangles)

correspond to the maximum maximorum flows. We have decided to use this discharge value because it is very difficult to obtain reliable estimates of the 10-year recurrence flows from the application of the simple probability laws currently applied in Québec (Gumbel, GEV, Pearson III or log-Pearson III) to annual series of discharges measured downstream of a dam. This difficulty is associated with the fact that the magnitude of floods is greatly modified by dams in both the inversed and homogenized flow regimes. For many stations, the Q_{max} values are lower than the Q_{10} values in the inversed flow regime and, to a lesser extent, in the homogenization flow regime (Figure 7). For these two regimes, this means that the recurrence of the maximum maximorum flows released downstream from the dams is less than 10 years. In other words,

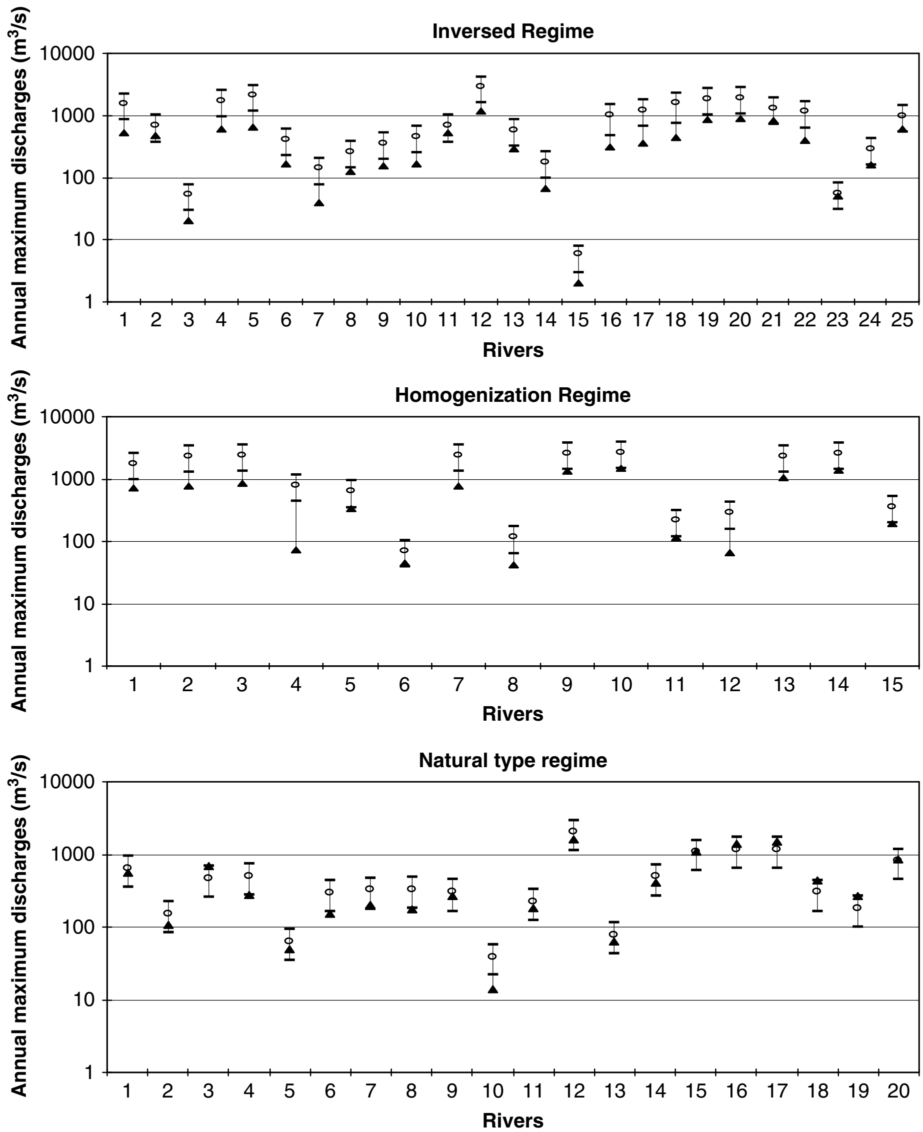

Figure 5. Comparison of the values of estimated (ED, circles) and observed (OD, triangles) annual maximum flows downstream from dams. The horizontal bars delimit the intervals of confidence of ED

the flows with a return period greater than the 10-year recurrence have disappeared. For the stations belonging to the natural-type flow regime, this effect is only present in watersheds smaller than 1000 km^2.

