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Article

Comparison of the Spatio-Temporal Variability of Annual Minimum Daily Extreme Flow Characteristics as a Function of Land Use and Dam Management Mode in Quebec, Canada

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Abstract: This study presents a comparison of the spatio-temporal variability of characteristics (magnitude, duration and timing) of annual minimum daily extreme flows (AMEF) as a function of land use and the mode of management of dams. Streamflow measured at stations not affected by dams at Joliette, along the L'Assomption River (agricultural watershed, 1340 km^2), and at Saint-Michel-des-Saints, on the Matawin River (forested watershed, 1390 km^2) on one hand, and downstream from the Rawdon dam (regulated natural-type management mode), on the Ouareau River (1260 km^2), which is the main tributary of the L'Assomption River, and from the Matawin dam (inverted-type management mode), on the Matawin River (4070 km^2), on the other hand, were compared over the period from 1930 to 2010. As far as the spatial variability of natural rivers is concerned, the magnitude and duration of AMEF are higher in the forested watershed than in the agricultural watershed. In regulated rivers, AMEF magnitude is higher downstream from the dam characterized by a natural-type management mode than downstream from the dam characterized by inversion-type management. However, downstream from the latter, AMEF occur much more frequently and very early in the year. As for temporal variability, the Lombard method did not reveal any influence of land use differences on the stationarity of series of AMEF characteristics. In contrast, differences in dam management mode result in occurrences of AMEF downstream from the inversion-type dam progressively earlier in the year. The duration and timing of AMEF are not correlated with the same climate variables, be it in natural rivers or downstream from dams.

Keywords: annual minimum daily extreme flows; land use; dam management mode; statistical analysis

1. Introduction

Minimum extreme flows are sensitive to environmental changes induced by climate variability and human activities (deforestation, reforestation, urbanization, agriculture, dams, *etc*.). However, the impacts of such environmental changes vary between climate regions and between watersheds within the same climate region (e.g., [1–7]). In the current climate-warming context, in the province of Quebec (Canada) for instance, a decrease in minimum streamflow is expected to result from increased evapotranspiration and lower springtime precipitation (lower infiltration) due to climate warming [8,9]. Human activity could, however, prevent such a decrease. For instance, in a climate-warming context, according to [8], deforestation would lead to a significant increase in minimum flows in summer in the Famine River watershed, a tributary of the Chaudière River. Using several general circulation models coupled with a hydrological model, [9] analyzed the impact of increased agricultural surface area, associated with increased temperature, on the evolution of summer minimum flows, among other things, in the Chaudière River watershed. Such predictions are often marred by relatively high uncertainty concerning the response of extreme hydrological events to climate warming (e.g., [10,11]). However, analysis of the spatial variability of minimum extreme flow characteristics during the growing season (May to October) revealed a decrease in magnitude of these flows in agricultural watersheds. The other characteristics (timing, frequency, variability) were not affected by agriculture [12]. Aside from deforestation and farming, the impacts of numerous dams and reservoirs in Quebec on spatial variability of extreme minimum flows have been analyzed [13]. These impacts depend on the type of dam management mode.

However, all these studies are restricted to the analysis of seasonal or monthly extreme minimum flows. Moreover, most of the studies focus on only one characteristic, namely magnitude, even though all characteristics (magnitude, frequency, duration, timing and variability) of extreme minimum flows affect fluvial ecosystem function (e.g., [14,15]). The analysis of all five characteristics is therefore important to better constrain the impacts of human activities and climate on the spatial and temporal variability of AMEF (annual minimum extreme flows) characteristics.

In light of the foregoing, the three objectives of this study are the following:

1. To compare the spatial and temporal variability of AMEF characteristics (magnitude, duration and timing) as a function of land use and dam management mode.

2. To compare the relationship between climate variables (temperature and precipitation) and AMEF characteristics as a function of land use and dam management mode.
3. To analyze the impacts of dam management mode on the relationship between AMEF characteristics and climate variables downstream from dams.

2. Methods

2.1. Study Area

To study the effect of land use and dam management mode, two watersheds were chosen based on the following three criteria:

- The geographic proximity of the two watersheds to ensure similar physiographic features.
- The availability of long-term streamflow and climate (temperature and precipitation) measurements. These measurements are required to determine the effect of climate warming, land use and dam management mode on the interannual variability of streamflow.
- The ability to delineate more closely the impacts of land use and dam management mode types on the interannual variability of annual minimum daily extreme flows.

