Chapter 3

Analysis of the Impacts of Changes in Streamflow and of Restoration on the Morphological Evolution of the Matambin River Channel in the St. Lawrence Lowlands (Quebec, Canada)

Ali Assani, Lisanne Chauvette and
Stéphane Campeau

Additional information is available at the end of the chapter

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Abstract

Although many plots of land that were once farmed have been reforested in the St Lawrence Lowlands of Quebec since the 1950s, no study has yet looked at the morphological impacts of this land-use change. To address this, we analyzed the evolution of the Matambin River (99 km^2) channel width and sinuosity using diachronic analysis of air photographs taken between 1935 and 2008. Results of this analysis show a roughly 21% decrease in mean channel bankfull width from 1935 to 1964. This time interval was characterized by a low frequency of strong flood flows in the region and a roughly 32% increase in the forested land area, the reforestation having started in the 1950s. After 1964, a trend of increasing mean channel bankfull width is observed. This increase is associated with the increase in frequency of strong flood flows in the region and a decrease in the amount of suspended sediments produced by soil erosion following the increase in forest cover in the watershed. In contrast, channel sinuosity did not change much over the period from 1935 to 2008.

Keywords: reforestation, streamflow, air photographs, width, sinuosity, Matambin, Quebec

1. Introduction

Unlike fluvial processes, the temporal evolution channel morphology in Quebec remains poorly studied. A few recent studies have looked at the impacts of dams on this evolution [1–3], and have highlighted the influence of flow management mode and lithology on the morphological evolution of channels downstream from dams and reservoirs. In the

Canadian Shield, where rivers are characterized by nearly regular sequences of alternating sandy and boulder reaches, the morphological impacts of an inversion of the natural cycle of flows (maximum flows occurring in winter and minimum flows in springtime during snowmelt) result in a trend of decreasing channel bankfull width in boulder reaches. Changes observed in sandy reaches are characterized by the multiplication and growth of islets and banks [3]. In the St Lawrence Lowlands, which are mainly underlain by unconsolidated deposits, dams lead to an increase in mean bankfull width, but a decrease in channel sinuosity [2].

As for the impacts of agriculture, which is restricted to the St Lawrence Lowlands, on the morphological evolution of channels, it is well established that drainage work done in the 1950s and 1960s led to a linearization of channels due to the artificial cutoff of numerous meanders, this linearization leading to channel widening. However, after many decades of intensive farming that resulted in massive watershed deforestation, gradual reforestation of previously farmed plots has been observed since the 1950s. This phenomenon is also observed in many other developed countries as a result of declining farming populations (e.g., [4–6]). Few studies have yet looked at the impacts of this land-use change (reforestation) on the morphological evolution of channels (e.g., [4, 6–16]) compared to studies looking at its hydrological impacts [17]. These different studies have shown that in addition to vegetation-related factors (age and type of trees, surface area covered, presence or absence of herbaceous strata, etc.), the impacts of reforestation also depend on the evolution of rivers flows and sediment grain size.

The impacts of reforestation on the morphological evolution of channels have not yet been studied in Quebec. Because of the growing increase in reforested surface area in many watersheds in recent decades, it is important to constrain the impacts of this phenomenon on the morphological evolution of channels. The goal of this study is to constrain the impacts of reforestation and hydroclimate variability on the morphology (width and sinuosity) of the Matambin River channel in Quebec.

2. Methodology

2.1. Description of the Matambin River watershed

The total surface area of the Matambin River watershed is 99 km^2. The river originates in the Canadian Shield and flows out into Lake Maskinongé, which is an outgrowth of the Maskinongé River, a tributary of the St Lawrence River. The Matambin River flows in large part through the St Lawrence Lowlands, which are characterized by a very low slope. It is relatively small watershed, its sinuous course, and the presence of farmlands (no major urban area or dam) are the main reasons for selecting this river. In addition, air photographs dating back to 1935 are available, allowing a diachronic analysis of changes in forest cover and channel morphology (**Figures 1** and **2**).

Elevation in the Matambin River watershed ranges from 135 to 500 m, the elevation of more than 80% of the watershed being less than 200 m within the St Lawrence Lowlands. The

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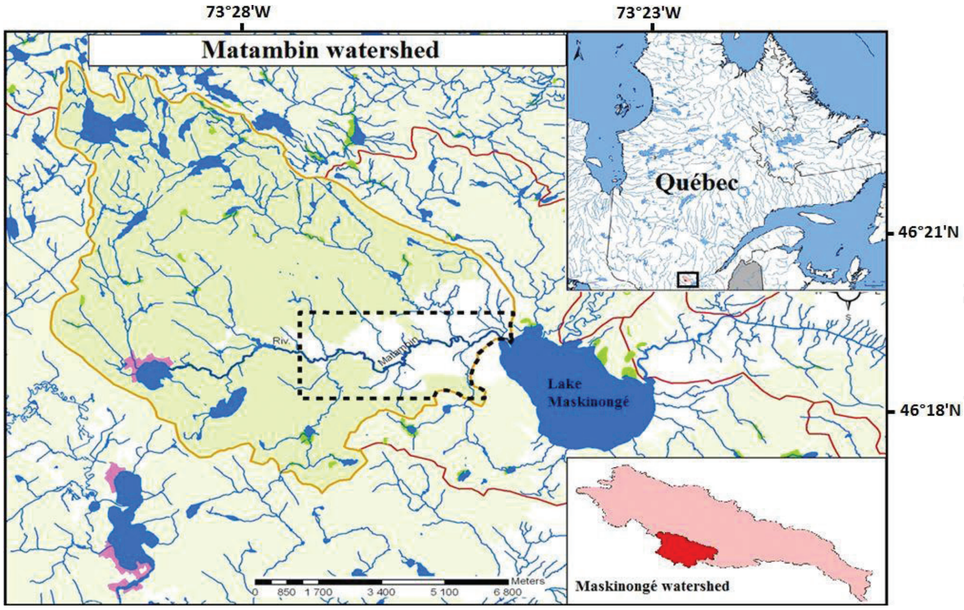

Figure 1. Location of the Matambin River watershed.

