Chapter 10

Analysis of the Influence of the 2007–2008 La Niña Events, Land Use, and Dam Management Modes on the 2008 Spring Freshet Characteristics in Quebec, Canada

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Additional information is available at the end of the chapter

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Abstract

The most intense spring freshet observed since 1950 in many regions of southern Quebec took place in 2008. The goal of the chapter was to examine the influence of natural (La Niña) and human (land use and dam management) factors on the characteristics (magnitude, duration, timing, and flow variability) of this freshet. As far as natural factors are concerned, a positive correlation was found between La Niña events (both moderate and strong) and flood peaks in natural rivers. Despite its high intensity, however, the 2008 freshet was produced by a relatively moderate 2007–2008 La Niña event. The influence of land use, for its part, resulted in a higher flood peak but of relatively shorter duration in the agricultural watershed (L'Assomption River) than in the forested watershed (Matawin River) due to greater runoff in the former watershed. Finally, dam management mode affected the timing, duration, and flow variability of the freshet, as well as the number of days with zero flow. The greatest changes were observed downstream from the Matawin dam, which causes an inversion of the natural annual cycle of flow.

Keywords: spring freshet, La Niña, land use, dam management modes, Quebec

1. Introduction

Flood characteristics (magnitude, duration, timing, frequency, and flow variability) are affected by complex interactions between natural (climate and physiography) and human (land use and dams) factors. The most intense spring freshet observed in many regions of southern Quebec since 1950 occurred in 2008. This freshet led to numerous floods and substantial material damage (e.g. [1]). However, no study has looked at the climatic causes of this freshet or the influence of human activity on its characteristics. The main goal of this chapter was to fill this gap by constraining the respective influence of climatic and human factors.

As far as natural climatic factors are concerned, Assani et al. [2] showed that annual maximum daily flows were significantly correlated with the Atlantic Multi-decadal Oscillations (AMO), Artic Oscillation (AO), and Southern Oscillation Index (SOI) climate indices in Quebec. However, this study did not look at the specific impacts of El Niño and La Niña events on these flows. From a climate standpoint, the 2007–2008 season was characterized by a moderate La Niña event [3]. One of the goals of the present chapter is to test for a link between La Niña events and the magnitude of spring maximum daily flows in southern Quebec, which, to date, has not been analyzed. Because the 2008 spring freshet was associated with the occurrence of a moderate La Niña event, the underlying hypothesis is that the characteristics of spring freshets are independent of the intensity of La Niña events in southern Quebec.

As far as human factors are concerned, many dams have been built in Quebec since the nineteenth century to develop natural resources and fulfill the demand for both domestic and industrial hydroelectric power [4]. Many studies have looked at the impacts of these works on streamflow [5–20] and have shown that the extent of changes in streamflow downstream from these dams depends, among other things, on the dam management mode. Four management modes have been identified and described, each corresponding with a specific regulated hydrological regime downstream from dams. The first regulated hydrological regime is characterized by an increase in winter flows and a decrease in spring flows compared to flows in natural rivers. However, the annual cycle of flows downstream from dams is preserved: minimum flows occur in winter, despite their increase, and maximum flows occur in the spring, during snowmelt. This regime is called the "natural-type" regulated hydrological regime because of its similarity with hydrological regimes observed in pristine rivers. The second regulated hydrological regime is characterized by nearly constant flows throughout the year, with much lower month-to-month flow variability than that observed in natural rivers. This is called the "homogenization-type" regulated hydrological regime. The third regulated hydrological regime is characterized by a significant increase in winter flows and a commensurate decrease in spring flows, resulting in a complete inversion of the annual cycle of flow downstream from the dams: maximum flows occur in winter in the absence of runoff (with precipitation falling mainly as snow), and minimum flows occur in springtime during snowmelt. This regime is called the "inversion-type" regulated hydrological regime due to the inversion of the annual cycle of flows. The fourth and final regulated hydrological regime is observed downstream from dams diverting water from one watershed to another. This regime, called the "diversion-type" regulated hydrological regime, is characterized by a significant decrease in minimum flows, with maximum flows being conserved.

Several studies looking at the impacts of land use (deforestation and agriculture) on flows in rivers in Quebec have shown that land use exerts a greater influence on minimum flows (decrease) than on maximum flows (e.g., [21–23]) with little effect on flood flows. Recently, Assani et al. [13] showed that in the agricultural L'Assomption River watershed, flood peaks are higher than in the forested Matawin River watershed. These authors did not look at the impacts of land use on other flood characteristics, however. The second specific goal of the present chapter is to analyze the impacts of dams and land use on the magnitude, duration, timing, and flow variability of the 2008 spring freshet by comparing these flows in the two watersheds. The underlying hypothesis is that the characteristics of the 2008 spring freshet were strongly influenced by land use and dam management modes.