The first watershed chosen based on these criteria is the L'Assomption River watershed, of which 30% is covered by farmland. The main crops are forage plants (40% of crop area), corn and soy (38% of crop area), and grain crops (19% of crop area). Two dams were built in this watershed on the main tributary of the L'Assomption River, the Ouareau River. The two dams are located, respectively, near the foot of the Canadian Shield (Rawdon dam) and near the confluence of the Ouareau and L'Assomption Rivers (Crabtree dam) (Figure 1). The effect of the Rawdon dam is analyzed in this study because continuous streamflow measurements going back to 1919 are available. In contrast, the Crabtree dam was built in 1967, so that the associated record of streamflow measurements is much shorter. The Rawdon dam management mode is of regulated natural-type flow, meaning that downstream from the dam, maximum flows occur in the spring, during snowmelt, and minimum flows occur in winter (Figure 2b), as in natural rivers (Figure 2a). Therefore, the dam does not change the natural annual hydrological cycle of flow [16,17]. Its impact on the hydrologic regime is restricted to a significant increase in flood flows [17]. The dam is roughly 15-m high and the total area of its reservoir is on the order of 190 ha, for a total volume of roughly 6,000,000 m^3 [17,18]. The second watershed studied is the Matawin River watershed, which is typical of forested watersheds in the Canadian Shield of Quebec. Because of unfavorable climate and soil conditions, no farming is carried out in this watershed. In 1930, a 25-m high dam was built on the Matawin River. The total surface area of the reservoir is roughly 9500 ha and its total volume is estimated at approximately 950,000,000 m^3. The dam management mode is of inversion-type, meaning that downstream from the dam, the annual hydrologic cycle of flows is completely inverted compared to that observed in pristine settings (Figure 2b): maximum flows are observed in winter while minimum flows occur in the spring, during snowmelt [18].

The L'Assomption River and its tributary, the Ouareau River, as well as the Matawin River, all originate in the Canadian Shield. Two thirds of the way down their respective courses, the L'Assomption and Ouareau flow through the St. Lawrence River Lowlands (Figure 1), the L'Assomption River flowing ultimately into the St. Lawrence. For its part, the Matawin River is entirely comprised within the

Canadian Shield, where it flows into the Saint-Maurice River. All three rivers show similar physiographic features due to the fact that they all flow through the Canadian Shield [17]. Differences in their physiographic features (elevation, slope, course length, drainage density, *etc.*) cannot affect the interannual variability of streamflow in the three rivers. This variability is affected by climate and/or human activity. From a hydrological standpoint, in times of low flow, both watersheds are exclusively fed by Canadian Shield aquifers, and as a result, AMEF characteristics of both watersheds can be readily compared, since the hydrogeological characteristics of these aquifers are similar.

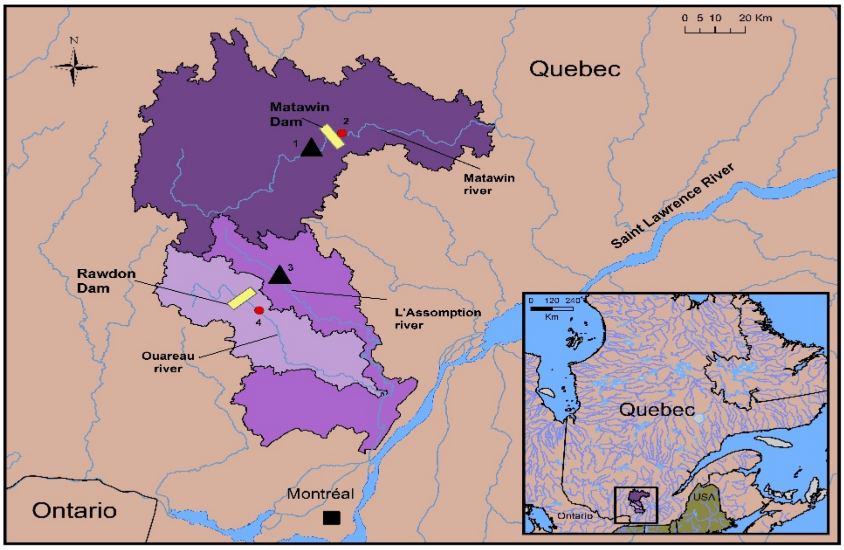
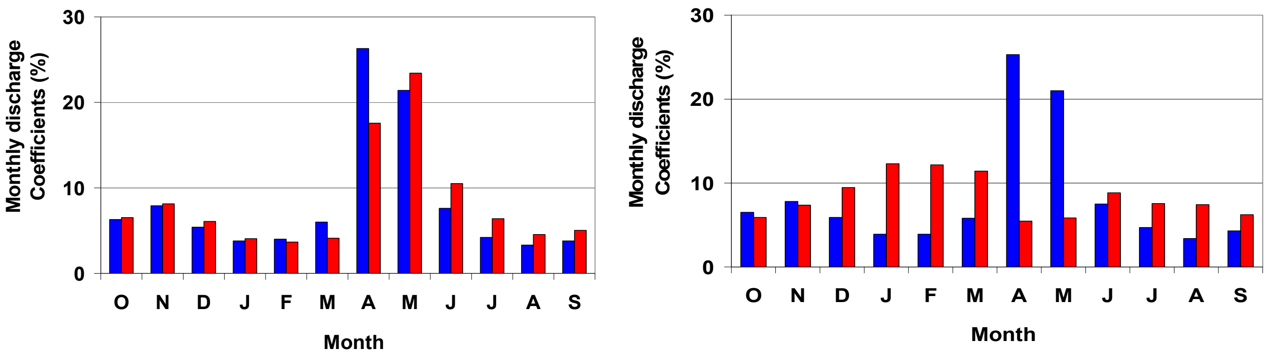