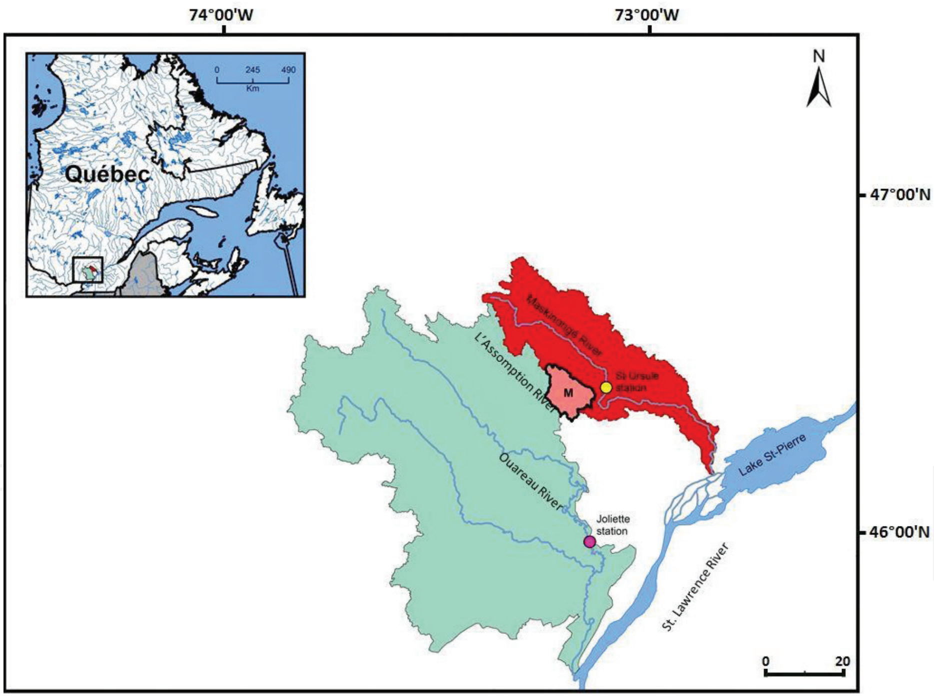

Figure 2. Location of the two water-gauging stations. M = Matambin River watershed.

Matambin River flows through undifferentiated glacial and fluvio-glacial alluviums, then downstream through lacustrine-marine deposits, and finally through marine and deltaic alluviums and undifferentiated alluviums. Thus, the river flows through deposits mainly consisting of fine clayey, silty, and sandy sediments.

From a hydrographic standpoint, the Matambin River watershed comprises numerous lakes, including five major ones, with surface areas ranging from 0.23 (Lac Migué) to 1.21 km^2 (Lac Blanc). Other lakes include Lac Quesnel (0.37 km^2), Lac Corbeau (0.48 km^2), and finally, Lac Matambin (0.60 km^2), located at the head of the Matambin River. All these lakes are within the Canadian Shield, upstream from the agricultural zone studied. The river is also fed by very small streams within the Canadian Shield. The study area is characterized by a humid continental type climate with warm summers (particularly in July) and very cold winters. Due to topographic variations within the watershed, precipitations range from 800 to 1359 mm in the Maskinongé River watershed.

Although it is located within the St Lawrence Lowlands, and as a result of reforestation, roughly 80% of the Matambin River watershed surface area is covered by forests, primarily mixed and deciduous in nature. There is very little logging in the area. According to an overview of the Matambin River watershed [18], no hectare of forest was logged from 2000 to 2005. No logging is planned in the near future. In the agricultural zone, 64% of plant production comprises perennial crops (473 ha of hay) and 36% are annual crops, including 103 ha of cereals, 68 ha of corn, 11 ha of horticultural crops, and 2 ha of berries.

2.2. Sources of hydrological and photographic data

In the absence of flow gauging station on the Matambin River, the closest station (station 052601) is located on the Maskinongé River, at the Canadian National (CN) railway bridge, near the town of Sainte-Ursule (1030 km^2), where flows have been measured daily since 1925. The station is located 20 km from the confluence of the Matambin and Maskinongé Rivers. Because no flow data for this station are available for the period from 1973 to 1978, flow data measured at the Joliette station in the L'Assomption River watershed, to the southeast of the Matambin River watershed, were also analyzed. In Joliette, the L'Assomption River watershed has a surface area of 1390 km^2, which is similar to that of the Maskinongé River watershed at the Sainte-Ursule station. Moreover, both rivers originate in the Canadian Shield and flow through the St Lawrence Lowlands before flowing out into the St Lawrence River. Consequently, their watersheds have similar climatic and physiographic characteristics, as shown by coefficients of correlation derived between flows in the two rivers (**Table 1**). In Joliette, flows have been measured since 1922, 3 years prior to the start of measurements on the Maskinongé River. Historical daily and monthly flow data for the two rivers (Maskinongé and L'Assomption) were provided by the Centre d'Expertise Hydrique du Québec (http://www.cehq.gouv.qc.ca/, viewed 2013-05-09).