2. Methods

2.1. Choice of watersheds

The analysis of the impacts of La Niña was carried out in two steps. The first step involved comparing the 2008 spring freshet characteristics with those of the 2007 and 2009 spring freshets under natural conditions at the Joliette station (1340 km^2) in the L'Assomption River watershed and the Saint-Michel-des-Saints station (1390 km^2) in the Matawin River watershed, on the one hand, and downstream from the Rawdon dam (1240 km^2), on the Ouareau River in the L'Assomption River watershed, the Matawin dam (4070 km^2) on the Matawin River, and the Manouane dam (3686 km^2) on the Manouane River, on the other hand. The second step involved correlating the magnitude of spring maximum daily flows at stations located in natural rivers (Joliette and Saint-Michel-des-Saints stations) and downstream from the Ouareau and Matawin dams with quarterly seasonal mean values for summer (from July to September), fall (from October to December), and winter (from January to March) of SOI indices corresponding with strong and moderate La Niña events since 1950 [3]. The location of the five flow-gauging stations analyzed is shown in **Figure 1**.

To analyze the impacts of land use, the characteristics of the 2008 freshet in the agricultural L'Assomption River watershed (Joliette station) and forested Matawin River watershed (Saint-Michel-des-Saints station) were compared. These two rivers originate in the Canadian Shield, and the whole of the Matawin River watershed falls within this geological unit, whereas only two-thirds of the L'Assomption River watershed is within this unit, the last third being in the St. Lawrence River Lowlands, where all agricultural activity is concentrated. There is no agriculture in the Matawin River watershed [7]. Because both watersheds have similar physiographic and climatic characteristics (e.g. [14, 20]), a comparison of spring freshet characteristics as a function of land use between the two watersheds is straightforward. Moreover, the watershed surface areas at their respective flow-gauging stations (Joliette station on the L'Assomption River and Saint-Michel-des-Saints station on the Matawin River) are also similar.

To analyze the impacts of dam management modes, a comparison of the characteristics of the 2007, 2008, and 2009 spring freshets downstream from four dams was carried out. These four dams are the Rawdon (natural-type regulated hydrological regime characterized by maximum flows in springtime and minimum flows in winter), Matawin (inversion-type regulated hydrological regime characterized by maximum flows in winter and minimum flows in springtime during snowmelt), and Manouane (diversion-type regulated hydrological regime characterized by a significant decrease in spring flows and minimum flows in all seasons) dams. The Manouane

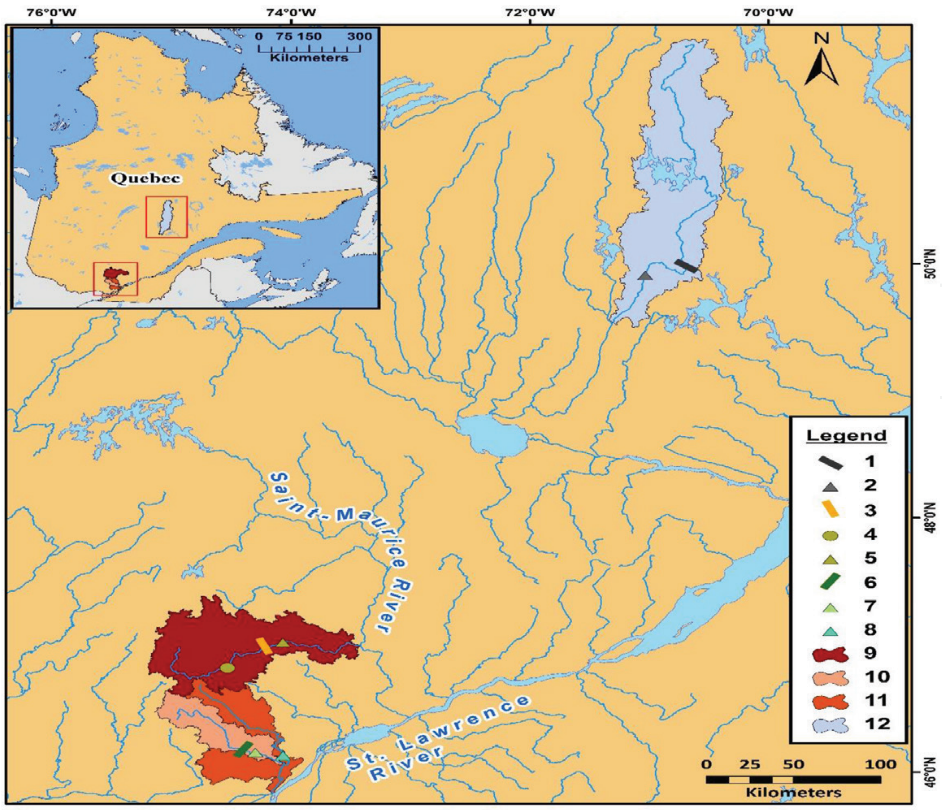

Figure 1. Location of dams and flow-gauging stations. 1 = Manouane dam, 2 = Manouane station, 3 = Matawin reservoir, 4 = Saint-Michel-Des-Saints station (upstream from Matawin reservoir), 5 = Matawin station (downstream from reservoir), 6 = Rawdon dam, 7 = Rawdon station (downstream from dam), 8 = Joliette station (L'Assomption river), 9 = Matawin watershed, 10 = Ouareau watershed, 11 = L'Assomption watershed, and 12 = Manouane watershed.