Figure 1. Location of the L'Assomption River and Matawin River watersheds. 1 = Saint-Michel des Saint station; 2 = Matawin downstream from dam station; 3 = Joliette station; and 4 = Oureau downstream from dam station.



(**a**) (**b**)

Figure 2. (**a**) Comparison of monthly discharge coefficients in natural rivers: L'Assomption River (blue bars) and Matawin River upstream from the Matawin dam (red bars); (**b**) comparison of monthly discharge coefficients in regulated rivers: Ouareau River downstream from the Rawdon dam (blue bars) and Matawin River downstream from the Matawin dam (red bars).

Streamflow in the L'Assomption River watershed has been measured continuously since 1925 at the Joliette station (watershed surface area at this station: 1340 km^2) and downstream from the Rawdon dam on the Ouareau River (watershed surface area: 1260 km^2). Streamflow at the Joliette station is not affected by dams on the Ouareau River, since the station is upstream from the confluence of the L'Assomption and Ouareau Rivers. Streamflow in the Matawin River watershed has been measured continuously since 1930 at the Saint-Michel-des-Saints station (watershed surface area: 1390 km^2) located upstream from the Matawin dam and at another station located immediately downstream from this dam (watershed surface area: 4070 km^2). Streamflow measurements at the Saint-Michel-des-Saints station are not affected by the presence of the dam [18]. Climate data are measured at the Joliette station in the L'Assomption River watershed and at the Saint-Michel-des-Saints station in the Matawin River watershed (Figure 1). These data are taken from the Environment Canada websites [19,20]. However, streamflow data measured downstream from the Matawin dam after 1994 were kindly provided by Hydro-Québec, which manages the dam.

2.2. Hydrological and Climate Series

Three characteristics of streamflow were used to assemble hydrological time series for each of the four stations and each year from 1930 to 2010:

- AMEF magnitude, which is the lowest daily flow value for each year from January to December.
- AMEF duration, which is defined as the number of days (expressed in days) during which the AMEF was measured in a single year. For both studied rivers the flow was perennial, being fed by groundwater during the low flow periods. Hence the AMEF corresponds to the lowest daily flow value recorded during a given year. Indeed, this minimum recorded value can remain constant for some time during the groundwater-fed low flow period, and in this study the AMEF duration was simply calculated as the number of days when this value is recorded, as opposed to choosing a fixed threshold.
- AMEF timing, which is the first date (expressed as a day of the year) when the lowest value of daily flow from January to December was measured.

Because it is not possible to define the variability of AMEF of annual series, this characteristic is not analyzed as part of this study.

Seven climate variable series were assembled as follows:

- a mean daily maximum temperature series (ATMAX) consisting of mean values of maximum daily temperatures measured each year from January to December;
- a mean daily minimum temperature series (ATMIN) consisting of mean values of minimum daily temperatures measured each year from January to December;
- a series of total precipitation (ATP) values fallen during each year from January to December;
- a series of total precipitation fallen exclusively as snow (ATSF) during each year from January to December. No data are available on the water content of snow;
- a series of total precipitation fallen exclusively as rain (ATRF) during each year from January to December;
- a mean daily maximum temperature series (STMAX) consisting of mean values of maximum daily temperatures measured during each summer (from July to September);

- a series of total precipitation fallen exclusively as rain (STRF) during each summer (from July to September).