Impacts of dams on the shape of the flow distribution curve

Figure 8 presents the coefficients of skewness of pristine and regulated rivers. Over 80% of pristine rivers have positive coefficients of skewness, between zero and one (Table II). No relationship seems to exist between the size of the watersheds and the degree of asymmetry (skewness) of the flow distribution curves. In regulated rivers, we observe an increase in the number of stations that are characterized by positive skewness and high value in the inversed and homogenization flow regimes. These changes are observed for large watersheds.

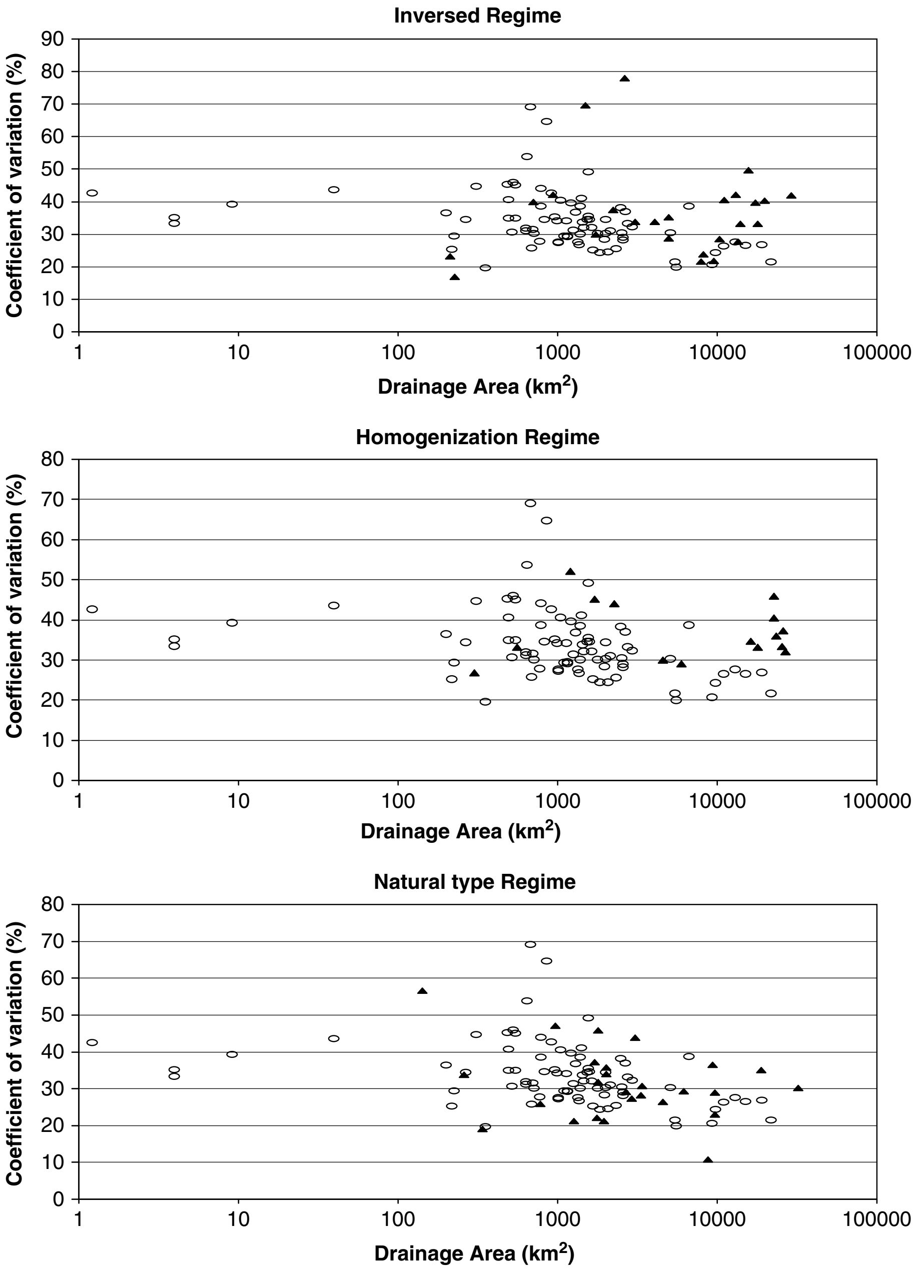

Figure 6. Comparison of the coefficients of variation of magnitude of annual maximum flows in unregulated rivers (circles) and regulated rivers (triangles)