River flows entirely within the Canadian Shield and is the main tributary of the Péribonka River, which flows out into Lac Saint-Jean. This is no agricultural activity in the Manouane River watershed. The characteristics of these three dams are shown in **Table 1**, and their monthly flow coefficients are presented in **Figure 2**.

Dams	Type	ID	Height (m)	Watershed surface area (km²)	Year of construction	Total storage capacity (m³)	Reservoir surface area (ha)
Taureau (Matawin River)	Reservoir	X0004459	25	4070	1930	946,000,000	9505
Rawdon (Ouareau River)	Hydroelectric power plant	X0004205	14.6	1259	1913	5,976,417	194
Manouane (Manouane River)	Diversion dam	X2015243	9.5	3600	2003	70,000,000	–

ID, identification number.

Table 1. Dam characteristics.

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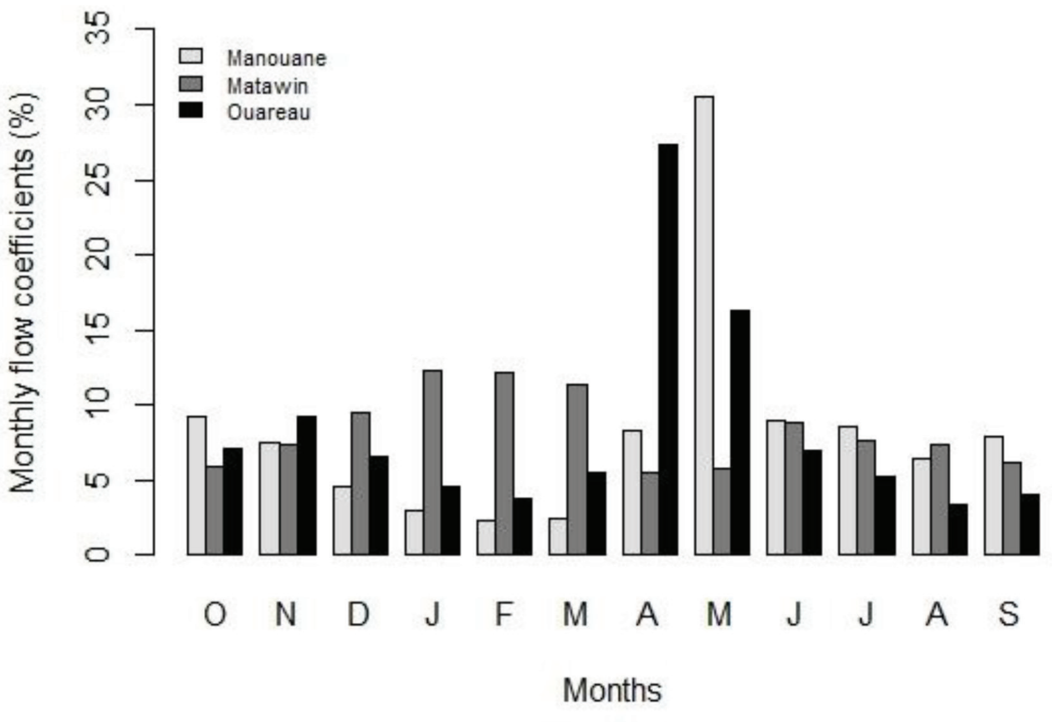

Figure 2. Monthly flow coefficients downstream from the three dams.

2.2. Sources of data and definition of spring freshet characteristics

Daily flow data downstream from the Rawdon and Manouane dams were taken from the website of the CEHQ [24]. As for flow data measured downstream from the Matawin dam, they were kindly provided by Hydro-Québec, the dam manager since 1963. SOI index data were taken from the National Oceanic and Atmospheric Administration (NOAA) website [25]. The characteristics of the 2007, 2008, and 2009 spring freshets used in the comparisons are as follows:

- Maximum flow magnitude (Q_{max}, spring maximum daily flow for a given year) during the spring freshet, expressed in $l/s/km^2$ in order to compare magnitude values between watersheds of different sizes.
- Timing (TQ_{max}) of these maximum flows, expressed in Julian days.
- Total duration in days (DQ_{max}) of the spring freshet, which is the total number of days that the freshet lasted.
- Spring freshet flow variability, measured using two indices [12]: the coefficient of variation (CV), expressed as a percentage, and the coefficient of immoderation (CI). The former index is a measure of the inter-day variability of flows during the freshet and the latter, which is the ratio of maximum (Qmax) and minimum (Qmin) flows during the freshet, is a measure of the maximum amplitude of the variability of extreme flows during the freshet.
- Total number of days with zero flow (NDZF) during the spring season (from April to June). These are the days during which flows become nil (total cessation of flow in channels).