2.3. Statistical Analysis of Hydroclimate Series

Statistical analysis was done according to the following steps:

- To analyze the impacts of land use and dam management mode on the spatial variability of AMEF characteristics and climate variables, mean values of these hydroclimate variables calculated over the period from 1930 to 2010 were compared using the paired t test. AMEF magnitude was converted to specific discharge to remove any effect of differences in watershed size. As far as AMEF timing is concerned, monthly frequencies for both watersheds were also compared.
- The Lombard method was used to analyze the impacts of land use and dam management mode on the temporal variability of AMEF characteristics. This method allows the detection of shifts (sharp or gradual) in mean and variance values of series and the determination of the precise dates of these shifts. The mathematical basis for this method was described by [21] as well as [22]. Its application to the analysis of hydroclimate data was documented, among others, by [23]. In applying this method, the null hypothesis (absence of shift in mean or variance) is rejected at the 5% level when the Sn value of the Lombard test derived for observed hydroclimate series is larger than the (theoretical) critical value of 0.0403. This method was applied after removing any autocorrelation present in the analyzed series using the pre-whitening procedure [24] and to series of standardized values.
- The last step of this statistical analysis consisted in correlating the seven climate variables to the three AMEF characteristics. To avoid any effect of size on coefficient of correlation values, this method was applied to standardized values of the hydroclimate variables.

3. Results

3.1. Comparison of the Spatial Variability of Climate Variables and AMEF Characteristics

Mean values of climate variables measured in both watersheds are shown in Table 1, which shows that temperature and precipitation are higher in the L'Assomption River watershed (agricultural watershed) than in the Matawin River watershed (forested watershed). However, the amounts of snow and of summer rain in the two watersheds do not differ significantly. Mean values of AMEF characteristics are presented in Table 2. For natural settings, AMEF magnitude and duration are lower in the L'Assomption River watershed than in the Matawin River watershed, whereas no significant difference in AMEF timing is observed between the two watersheds. Indeed, in both watersheds, AMEF are frequent in August and September, towards the end of the summer season (Figure 3a). For regulated settings, AMEF magnitude is lower downstream from the Matawin dam (inversion management mode) than downstream from the Ouareau dam (natural management mode). However, AMEF occur much more frequently and earlier in the year downstream from the former than from the latter dam. Figure 3b reveals that AMEF occur frequently in October downstream from the Ouareau River dam, while they occur in April, during snowmelt, downstream from the Matawin River dam.

Table 1. Comparison of mean values of climate variables in the L'Assomption (agricultural) and Matawin (forested) watersheds using the paired t test.

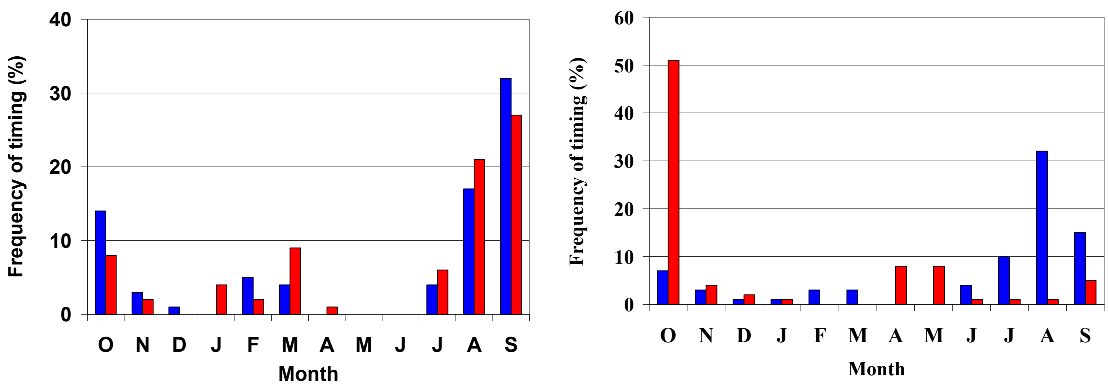
Climate Variables	L'Assomption River Watershed	Matawin River Watershed	p-value
ATMAX (°C)	10.5	8.8	**0.000**
ATMIN (°C)	0.43	−3.1	**0.000**
ATP (mm)	942	882.1	**0.007**
ATSF (cm)	210.9	229.9	0.116
ATRF (mm)	727.8	658.7	**0.001**
STMAX (°C)	23.8	21.4	**0.000**
STRF (mm)	263.7	281	0.067

Note: Statistically significant p-values at the 5% level are shown in bold.

Table 2. Comparison of mean values of daily annual minimum flow characteristics using the paired t test (1930–2010).

Flow Characteristics	Pristine Rivers			Regulated Rivers		
	L'Assomption	Matawin (Upstream from Dam)	p-values	Ouareau	Matawin (Downstream from Dam)	p-values
Magnitude (l/s/km^2)	2.14	3.33	**0.000**	2.39	0.06	**0.000**
Duration (Days)	1.2	3.3	**0.000**	1.54	75.1	**0.000**
Timing (Day of year)	243.5	255.8	0.393	260.9	77.5	**0.000**

Note: Statistically significant p-values at the 5% level are shown in bold.