Flows	Winter	Spring	Summer	Fall
Daily maximum flows	0.8233	0.5815	0.8327	0.9191
Mean daily flows	0.8012	0.7477	0.8483	0.9616

Note: All coefficients of correlation are statistically significant at the 1% level.

Table 1. Coefficients of correlation calculated between flows measured at the Joliette (L'Assomption River) and Sainte-Ursule (Maskinongé River) stations during the period from 1930 to 2010.

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Air photographs were obtained for several decades from 1930 to 2008. However, for this study, air photos taken in the 1940s were excluded because they were taken during a wartime period. Photos from the 1950s were also excluded because of their inadequate scale (errors on the outline of banks would have been too large). Results for photos taken in the 1980s are not presented because they are not significantly different (no significant morphological change) from those for the following decade. Although we attempted to select air photographs taken at similar time and/or under similar hydrological conditions, it was sometimes difficult to do so given the photos available. However, given that the outlines of banks were constrained at bankfull flow level, this is not an issue if photos were not taken when flows were above bankfull flows. **Table 2** shows some of the characteristics of selected air photographs. Because of the low coverage (two photos covering only the lower course), photographs taken in 1975 were only used for assessing land use in the agricultural zone.

No data exist on soil erosion in the watershed. As for measurements of suspended solids carried by the Matambin River and other Quebec rivers, they are only available for the period from 2013 to 2015, and were taken by the Quebec Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques (http://www.mddelcc.gouv.qc.ca/eau/Atlas_interactif/stations/stations_rivieres.asp, viewed 2017-02-09).

2.3. Data analysis

2.3.1. Analysis of hydrologic data

As part of this study is aimed at explaining the potential influence of streamflow on the morphological evolution of the Matambin River channel, two types of seasonal flow series were analyzed: a series of seasonal maximum daily flows and a series of seasonal mean daily flows. The first series comprises the highest daily flows measured each season and each year. The second series comprises the mean values of daily flows in each season and each year. Years were divided in seasons following an approach used by many authors in Quebec [19–21] for ease of comparison of results. Thus, seasons were defined as: winter (January–March), spring (April–June), summer (July–September), and fall (October–December). This is the scheme that best reflects the natural hydrological cycle in Quebec, Canada.

Date taken	Series	Scale	Daily discharge (m^3/s)*
08 October 1935	A5259	1/15,000	8.5
02 September 1964	Q64545	1/15,840	2.38
30 June 1975	Q75330	1/15,000	-
23 July 1997	HMQ97138	1/15,000	4.83
12 June 2008	Q08001	1/15,000	17.54

*Discharge measured at the Sainte-Ursule station on the Maskinongé River. These flows are lower than bankfull flow. Photographs for 1964 were enlarged to 1:15,000.

Table 2. Characteristics of analyzed air photographs.

The two hydrologic series were analyzed to constrain the temporal variability of flow. Because the first air photographs available date back to the 1930s, the same year was taken as the beginning of the hydrologic analysis. It is worth recalling that many statistical tests and methods can be used to analyze the temporal variability of streamflow [22]. However, the two approaches widely used in hydrology are the Mann-Kendall test and the linear regression method. These two tests are not without drawbacks, however:

- They do not detect a gradual or abrupt change in mean or variance of hydrologic series analyzed.
- They do not constrain the precise timing of such changes.

The Lombard method [23] was used to overcome these two weaknesses. This is a general method for detecting a gradual or abrupt change in the mean value of a hydrological series, given that methods commonly used in hydrology (e.g., Petittt method) do not allow the detection of gradual and abrupt changes. From a statistical standpoint, the mathematical aspects of this method are described in Refs. [23, 24]. Applications of the Lombard method in hydrology and geomorphology are presented in many papers (e.g., [24–26]). It should be mentioned that it was possible to use the Lombard method in this study because the series analyzed did not show any autocorrelation.

Given a series of observations, noted $X_1, \ldots, X_n$, where X_i is the observation taken at time $T = i$. These observations are supposed to be independent. If μ_i refers to the theoretical mean of X_i, then a possible pattern for the mean is given by Lombard's smooth-change model where

$$\mu_i = \begin{cases} \theta_1 & \text{if } 1 \le i \le T_1 \\ \theta_1 + \dfrac{(i - T_1)(\theta_2 - \theta_1)}{T_2 - T_1} & \text{if } T_1 < i \le T_2 \\ \theta_2 & \text{if } T_2 < i \le n \end{cases} \tag{1}$$

In other words, the mean changes gradually from θ_1 to θ_2 between times T_1 and T_2. As a special case, one has the usual abrupt-change model when $T_2 = T_1 + 1$.

In order to test formally whether the mean in a series is stable or rather follows model (1), one can use the statistical procedure introduced by Lombard [23]. To this end, define R_i as the rank of X_i among $X_1, \ldots, X_n$. Introduce the Wilcoxon score function $\phi(u) = 2u - 1$ and define the rank score of X_i by

$$Z_i = \frac{1}{\sigma_\phi}\left\{\phi\left(\frac{R_i}{n+1}\right) - \overline{\phi}\right\}, \quad i \in \{1, \ldots, n\} \tag{2}$$

where

$$\phi = \frac{1}{n}\sum_{i=1}^{n} \phi\left(\frac{i}{n+1}\right) \quad \text{and} \quad \sigma_\phi^2 = \frac{1}{n}\sum_{i=1}^{n} \left\{\phi\frac{i}{n+1} - \overline{\phi}\right\}^2 \tag{3}$$

Lombard's test statistic is

$$S_n = \frac{1}{n^5}\sum_{T_1=1}^{n-1} \sum_{T_2=T_1+1}^{n} L_{T_1 T_2}^2 \tag{4}$$

where

$$L_{T_1, T_2} = \sum_{j=T_1+1}^{T_2} \sum_{i=1}^{j} Z_i \tag{5}$$

At the 95% confidence interval, one concludes that the mean of the series changes significantly according to a pattern of type (1) whenever $S_n > 0.0403$. This value corresponds to Test Lombard statistic value (see [23]) defining the significance level at 5% for the test. Note that the equation proposed by [23] to detect multiple abrupt changes in the mean of a statistical series was also applied. This formula confirmed results obtained using Eq. (1).