For precipitation, data were taken from a Quebec scale map of the amount of snow (snowfall) measured during the winter of 2007–2008 (from November 2007 to March 2008) by the Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques (Mddelc) [26, 27].

3. Results

3.1. Analysis of the influence of La Niña events and land use on the characteristics of spring freshets in natural rivers

The characteristics of the 2007, 2008, and 2009 spring freshets are presented in **Table 2**, and the inter-day variability of freshet daily flows is shown in **Figures 3** (Joliette station) and **4** (Saint-Michel-des-Saints station). In both watersheds, the magnitude of the freshet (Q_{max}) was higher in 2008 (La Niña year) than in 2007 and 2009. However, during the 3 years, this magnitude is higher in the agricultural watershed (L'Assomption River) than in the forested watershed (Matawin River). As for freshet duration, the 2008 freshet lasted longer than the 2009 freshet but not as long as the 2007 freshet. The 2008 freshet occurred nearly synchronously in both watersheds. In the agricultural watershed, the 2008 spring freshet occurred almost on the same date as the 2007 freshet but later than in 2009 (**Figure 3**). In contrast, in the forested Matawin River watershed, the 2008 freshet occurred slightly earlier than in 2007 and 2009 (**Figure 4**). The two flow variability indices (CV and CI) reveal that the variability of flows during the 2008 freshet was stronger than in 2009 but not as high as in 2007. In both watersheds, values of both flow variability indices are similar. Finally, no days with zero flow were observed in either watersheds during the 3 years.

Table 3 compares values of the magnitude of spring maximum daily flows as a function of moderate and strong La Niña events since 1950. The highest magnitude value since 1950 was

	L'Assomption River (agricultural watershed)			Matawin River upstream from dam (forested watershed)		
	2007	2008	2009	2007	2008	2009
Q_{max} (l/s/km^2)	187.3	206.7	143.3	123.7	157.1	99.7
Duration (days)	31	24	15	43	31	24
Timing (JD)	115	114	96	117	115	119
CV (%)	65.1	48.4	46	69.4	51.4	32.3
CI	12.1	5.7	3.6	8.3	5.4	2.8
NZFD	0	0	0	0	0	0

JD, Julian day; timing of Q_{max} 2008, La Niña year; NZFD, number of zero flows days.

Table 2. Comparison of the characteristics of spring freshets under natural conditions.

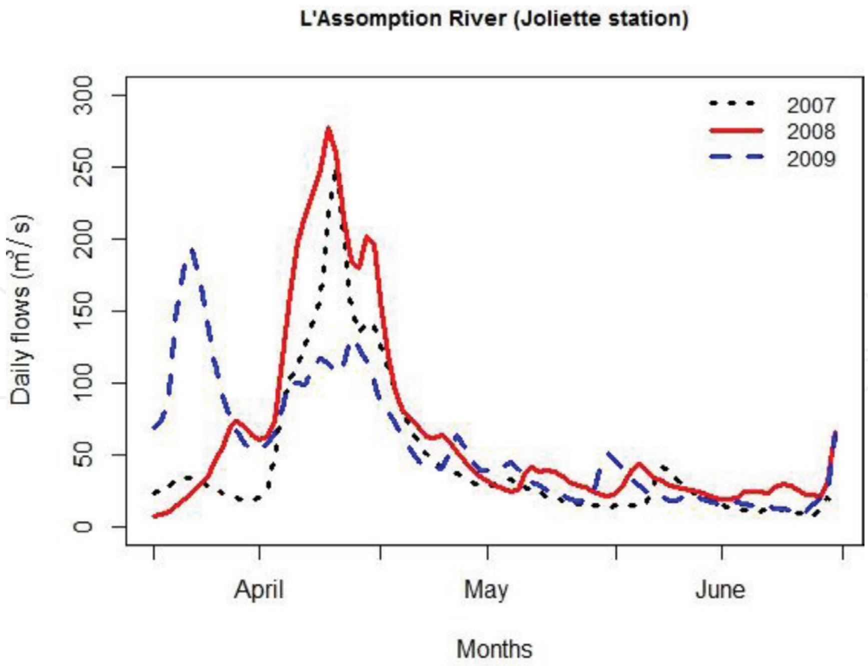

Figure 3. Comparison of the inter-day variability of spring daily flows in 2007 (blue or fair grey dotted curve), 2008 (red or grey full curve, La Niña year), and 2009 (black or dark grey broken or discontinuous curve) at the Joliette station on the L'Assomption River.