(**a**) (**b**)

Figure 3. Comparison of the monthly frequency of AMEF from 1930 to 2010 (**a**) the L'Assomption River (blue bars) and Matawin River upstream from the Matawin dam (red bars); (**b**) the Rawdon dam on the Ouareau River (blue bars) and from the Matawin dam on the Matawin River (red bars).

3.2. Comparison of the Temporal Variability of Hydroclimate Variables

As far as climate variables are concerned, results from the Lombard method reveal significant changes in mean minimum temperatures as well as mean total precipitation and mean rainfall (Table 3) in the L'Assomption River watershed. A shift in mean values of minimum temperature took place in 1950, while shifts in total precipitation and total rainfall occurred, respectively, in 1956 and 1960. Mean values of all three climate variables increased significantly after these shifts. In contrast, no shift in mean values of climate variables is observed for the Matawin River watershed. As for AMEF characteristics, their temporal variability is presented in Figures 4–6. Use of the Lombard method revealed that, in natural settings, AMEF duration is the only characteristic that shows a shift in mean values (Tables 4 and 5), this break having occurred in 1950 in the L'Assomption River watershed and in 1978 in the Matawin River watershed. This shift is abrupt for the former watershed, but gradual for the latter, and in both watersheds, AMEF duration decreased significantly after the shifts. This change in AMEF duration is also observed downstream from the dams. However, the shifts in mean are not synchronous in the L'Assomption River watershed, having occurred later downstream from the Ouareau River dam than upstream. In the Matawin River watershed, the shifts in mean values of AMEF duration upstream and downstream from the dam are synchronous. A break in mean values of AMEF timing is also observed in 1975 (Table 5) downstream from the Matawin River dam, after which AMEF tend to occur earlier in the year.

Table 3. Comparison of the stationarity of climate variables in the two watersheds using the Lombard method (1930–2010)

Climate Variables	L'Assomption River Watershed			Matawin River Watershed		
	Sn	T1	T2	Sn	T1	T2
ATMAX	0.0324	–	–	0.0275	–	–
ATMIN	0.1566	1949	1950	0.0106	–	–
ATP	0.1117	1955	1956	0.0285	–	–
ATSNF	0.0156	–	–	0.0145	–	–
ATRNF	0.1209	1959	1960	0.0285	–	–
STMAX	0.0214	–	–	0.0338	–	–
SRNF	0.0135	–	–	0.0195	–	–

Notes: Sn = Lombard test statistic. Statistically significant Sn values at the 5% levels are shown in bold. T1 and T2 = dates of start and end, respectively, of shifts in mean.

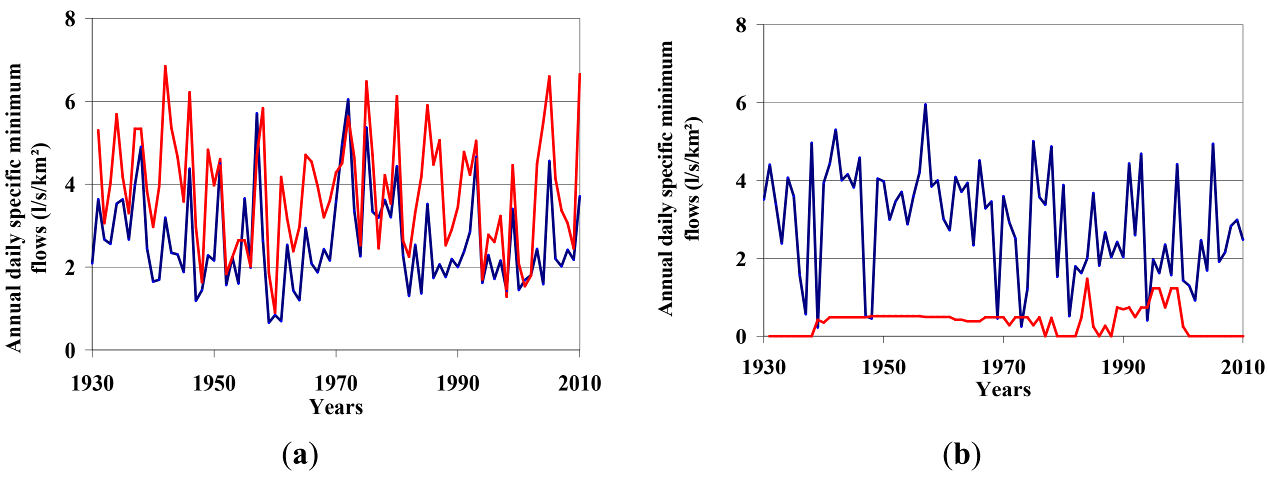
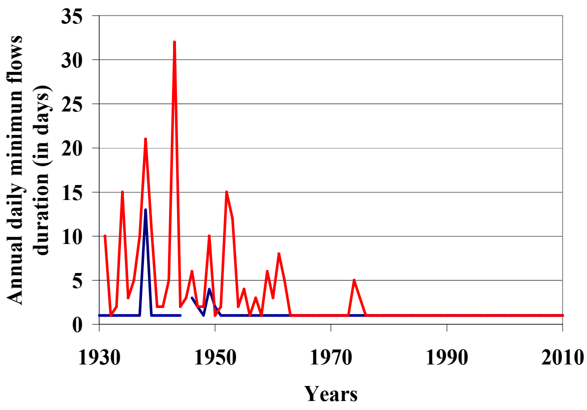
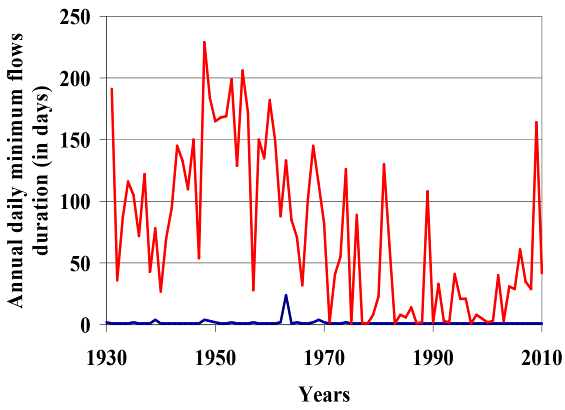