2.3.2. *Analysis of air photographs*

We have described the method used in detail in some of our previous work [1–3]. Diachronic analysis of aerial photographs taken at different times was used to obtain data on the evolution of forested surface and on morphology (**Table 2**). Aerial photograph analysis was done in three steps: georeferencing, orthorectification, and mosaicing. Before being georeferenced, photos were first scanned at a resolution of 600 dots per inch (DPI) and 8 bits (color depth). The resulting resolution is estimated at 0.6 m (for photos taken at 1:15,000). The root mean square error (RMSE) of the geometric rectification on photos captured at different times was <0.1 m after the scanned photos underwent a second-order polynomial transformation. The Geomatica (PCI Geomatics 2003) OrthoEngine package was used for georeferencing, which involved the use of 10 ground control points spatially distributed over the whole photo area. UTM coordinates were taken from a 1:15,000 topographic map (surveyed 1995) from the Base de données topographiques du Québec (Quebec Topographic Database). Photos were orthorectified after being georeferenced, which consisted in correcting for spatial distortion arising from the inclination of the camera and/or terrain relief. Camera orientation parameters, the various known reference points, and the digital elevation model (DEM) were used for this correction. Mosaics of the georeferenced and orthorectified photos were then assembled (one mosaic for each year photos were taken) to produce an orthophotograph covering the entire study area.

After aerial photograph processing, the ESRI ArcGIS software was used to digitize river banks (at bankfull level as defined by the vegetation edge). A three-dimensional digital stereoscope (forward overlapping aerial photo pairs), which allows three-dimensional viewing of the channel, was used to limit error on bank outline. Automated drawing of straight lines perpendicular to the channel using an ArcGIS extension developed at the Laboratoire Interdisciplinaire d'Application en Géomatique Environnementale (LIAGE) and integrated into ArcGIS was used to measure channel width. This step eliminates human error associated with drawing of perpendicular lines and thus in channel bankfull width measurements. Automated drawing of perpendicular lines at the same location between two points separated by the same distance on air photos taken at different times, which is difficult to do manually, is also possible using this software. After banks are delineated, the perpendicular lines are drawn by first finding the midpoint between the two banks in each cross-section, then joining all midpoints into a centerline, and finally drawing lines perpendicular to this centerline at all midpoints. All air photos taken at different times were processed in this way. More than 20 bankfull channel width measurements (depending on the total length of the analyzed reach) were taken with the software at a 100-m regular spacing. This interval was selected to reduce the spatial autocorrelation effect and make it possible to analyze long statistical series. Channel sides delineated from aerial photography were validated with ground observations. Fairly precise definition of channel side limits used to calculate the channel bankfull width was possible using this technique. The validity of bank delineation based on aerial photographs was tested using field measurements taken during several field visits. The fact that flows at the time the photographs were taken were less than bankfull made it possible to carry out diachronic analysis of the aerial photographs (see **Table 2**).

Air photo interpretation (width measurement from aerial photos) was done by two independent operators to determine the maximum error on bankfull width measurements associated with photo interpretation. The maximum difference in bankfull mean width at a given station between the values obtained by the two operators was <1 m, and this value is deemed to represent the maximum error on channel width measurements from photo interpretation at a given station. The same results were obtained from analysis of the temporal variability of channel width carried out by both the operators. The non-parametric Kruskal-Wallis and parametric analysis of variance (ANOVA) tests were used to compare bankfull width values measured at different times for each river.

The outlines of forested settings were traced from available digital land use maps using the ArcGIS software (version 9.2) to delineate agricultural settings and assess the evolution of agricultural and forested surface areas over time. Reforested area boundaries on photographs taken at different times were superimposed within the study framework.

3. Results

3.1. Temporal variability of flows

Values of the Lombard method S_n statistic are presented in **Table 3**. Only maximum daily flows in winter changed significantly for the two rivers. However, for the Maskinongé River, winter mean daily flows also increased significantly. This increase, which is abrupt for both rivers, occurred in the early 1970s. No significant change is observed for the other three seasons. However, it is important to note that, despite this lack of change in mean value of the magnitude of maximum flows, a higher frequency of high magnitude flows is observed for the L'Assomption River after 1970 (**Table 4**) for all four seasons, particularly in springtime. A comparison of the interannual variability of maximum daily flows for each of the four seasons for both rivers is presented in **Figures 3–6**.