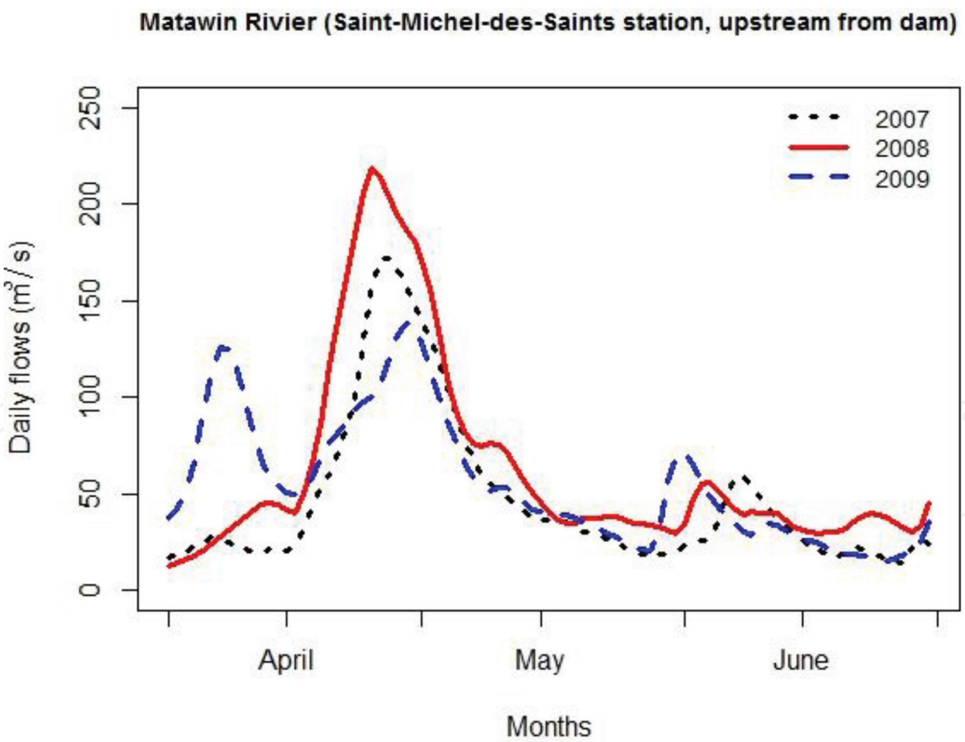

Figure 4. Comparison of the inter-day variability of spring daily flows in 2007 (blue or fair grey dotted curve), 2008 (red or grey full curve, La Niña year), and 2009 (black or dark grey broken or discontinuous curve) at the Saint-Michel-Des-Saints station upstream from Matawin dam (Matawin River).

Year of occurrence of La Niña events	Intensity of events*	Maximum flows	
		Joliette station (L'Assomption river)	Saint-Michel-Des-Saints station (Matawin River)
1955–1956	M	87	113
1970–1971	M	140	149
1973–1974	S	214	212
1975–1976	S	262	173
1988–1989	S	121	122
1998–1999	M	115	118
1999–2000	M	160	135
2007–2008	**M**	**277**	**218**
2010–2011	M	229	175

*Null [3].

M, moderate event; S, strong event.

The informations about 2007-2008 La Niña event are showed in bold.

Table 3. Comparison of maximum daily flows (m^3/s) for spring flood peaks in pristine rivers as a function of La Niña event intensity since 1950.

measured during the 2007–2008 event in both watersheds, despite the moderate intensity of this La Niña event. There is, however, a significant positive correlation between La Niña event intensities, expressed by values of the SOI indices, and the magnitude of spring freshets in both watersheds (**Table 4**). This correlation is only significant for winter SOI indices.

River stations	JAS	OND	JFM
Joliette station (L'Assomption River)	0.0014	0.3411	**0.6472**
Saint-Michel-Des-Saints (Matawin River)	−0.1885	0.3317	**0.7728**

JAS, from July to September; OND, from October to December; JFM, from January to March. Statistically significant coefficients of correlation at the 5% level are shown in bold.

Table 4. Coefficients of the correlation between spring flood peaks and mean quarterly seasonal indices for the nine moderate and strong La Niña events (SOI indices values) since 1950 in natural rivers.