Figure 4. Comparison of the temporal variability of AMEF **magnitude** from 1930 to 2010 (**a**) the L'Assomption River (blue curve) and Matawin River upstream from the Matawin dam (red curve); (**b**) (specific discharge) in the Ouareau River downstream from the Rawdon dam (blue curve) and in the Matawin River downstream from the Matawin dam (red curve).

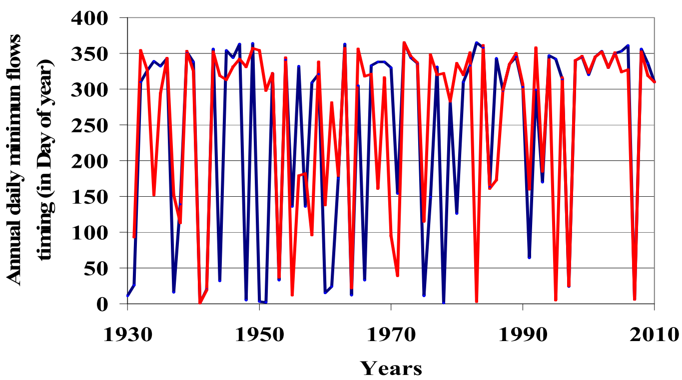


(**a**)

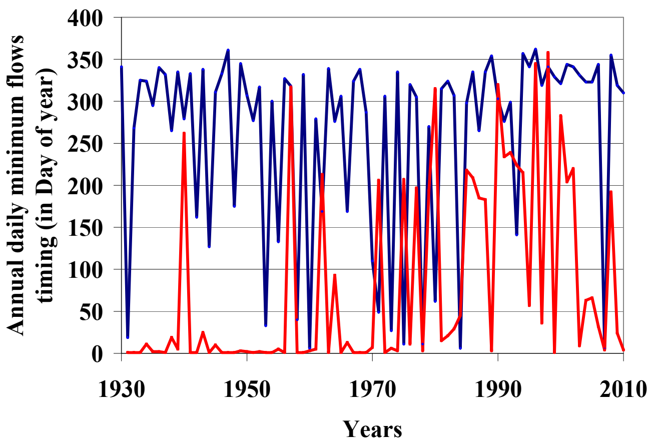


(**b**)

Figure 5. Comparison of the temporal variability of AMEF **duration** from the Matawin dam (red curve) from 1930 to 2010 (**a**) the L'Assomption River (blue curve) and Matawin River upstream; (**b**) the Ouareau River downstream from the Rawdon dam (blue curve) and in the Matawin River downstream.



(**a**)



(**b**)

Figure 6. Comparison of the temporal variability of AMEF **timing** from the Matawin dam (red curve) from 1930 to 2010 (**a**) the L'Assomption River (blue curve) and Matawin River upstream; (**b**) the Ouareau River downstream from the Rawdon dam (blue curve) and in the Matawin River downstream.