3.2. Evolution of forest cover in the agricultural zone within the Matambin River watershed

In 2008, 81.56 km^2 of the 98.03 km^2 of the Matambin River watershed were forested or 83.2% of the watershed, the deforested area thus representing 16.47 km^2 or 16.8% of the watershed. Diachronic analysis of air photographs of forested areas revealed that, in the agricultural zone, the proportion of forests increased from 1935 to 2008, from 13.2% (1.27 km^2) in 1935 to 27.1% (2.12 km^2) in 2008. Hence, this proportion more than doubled over the years at the expense

Seasons	Maskinongé River			L'Assomption River		
Seasonal daily maximum flows						
	Sn	**T1**	**T2**	**Sn**	**T1**	**T2**
Winter	**0.0608**	1970	1971	**0.0827**	1971	1972
Spring	0.0119	–	–	0.0249	–	–
Summer	0.0302	–	–	0.0058	–	–
Fall	0.0400	–	–	0.0337	–	–
Seasonal mean daily flows						
Winter	0.0525	1970	1971	0.0024	–	–
Spring	0.0345	–	–	0.0014	–	–
Summer	0.0149	–	–	0.0339	–	–
Fall	0.0353	–	–	0.0330	–	–

Note: Lombard test results. Values of S_n (Lombard test statistics) >0.0403 that are statistically significant at the 5% level are shown in bold. T_1 and T_2 are the years of start and end, respectively, of the shift in a mean value.

Table 3. Analysis of the interannual variability of flows in the Maskinongé and L'Assomption Rivers during the period from 1930 to 2010.

Seasons	1935–1964	1965–1994
Winter (≥100 m^3/s)	2	4
Spring (≥250 m^3/s)	2	5
Summer (≥100 m^3/s)	0	2
Fall (≥150 m^3/s)	1	2

Table 4. Comparison of the frequency of strong seasonal maximum daily flows for the L'Assomption River at the Joliette station over the period from 1930 to 2010.

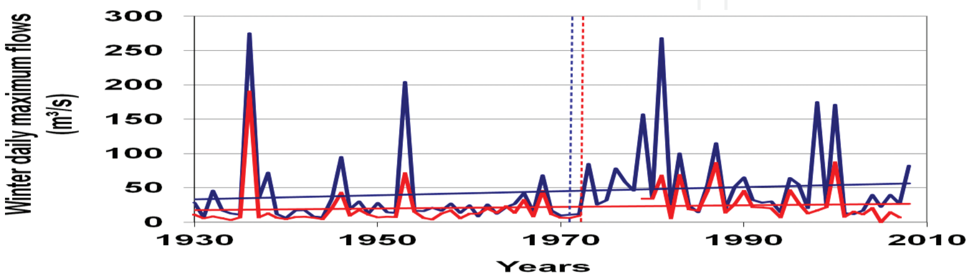

Figure 3. Variability of winter daily maximum flows at the Joliette station on the L'Assomption River (blue curve or dark grey) and Sainte-Ursule station on the Maskinongé River (red curve or fair grey) during the period from 1930 to 2010. Vertical dotted lines represent years of shifts in mean values of flows (blue curve or dark grey) and (red curve or fair grey).

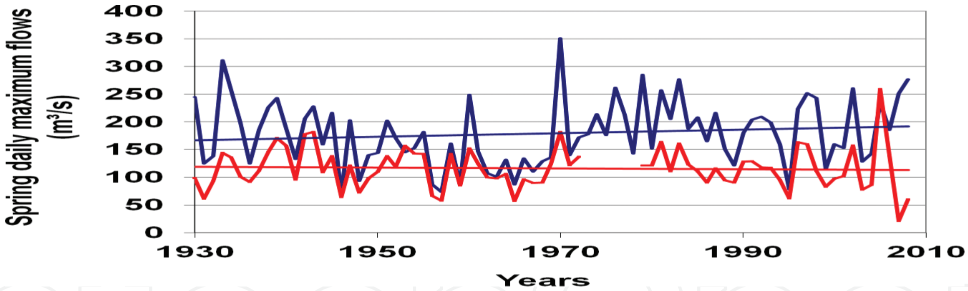

Figure 4. Variability of spring daily maximum flows at the Joliette station on the L'Assomption River (blue curve or dark grey) and Sainte-Ursule station on the Maskinongé River (red curve or fair grey) during the period from 1930 to 2010.

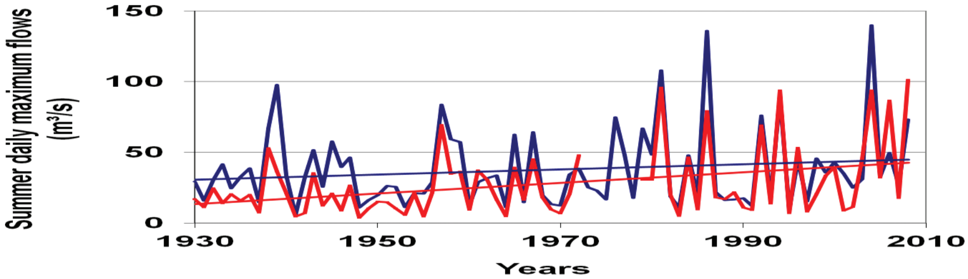

Figure 5. Variability of summer daily maximum flows at the Joliette station on the L'Assomption River (blue curve or dark grey) and Sainte-Ursule station on the Maskinongé River (red curve or fair grey) during the period from 1930 to 2010.