3.2. Analysis of the influence of dam management modes on the characteristics of spring freshets

As in natural rivers, the magnitude of freshet flows is higher in 2008 than in 2007 and 2009 downstream from the three dams (**Table 5** and **Figures 5–7**). A comparison of the dams shows that magnitude is lower downstream from the Matawin dam, characterized by an inversion-type flow regime, than being downstream from the other two dams. The freshet lasted longer in 2008 than in 2007 and 2009 downstream from the Ouareau and Manouane dams, but the opposite is true downstream from the Matawin dam, where the duration of the 2008 spring

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	Ouareau (natural-type regime)			Matawin (inversion-type regime)			Manouane (diversion-type regime)		
	2007	2008	2009	2007	2008	2009	2007	2008	2009
Q_{max} (l/s/km^2)	235.4	259.4	183.1	29.2	60.4	53.2	50.6	108.3	81
Duration (days)	30	41	15	23	14	28	39	58	41
Timing (JD)	114	114	95	152	179	156	129	121	136
CV (%)	68.4	70	49.3	37.7	36.7	59.4	61.2	71.6	59.3
CI	12.2	10.7	4.4	119	246	216.6	12.2	19.4	14
NZFD	0	0	0	48	13	29	0	0	0

JD, Julian Days; Timing of Q_{max} 2008, La Niña year; NZFD, number of zero flows days.

Table 5. Comparison of the characteristics of spring freshets downstream from three dams.

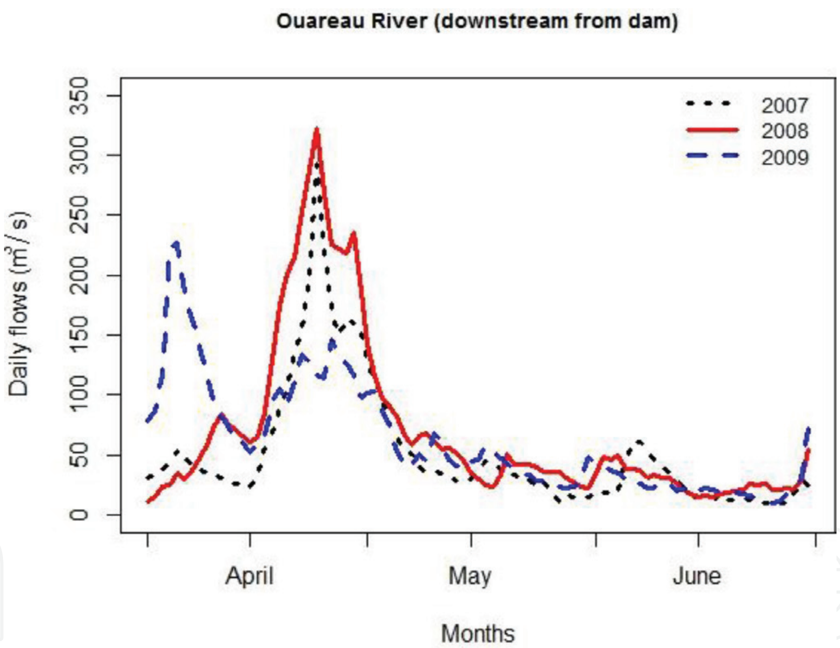

Figure 5. Comparison of the inter-day variability of spring daily flows in 2007 (blue or fair grey dotted curve), 2008 (red or dark grey full curve, La Niña year), and 2009 (black broken or discontinuous curve) downstream from Ouareau dam.

freshet was roughly half as long as those of the 2007 and 2009 freshets. Downstream from the Matawin dam, the freshet occurred later in the season in 2008 than in 2007 and 2009, whereas from the Manouane dam, it occurred early in the season. The inter-day variability of flows (CV) for the 2008 freshet was lower downstream from the Matawin dam than downstream from the other two dams. However, the maximum amplitude of extreme daily flow variations during the freshet, expressed as the coefficient of immoderation (CI), was stronger downstream from the Matawin dam than from the other two dams. Finally, despite the occurrence