Table 4. Comparison of the stationarity of annual daily minimum flows in natural rivers using the Lombard method (1930–2010).

Flow Characteristics	L'Assomption River			Matawin River (Upstream from Dam)		
	Sn	T1	T2	Sn	T1	T2
Magnitude	0.0090	–	–	0.0109	–	–
Timing	0.0344	–	–	0.0092	–	–
Duration	**0.0680**	1949	1950	**0.3817**	1961	1978

Notes: Sn = Lombard test statistic. Statistically significant Sn values at the 5% levels are shown in bold. T1 and T2 = dates of start and end, respectively, of shifts in mean.

Table 5. Comparison of the stationarity of annual daily minimum flows in regulated settings using the Lombard method (1930–2010).

Flow Characteristics	Ouareau River			Matawin River (Downstream from Dam)		
	Sn	T1	T2	Sn	T1	T2
Magnitude	0.0046	–	–	0.0065	–	–
Timing	0.0327	–	–	**0.2770**	1974	1975
Duration	**0.0712**	1974	1975	**0.3223**	1961	1978

Notes: Sn = Lombard test statistic. Statistically significant Sn values at the 5% levels are shown in bold. T1 and T2 = dates of start and end, respectively, of shift in mean.

3.3. Analysis of the Link between AMEF Characteristics and Climate Variables

Coefficient of correlation values calculated between the three AMEF characteristics and the seven climate variables are shown in Tables 6 and 7. In natural rivers, AMEF magnitude is significantly correlated with total precipitation and rainfall in both watersheds, this correlation being positive. AMEF timing is positively correlated with maximum temperatures in the L'Assomption River watershed, while in the Matawin River watershed, it is negatively correlated with total precipitation as well as with annual and summer rainfall, but positively correlated with maximum summer temperature. Finally, AMEF duration is positively correlated with summer rainfall in the L'Assomption River watershed only.

Table 6. Coefficients of correlation between characteristics of annual daily minimum flows and climate variables in natural settings (1930–2008).

Climate Variables	L'Assomption River			Matawin River (Upstream from Dam)		
	Magnitude	Timing	Duration	Magnitude	Timing	Duration
ATMax	−0.0304	0.2697 *	0.0578	0.0000	0.1109	−0.0276
ATMin	−0.1067	0.0222	−0.1047	0.0506	0.1689	−0.0761
ATP	0.5040 *	−0.0897	−0.0683	0.3502 *	−0.3759 *	−0.0387
ATSNF	0.2481 *	−0.1482	0.0967	−0.2232	0.0981	−0.0375
ATRNF	0.4069 *	−0.0662	−0.1252	0.3292 *	−0.3397 *	−0.1277
STMAX	−0.0059	0.1500	0.0523	0.0000	0.3617 *	0.0085
SRNF	0.4142 *	0.1583	0.2855 *	0.0000	−0.3516 *	−0.0153

Note: * = statistically significant coefficients of correlation at the 5% level.

Table 7. Coefficients of correlation between characteristics of annual daily minimum flows and climate variables in regulated rivers (1930–2008).

Climate Variables	Ouareau River			Matawin River (Downstream from Dam)		
	Magnitude	Timing	Duration	Magnitude	Timing	Duration
ATMax	−0.0584	0.2697 *	−0.0968	−0.0072	−0.0139	−0.0616
ATMin	−0.0098	0.0222	−0.0177	0.1477	−0.0970	−0.0180
ATP	0.2249	−0.0897	−0.1611	0.1537	0.0015	−0.1005
ATSNF	0.2678 *	−0.1482	0.0795	−0.1179	−0.1092	−0.0065
ATRNF	0.1578	−0.0662	−0.0631	0.1216	0.2103	−0.3314
STMAX	−0.1360	0.1500	−0.0467	−0.1006	0.1192	−0.0667
SRNF	0.1933	0.1583	0.1070	0.0087	−0.0342	−0.1971

Note: * = statistically significant coefficients of correlation at the 5% level.

Downstream from the Ouareau dam, the magnitude and timing of AMEF are positively correlated, respectively, with the amount of snow (ATSNF) and maximum temperatures (ATMAX). Duration is not significantly correlated with any climate variable. In contrast, downstream from the Matawin River dam, the first two characteristics are not significantly correlated with any climate variable, while duration is negatively correlated with the amount of rain (ATRNF).

4. Discussion and Conclusion

The impacts of land use and dam management modes on the spatial and temporal variability of AMEF characteristics (magnitude, duration and timing) as a function of climate variables were constrained as part of this study. To do so, two contiguous watersheds with similar physiographic and hydrogeological characteristics were selected, the L'Assomption River and Matawin River watersheds. The former is an agricultural watershed comprising a dam characterized by a natural-type management mode (maximum flows in the spring and minimum flows in winter), while the latter watershed is entirely forested and comprises a dam with an inversion-type management mode (maximum flows in winter and minimum flows in the spring).