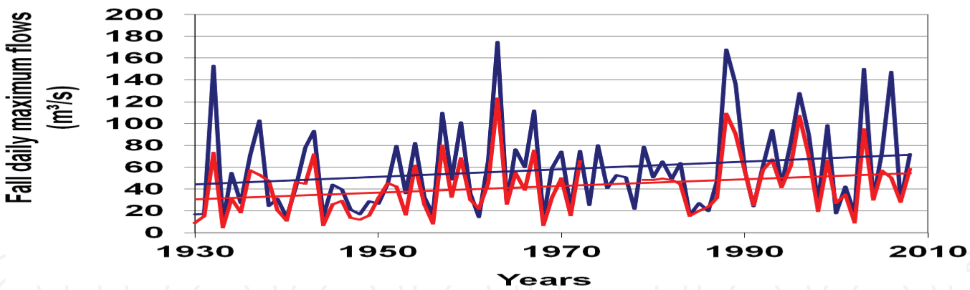

Figure 6. Variability of fall daily maximum flows at the Joliette station on the L'Assomption River (blue curve or dark grey) and Sainte-Ursule station on the Maskinongé River (red curve or fair grey) during the period from 1930 to 2010.

of cultivated land. While forested land increased gradually through the years, two increases took place between 1935 and 1964 (+32.4%) and between 1975 and 1997 (+23.92%) (**Table 5** and **Figure 7**). In terms of cumulative percentage, the reforested surface area went from 32.37% in 1964 to 56.27% in 1997 in the agricultural zone. It is worth pointing out that reforestation activities began only in the 1950s throughout Quebec, as in many developed countries, as a result of the decline of farming populations for various reasons: intensification (motorization, mechanization, use of fertilizers, selection of high-yield seeds, use of pesticides, etc.) and increase in secondary and tertiary industry activities (e.g., [4–5, 27]). Thus, the significant 32.4% increase in forested surface area in the watershed took place between 1950 and 1964.

	1935	1964	1975	1997	2008
Forested surface area	1.27	1.68	1.71	2.08	2.12
Increase rate (%)	–	32.3	1.7	22.2	1.6
Cumulated increase rate (%)	–	32.3	34	56.2	57.8

Table 5. Evolution of forested surface area (reforestation in km²) in the agricultural zone in the Matambin River watershed (1935–2008).

3.3. Evolution of Matambin River channel bankfull width and sinuosity

Analysis of the longitudinal variability of the bankfull width of the Matambin River channel using the Lombard method revealed no significant change in the mean value of this width (results not presented) from upstream to downstream despite the increase in watershed surface area. This is due to the fact that the river has very few tributaries in the agricultural area (St Lawrence Lowlands) through which its lower reaches flow. As far as temporal variability is concerned, mean values of bankfull width and sinuosity are presented in **Table 6** and **Figure 8**. Results of the comparison of these mean values using the Kruskal-Wallis method and the Tukey test are shown in **Tables 7** and **8**, respectively. These tables show that mean bankfull width first decreased from 1935 to 1964 (−21%) and then increased gradually (+12%) from 1964 to 2008. The Kruskal-Wallis test reveals that the decrease is statistically significant at the 1% level. The Tukey test (**Table 8**) shows that the mean value of channel bankfull width in 1935 is significantly different from values for subsequent years. In contrast, the increase in width observed after 1964 is not statistically significant because mean values of width measured for 1964, 1997, and 2008 are not significantly different. Sinuosity, for its part, varied little over time, increasing very slightly between 1934 and 1964, and then decreasing after 1964 due to the cutoff of some meanders (**Figure 9**).

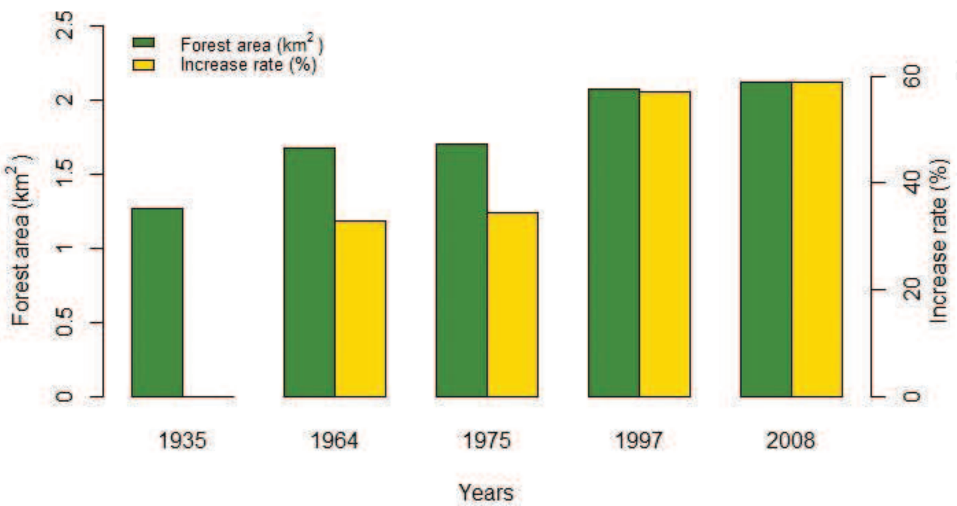

Figure 7. Evolution of the forested surface area in the agricultural zone. Green bars = forested surface area in km²; yellow bars = cumulative percentage of agricultural surface area.

Year	Mean	Standard deviation	Sinuosity
1935	16.5 (935)	5.45	1.77
1964	13 (806)*	4.63	1.51
1997	13.4 (935)	4.52	1.75
2008	14.3 (935)	4.38	1.71

Note: ( ) = total number of bankfull width measurements.
*Air photos lacking for part of the channel.

Table 6. Comparison of the temporal evolution of the mean value of bankfull width (*m*) and the sinuosity of the Matambin River channel in the reforested agricultural zone over the period from 1935 to 2008.