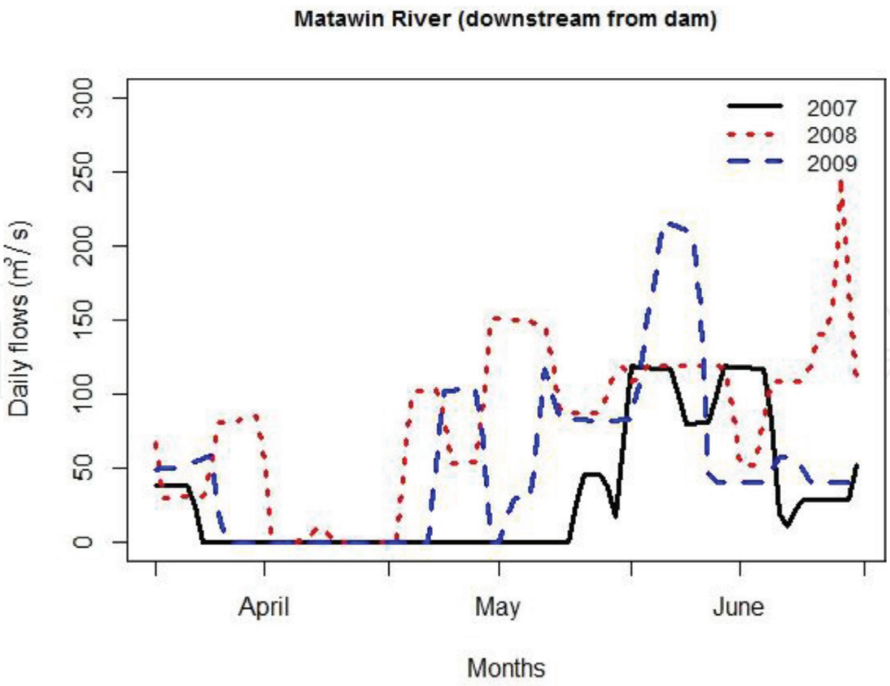

Figure 6. Comparison of the inter-day variability of spring daily flows in 2007 (blue or fair grey dotted curve), 2008 (red or dark grey full curve, La Niña year), and 2009 (black broken or discontinuous curve) downstream from Matawin dam.

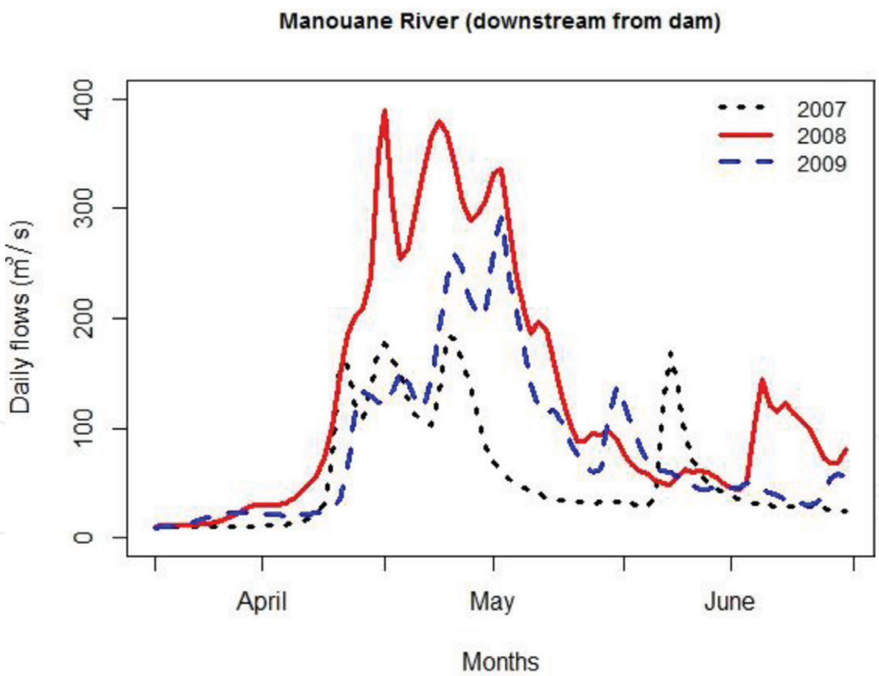

Figure 7. Comparison of the inter-day variability of spring daily flows in 2007 (blue or fair grey dotted curve), 2008 (red or dark grey full curve, La Niña year), and 2009 (black broken or discontinuous curve) downstream from Manoaune dam.

of the freshet, 13 days with zero flow were observed downstream from the Matawin dam, unlike the other two dams. However, this frequency of days with zero flow downstream from the Matawin dam was lower in 2008 than in 2007 and 2009. Finally, **Table 6** reveals the lack of any statistically significant correlation between SOI indices, which are associated with La

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Stations	JAS	OND	JFM
Downstream from Ouareau dam station	−0.1774	0.1466	0.5557
Downstream from Matawin dam station	−0.0614	0.3559	0.3762

JAS, from July to September; OND, from October to December; JFM, from January to March. No coefficient of correlation is statistically significant at the 10% level.

Table 6. Coefficients of correlations between spring flood peaks and mean quarterly seasonal indices for the nine moderate and strong La Niña events (SOI indices values) since 1950 downstream from the dams.

Niña events, and spring maximum daily flows downstream from the dams, contrary to what is observed for natural rivers, indicating that dams alter the link between climate factors and freshet flows.

4. Discussion

Very few studies in the literature have looked at the relationship between freshet characteristics and La Niña events. As far as the magnitude of freshets at the global scale is concerned, Ward et al. [27] observed that there are more areas in which annual floods intensify with La Niña and decline with El Niño than vice versa. This observation is consistent with results of the present study. Thus, a positive correlation was observed between the magnitude of spring freshets and values of winter quarterly (JFM) indices associated with moderate and strong La Niña events. This correlation, however, is only observed for natural rivers and is lacking downstream from dams. Despite this positive correlation in natural rivers, the 2008 spring freshet, which was the most intense since 1950 in most regions of southern Quebec, was caused by a moderate La Niña event. Two factors may account for the exceptionally high intensity of the 2008 spring freshet [26–28]:

- Abnormally high snowfalls during the winter of 2007–2008 (from November to March). In most regions of Quebec, the highest snowfalls since 1950 were recorded. In all regions of Quebec, the amount of snow that fell during that season was at least twice as large as the normal seasonal amount.
- Abundant rainfall from April 28 to May 2, which accelerated melting of this abundant snow, causing flooding and landslides in several regions of southern Quebec.