Comparison of the mean values of AMEF timing revealed that these flows occur frequently in August and September in both watersheds. However, while their timing is synchronous, AMEF in the forested Matawin River watershed are higher and last longer than in the agricultural L'Assomption River watershed. Differences in precipitation cannot account for this difference between the two watersheds, because precipitation is higher in the latter (agricultural) watershed than in the former (forested). Like precipitation, annual and summer temperatures are higher in the agricultural watershed than in the forested watershed, and this difference in temperature may account for the higher magnitude and duration of AMEF in the forested watershed, as relatively higher temperature promotes evapotranspiration, leading to reduced AMEF magnitude and duration in the agricultural watershed. This factor was mentioned by [12] for other Quebec watersheds. According to these authors, the decrease in AMEF magnitude in agricultural watersheds does not result from reduced infiltration in these watersheds since peak flood flows in agricultural watersheds are not significantly different from those observed in forested watersheds. Such a decrease in the magnitude of minimum flows with a higher proportion of agricultural land in a watershed has been observed in many watersheds in the United States [6], among other places.

In contrast, in Great Britain, an increase in agricultural area tends to lower the magnitude of minimum flows [5].

The lack of a statistically significant correlation between temperature and flow characteristics may be explained by the fact that, unlike rainfall, temperature does not directly affect minimum flow characteristics; its influence being affected by evapotranspiration and/or runoff [25]. The study has highlighted the predominant influence of dam management mode on the spatial variability of AMEF characteristics in regulated rivers. Thus, downstream from the Matawin River dam, characterized by an inversion-type management mode, AMEF magnitude is much lower than downstream from the Ouareau River dam, characterized by a natural-type management mode. Furthermore, downstream from the former dam, AMEF last longer and occur earlier in the year than downstream from the latter. The inversion-type management mode is characterized by water storage in reservoirs in springtime during snowmelt, and water release in winter to supply hydroelectric power plants located downstream. Water storage in the spring produces long-lasting AMEF that frequently occur early (April) in the year. Thus, downstream from this type of dam, AMEF are not affected by evapotranspiration, but rather by large-scale water storage in reservoirs in the spring, during snowmelt.

As far as the temporal variability of AMEF characteristics is concerned, the only difference observed between the non-regulated rivers is the date and nature of the shift in mean values of AMEF duration. In the forested watershed, this shift occurred later and is gradual compared to the shift in mean observed in the agricultural watershed. In the latter watershed, this shift is synchronous with the break in minimum temperature. However, it was not possible to draw a causal link between the two variables. For regulated settings, little change is observed in the temporal variability of AMEF characteristics downstream from the two dams studied. The only significant change is a shift in mean AMEF timing downstream from the Matawin River dam, a shift that is not observed downstream from the other dam, nor in natural settings.

Analysis of correlation between the climate variables and the three AMEF characteristics revealed generally low coefficients of correlation, none of these coefficients exceeding 0.600, implying a weak linear relationship between AMEF characteristics and climate variables. Be that as it may, in both the agricultural and forested watersheds, AMEF magnitude is better correlated with precipitation (particularly as rain) than with temperature. This positive correlation is explained by the occurrence of AMEF during the warm summer season, when aquifers are exclusively fed by rainwater infiltration. As for the timing of AMEF, while it is similar in the two watersheds, this characteristic is not significantly correlated with the same climate variables in the two watersheds: in the agricultural watershed, it is positively correlated with maximum temperature, while in the forested watershed, it is positively correlated with maximum summer temperature, and negatively correlated with precipitation. It follows that precipitation and temperature seem to have opposite effects on AMEF timing. As for AMEF duration, it is positively correlated with summer rain in the agricultural watershed, this correlation being absent in the forested watershed. Finally, these correlations change downstream from the dams, the largest difference being observed downstream from the inversion-type Matawin River dam.

In conclusion, human activity affects AMEF characteristics to varying degrees. Agriculture reduces the magnitude and duration of AMEF compared to the forested watershed. In the case of dams, the extent of changes in AMEF characteristics depends on the mode of management, with greater changes observed downstream from inversion-type dams.

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Author Contributions

Jean-Michel Sylvain and Ali Assani conducted data analyses, participated in writing all sections of the manuscript and to the elaboration of figures. Raphaëlle Landry elaborated figures and contributed to statistical analyses and to writing of the methods section. Christophe Kinnard and Jean-François Quessy contributed to writing of the results and discussion sections, and reviewed the whole manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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