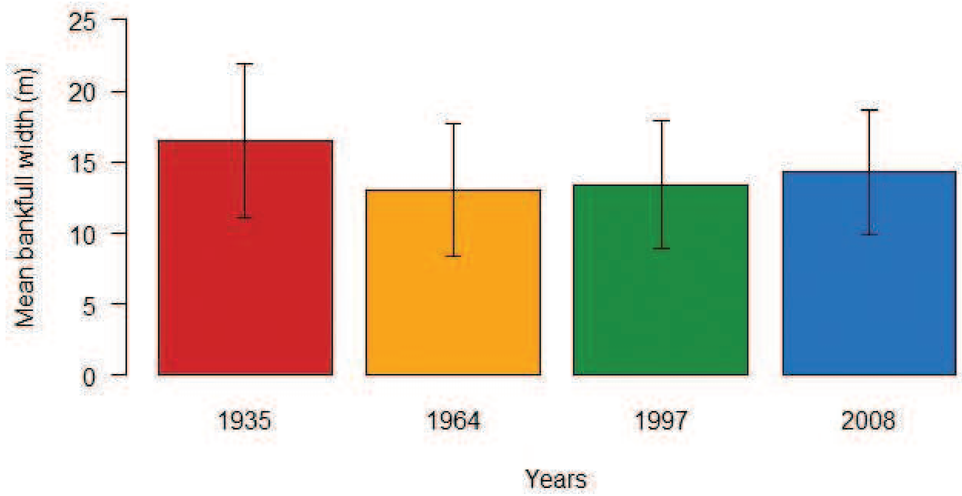

Figure 8. Evolution of mean bankfull width of the Matambin River. Vertical lines represent standard deviation values for the means.

Sources	SM	DL	CM	F	p-Value
Years	6478.771	3	2159.590	94.956	0.000
Error	82307.529	3619	22.743		

Note: SM = sum of squares; DL= number of degrees of freedom; F = calculated value of the Fisher-Snedecor test.

Table 7. Comparison of mean values of bankfull width of the Matambin River channel in the agricultural zone using analysis of variance with a single classification criterion.

Years	1935	1964	1997	2008
1935	1			
1964	**0.000**	1		
1997	**0.000**	0.217	1	
2008	**0.000**	**0.001**	**0.000**	1

Note: Probability values < 0.05 are statistically significant at the 5% level.

Table 8. Comparison of mean values of bankfull width of the Matambin River channel in the agricultural zone using the *post hoc* Tukey test.

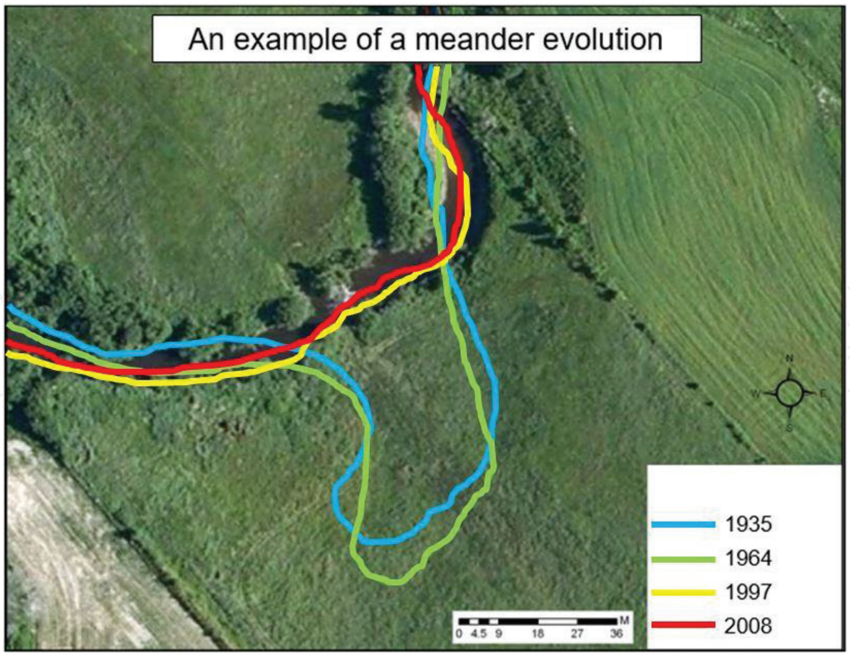

Figure 9. Example of meander cutoff. Lines represent the central axis of the river channel in different years.

4. Discussion and conclusion

In many developed countries, a significant decrease in farming populations has been observed since the second half of the last century. This decrease has led to cultivated land being abandoned, and this land has been taken over by natural vegetation and/or reforested by humans. The hydrological and morphological consequences of these land-use changes have been studied in several countries (e.g., [4, 6, 8–9, 11, 14, 16, 28]). However, despite the increase in reforested land since the 1950s in the St Lawrence Lowlands, no study has yet looked at the morphological impacts of such changes in Quebec. This study analyzed the morphological evolution of the Matambin River channel, along with the reforestation of previously cultivated land. Diachronic analysis of air photographs revealed that the reforested surface area has more than doubled in the agricultural zone from 1950 to 2008. During the same period, two phases of morphological evolution of channel width are observed: a first phase characterized by a significant decrease (−21%) in mean bankfull width which occurred between 1935 and 1964, followed by a second phase characterized by a trend of increasing width from 1964 to 2008. There were no concomitant changes in sinuosity, which changed very little over time.

Prior to the start of reforestation in the agricultural zone during the 1950s, agricultural activities generated large amounts of suspended sediments in this zone caused by soil erosion. Rivers that drain these lands transport much larger suspended loads than rivers draining forested areas, as **Figure 10** clearly shows. The deposition of these large amounts of suspended sediments in the alluvial plain and along the banks could account for the decrease in mean width observed from 1935 to 1964, taking into account the fact that reforestation started only in the 1950s. In addition, *the decrease in* frequency of strong floods observed (see **Table 4**) in the area over the same period would have promoted this deposition while reducing the capacity of the river to carry away all sediments produced by soil erosion (e.g., [29]).