DISCUSSION AND CONCLUSIONS

The comparative analysis of the impacts of dams on the annual maximum flow characteristics in the three artificialized hydrologic regimes (inversed, homogenization and natural-type flow) observed in Québec has revealed that (Table III):

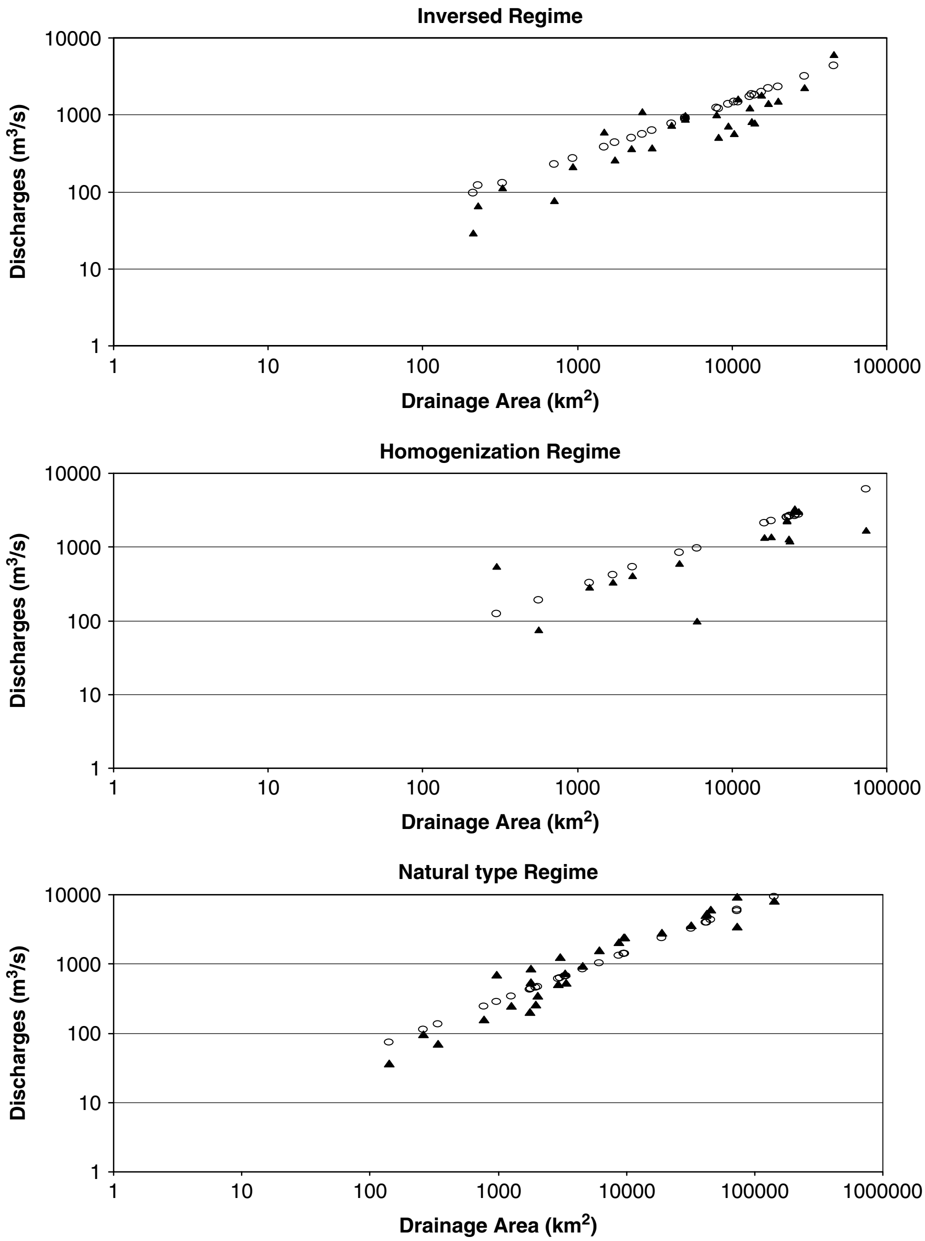

Figure 7. Comparison between $Q_{\max}$ (triangles) and Q_{10} (circles) estimated in regulated rivers

- The dams alter all the annual maximum flow characteristics to varying degrees (timing, magnitude, interannual variability of magnitude and timing, and the shape of the distribution curve).
- The amplitude (scope) of these changes depends on the type of regulated hydrologic regime and the watershed size.