As far as land use is concerned, a comparison of the characteristics of the 2008 spring freshet between the agricultural L'Assomption River watershed and the wholly forested Matawin River watershed showed that spring freshets are of higher magnitude and longer duration in the former watershed than in the latter. These differences in hydrological behavior of the freshets are accounted for higher runoff in the agricultural watershed due to reduced plant cover and enhanced soil compaction (decreased porosity) caused by farm machinery [13]. However, very little difference was observed in the timing and amplitude of freshet flow variability between the two watersheds.

Downstream from the dams, the magnitude of the 2008 freshet was also higher than in 2007 and 2009, regardless of management mode. Therefore, this factor did not influence the magnitude of flows downstream from the dams compared to natural rivers during extreme hydrological events such as the 2008 spring freshet. Flows during this freshet were higher both in natural rivers and downstream from dams. In contrast, the other characteristics of the 2008 spring freshet were strongly affected by differences in dam management modes. Thus, the other characteristics of the 2008 freshet downstream from the Matawin dam, characterized by an inversion-type regulated regime, are significantly different from those observed downstream from the other two dams. The inversion-type management mode is characterized by storage of water in the reservoir during springtime (snowmelt and rainfall) and summer (rainfall) and its evacuation in winter. There are two reasons for this practice:

- To supply water to hydroelectric power plants built downstream from the reservoirs to produce electricity in winter. Thus, water stored in spring and summer is released in winter to supply power plants built downstream because precipitation falls mainly as snow (there is no water input from runoff). In the case of the Matawin dam, its reservoir is used to supply water in winter to hydroelectric power plants located downstream on the Saint-Maurice River. This substantial water storage accounts for the occurrence of days with zero flow downstream from this dam despite the fact that the freshet is actually taking place in natural rivers (see **Figure 6**).
- To control flood downstream from the reservoirs. To limit flooding caused by natural tributaries downstream from reservoirs, large amounts of water are stored in these reservoirs during strong spring freshets, such as the 2008 freshet. This flood control accounts for the relatively short and late nature of the 2008 freshet downstream from the Matawin dam. Releasing water at the start of the freshet in May would have enhanced the effects of flooding caused by natural tributaries downstream from the reservoir and on the Saint-Maurice River. To limit these effects, all the water from the freshet was first stored in the reservoir (occurrence of days with zero flow downstream from the reservoir), to be released downstream from the reservoir later in June (late occurrence of the freshet downstream from the reservoir) over a relatively short period (short duration of the freshet downstream from the reservoir).

This practice also resulted in a significant decrease in the magnitude of the freshet downstream from the Matawin dam, its late timing (in June rather than in May), its relatively short duration, and the strong amplitude of its flow variability due to the occurrence of days with zero flow resulting from the storage of all water derived from snowmelt and rainfall at the end of April and beginning of May 2008.

5. Conclusion

This chapter highlighted a significant positive correlation between the magnitude of spring flood peaks and the intensity (moderate and strong) of La Niña events in Quebec since 1950 in natural rivers. Thus, in Quebec, high La Niña intensities are associated with higher magnitudes of flood peaks. Despite this relationship, however, the magnitude of the 2008 spring freshet, the strongest to have occurred in Quebec since 1950, is associated with a moderate 2007–2008 La Niña event. Abnormally high snowfall in winter (from November 2007 to March 2008) and very high rainfall in the spring (from April 28 to May 2) account for the exceptionally high intensity of this freshet. Thus, both in natural rivers and downstream from dams, the magnitude of the 2008 spring freshet was the highest on record since 1950. This magnitude was much higher in the agricultural L'Assomption River watershed than in the forested Matawin River watershed. In addition, the freshet was of shorter duration in the former watershed than in the latter. This difference in land use, however, did not affect the other characteristics of the 2008 freshet (timing of flood peak, variability of flows). Downstream from the dams, differences in management modes had a significant influence on the characteristics of this freshet. Thus, downstream from the Matawin dam, characterized by the storage of snowmelt- and rainfall-derived water in spring and summer and the release of this water the following winter for hydroelectric generation (inversion-type management mode), the 2008 spring freshet was characterized by a relatively short duration, a late occurrence of flood peaks, a high amplitude (variability) of extreme flows, and, above all, the occurrence of days with zero flow, contrary to what was observed downstream from the other two dams. The chapter shows that the same extreme hydroclimate event, namely the spring freshet, does not induce the same hydrological impacts downstream from different dams due to their different flow management modes. This must be considered when assessing reserved flows required for the restoration and conservation of the ecological integrity of fluvial ecosystems in Quebec.

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