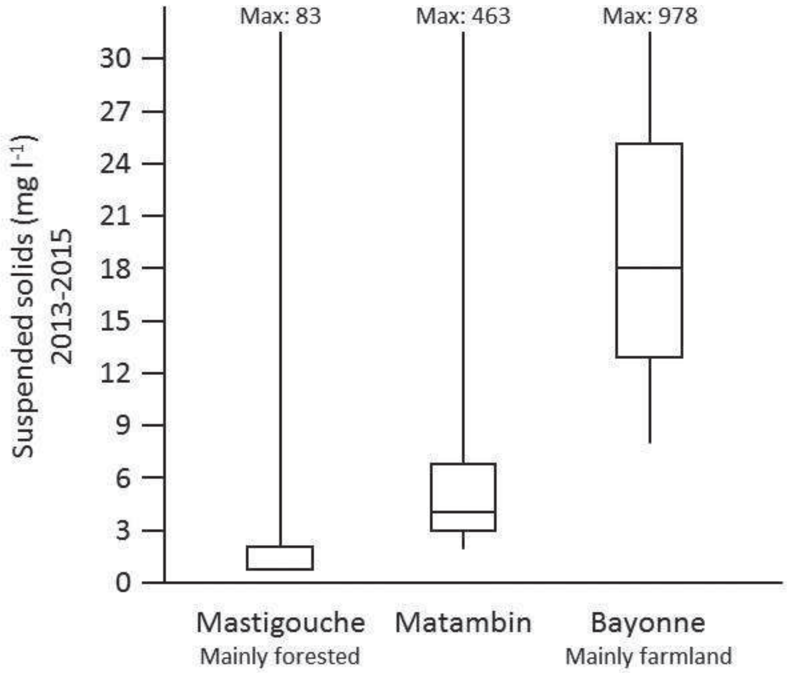

Figure 10. Comparison of mean and maximum suspended solid concentrations carried by the Mastigouche (forested watershed, drainage area: 589.4 km^2), Matambin (reforested agricultural watershed, drainage area: 95.5 km^2), and Bayonne (agricultural watershed, drainage area: 363.3 km^2) Rivers from 2013 to 2015, in Quebec.

After 1964, channel width tended to increase gradually, and this increase, although slow, seems to be ongoing. Two factors may account for this change: (1) the increased frequency of strong flood flows in the area (see **Table 4**), and (2) the significant decrease in the amount of sediments derived from erosion following reforestation. As far as this latter factor is concerned, no long-term data are available on suspended loads carried by the Matambin River. However, a comparison of mean and maximum suspended solid concentrations over the period from 2013 to 2015 in three Quebec watersheds characterized by different land uses clearly shows that the Bayonne River (agricultural watershed) carries on average at least three times the suspended load as the Matambin (reforested agricultural watershed) and Mastigouche (mainly forested watershed) Rivers (**Figure 10**). From these results, we can state with certainty that the Matambin River also carried large suspended loads prior to reforestation of its watershed because it drains the same type of soils as the Bayonne River. Be that as it may, [7] observed a similar trend in the Warche River watershed upstream from the Butgenbach reservoir in Belgium. After farming ceased, giving way to prairies and reforestation by humans, the Warche River channel grew significantly over time due to the decreasing amount of sediments derived from formerly cultivated soils. Moreover, as in the case of the Matambin River, this channel widening was accompanied by very slight changes in channel sinuosity. In the case of the Matambin River, the effect of lower suspended loads on channel widening is thought to be sustained by the increasing frequency of strong flood flows. However, unlike the Warche River, the Matambin River channel is sometimes obstructed by dead wood in many places. The presence of such obstacles may reduce the erosional capacity of the river (e.g., [28]), thus slowing down the channel widening process.

However, in a number of European countries, several studies have shown that reforestation of old agricultural zones has led to a significant decrease in the width of channels. These studies, however, were done in areas characterized by rugged topography (mountainous areas or plateaus) and in rivers with bedloads consisting primarily of gravel or boulders. In addition, in most of these studied watersheds, streamflow decreased significantly due to a decrease in the amount of rain. Even in Quebec, in this type of rivers, the decrease in suspended load observed downstream from some dams has led to a decrease in channel width in boulder reaches (e.g., [30]). This decrease is also accounted for by the near disappearance of all floods with >2 years recurrence intervals after construction of the dams. In contrast, in sandy reaches consisting primarily of easily erodible fines, no change in channel width has been observed as a result of the decrease in strong flood flows.

Finally, one of the goals of this study was to check the validity of relationships set forth by [31] to account for changes in morphological variables of channels as a function of liquid and solid flows (bedload and suspended load). As far as width is concerned, according to these relationships, a decrease in streamflows associated with an increase in solid flows could lead to an increase or a decrease in width. In the case of the Matambin River, a significant decrease in width is observed between 1935 and 1964, a period during which the frequency of strong flood flows decreased while the amount of suspended sediments remained relatively large. In contrast, from 1964 to 2008, these changes in liquid and solid flows were inverted in the watershed, resulting in a trend of increasing channel width. However, unlike width, the sinuosity of the Matambin River was not very strongly affected by changes in the amount of liquid and solid flows in the watershed. Given the above, from a management standpoint, reforestation of old farmlands primarily leads to the cessation of channel narrowing and has little effect on channel sinuosity, allowing the conservation of most available habitats for aquatic and semi-aquatic organisms.

Author details

Ali Assani*, Lisanne Chauvette and Stéphane Campeau

*Address all correspondence to: Ali.Assani@uqtr.ca

Department of Environmental Sciences, University of Quebec at Trois-Rivières, Trois-Rivières, Québec, Canada

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