The regulated hydrologic regime most affected by the changes is undoubtedly the inversed flow regime. The changes induced by the dams are a very significant decrease in the frequencies of annual maximum flows at

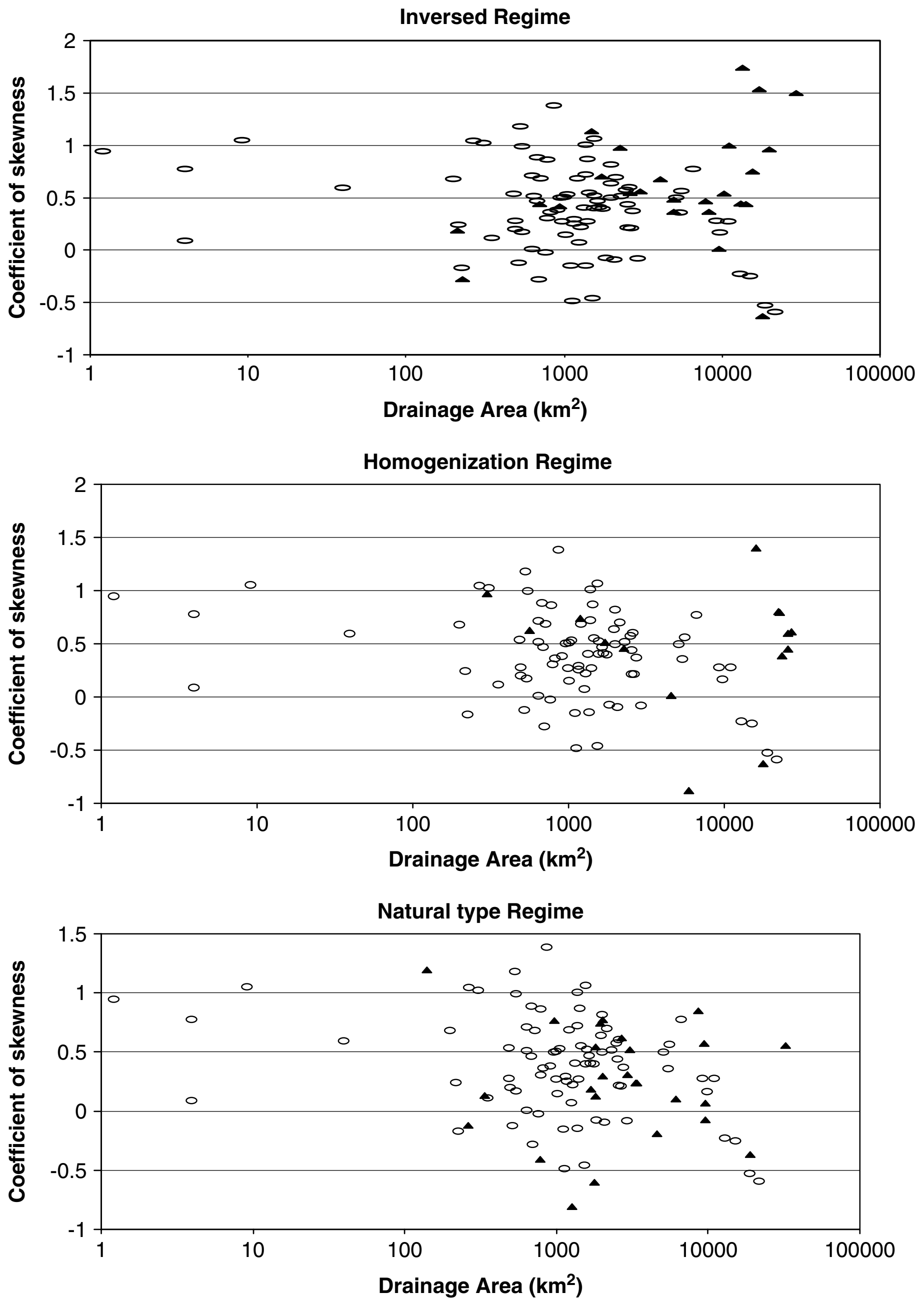

Figure 8. Comparison of coefficients of skewness of annual maximum flows between unregulated rivers (circles) and regulated rivers (triangles)

the height of the snowmelt period (April and May), a strong interannual variability of the dates of occurrence of these flows, a significant reduction and strong interannual variability of the magnitudes of discharges, the disappearance of flood with a recurrence of over 10 years and a more pronounced skewness of the flow distribution curves. All these changes particularly affect drainage basins larger than 10 000 km^2. Similar

Table II. Comparison of signs of coefficients of skewness of annual maximum flows between pristine rivers and regulated rivers

Hydrologic regime type	Skewness (%)	
	Negative	Positive
Pristine	19·5	80·5
Inversed	8·0	92·0
Homogenization	11·8	89·2
Natural	28·0	72·0

Table III. Summary of impacts of dams on annual maximum discharges characteristics in Québec

Regime	Timing		Magnitude		10-year recurrence frequency	Coefficient of skewness	
	Average	Interannual variability	Average	Interannual variability		Value	Sign
Inversed	Change	Change	Change	Change	Change	Change	Change
Homogenization	Weak change	Weak change	Change	Weak change	Change	Weak change	Change
Natural type	No change	No change	No change	No change	Weak change	No change	Weak change

changes are also observed in the homogenization flow regime, but they are not marked as in the inversed flow regime. Finally, in the artificialized natural flow regime, the impacts of dams only entrain a slight increase in the frequencies of the annual maximum flows in December and January and the disappearance of flows with more than a 10-year recurrence for some watersheds smaller than 1000 km^2.

In Québec, the inversed flow regime is associated with reservoir dams (Assani *et al*., 2004). These dams are generally intended to supply water during the winter period to the hydroelectric generating stations located downstream and to prevent spring floods when the snow is melting. Thus, in the spring (April and May), snowmelt water is stored to fill the reservoirs. But when the size of the watersheds increases, the quantity of water stored diminishes in spring. The river then changes to the 'homogenization' flow regime. This is basically different from the inversed flow regime by the absence of monthly minimum discharges in the spring when the snow is melting. This absence can thus mitigate the impacts of dams on the aquatic and riparian ecosystems. In Québec, this type of regime often corresponds to reservoir dams equipped with hydroelectric generating stations to produce hydroelectric power all year round. In winter, the water is turbinated to generate electric power. In spring, part of the melt water is stored and another portion is used to generate power. These dams are generally built on large watercourses that have relatively heavy flows. This does not require a major storage of melt water in the spring, as in the case of reservoir dams. The homogenization flow regime is the regime most commonly observed in continental or mountainous temperate climates, owing to the increase in winter flows to generate hydroelectric power (Reily and Johnson, 1982; Maheshwari *et al*., 1995; Andrews and Pizzi, 2000; Merrit and Cooper, 2000; Leconte *et al*., 2001). The water stored in spring can also serve for irrigation or for air conditioning in the summer. As for the natural flow regime, it is most often associated with run-of-river dams, which are almost all equipped with hydroelectric generating stations to produce power. Most of these dams do not have reservoirs. In the winter, they are fed directly by the reservoir dams, generally located upstream. In the spring, when water is stored in the reservoir dams, they are fed directly by snowmelt water. During this period, power demand declines due to the rise in temperature. However, some dams in this category are also used to control floods. They can, therefore, store enough water in the spring without causing an inversion of the natural flow cycle.

Owing to the dispersion and the ad hoc nature of the studies of dam impacts on flood levels in particular and on hydrologic regimes in general, there is no typology of dam impacts on annual maximum flows in the scientific literature. However, many studies have shown that dams generally cause a decrease in the magnitude of the annual maximum discharges (e.g. Maheshwari *et al*., 1995; Richter *et al*., 1998; Abam, 1999; Assani *et al*., 1999; Erskine *et al*., 1999; Loizeau and Dominik, 2000). This decrease does not affect all flood levels to the same degree. In some cases it is the high flood levels that are most affected (Assani *et al*., 1999; Loizeau and Dominik, 2000), whereas in other cases they are virtually unchanged (Vivian, 1994; Maheshwari *et al*., 1995). On the other hand, almost all of these studies have limited their analysis of the impact of the dams to the magnitude and frequency of the discharges. Therefore, the impacts of the dams on the other characteristics are not very well known, although Maheshwari *et al*. (1995) observed an increase in the values of the coefficients of variation of magnitude and the coefficients of skewness of the annual maximum flows downstream from certain dams built on the Murray River in Australia.

The alteration of the characteristics of annual maximum flows induced by dams also undoubtedly cause changes in the morphology, flora and fauna of Québec rivers. These changes are not yet quantified. Our next aim is to quantify these changes in order to propose a specific protocol for restoration of each type of regulated hydrologic regime.

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