GEOMORPHOLOGICAL IMPACTS of Channel Straightening in an Agricultural Watershed, Southwestern Québec

Yannick Rousseau and Pascale M. Biron
Concordia University

ABSTRACT

River straightening was widely used in the 20th century to drain fields more rapidly in the spring and increase food productivity in agricultural watersheds. Although straightening has now ceased, dredging remains the leading strategy utilised in southwestern Québec to counter straightened channels' natural re-meandering processes. This research assesses the geomorphological impacts of dredging straightened agricultural rivers and evaluates alternative solutions addressing bank erosion issues. The case study of the Richer Stream, an extensively altered agricultural river encompassing two sharp bends in a reach flowing between a residential area and an agricultural field is examined. GIS analysis of the channel planform allowed the identification of geometrical changes that occurred between 1932 and 2006 and revealed a decrease of 2.2 km in the entire stream length and of 347 m in the residential reach, resulting in slope increases of 32 and 63 percent at the watershed and residential reach scale, respectively. High-resolution topographic data were acquired in the residential reach to capture channel dimensions and shapes six years after it was last dredged. Evidences of river adjustment towards a sinuous planform include a widening of the channel through bank particle erosion and mass failure mechanisms, channel aggradation, and a 6-percent increase in sinuosity. A marked increase of bed shear stress and stream power values in bends suggests their high instability; dredging is unsustainable in this context. The proposed alternative solutions include improved management strategies such as enlarging riparian vegetated strips or letting meanders redevelop, hydraulic structures, bioengineering techniques and channel alteration.
Keywords: bank stabilization, bioengineering, channelization, erosion control, hydraulic structure, river straightening

Introduction

During the last century, many streams in agricultural landscapes of Europe and in North America were straightened to drain fields more rapidly in the spring, resulting in increased food productivity and facilitated crop maintenance following the removal of meander belts (Hupp 1992; Rhoads and Herricks 1996; Scheumann and Freisem 2002; Simon and Rinaldi 2006; Beaulieu 2007). Straightening thus benefited rural income, and reduced the frequency and magnitude of overbank flow events for individuals and infrastructure (Hupp 1992). In the St. Lawrence Lowlands in Québec, channel straightening and widening were supported and encouraged by governmental authorities from 1917 to 1986 (Ministry of Agriculture, Food and Fisheries of Québec [MAFFQ] 2001). It is estimated that 30,000 km of meandering rivers were straightened in the St. Lawrence Valley between 1944 and 1976, and an additional 14,000 km of straight channels were created, draining approximately 1.5 million hectares of land (Boutin et al. 2003; Beaulieu 2007). Since then, dredging was used on a regular basis to re-establish the modified channel dimensions (Beaulieu 2007).

From both ecological and geomorphological perspectives, many of the straightening projects are unsustainable (Brookes and Sear 1996; Frothingham et al. 2002). However, there is a general paucity of available information about past restoration projects (Bernhardt et al. 2005; Brooks and Lake 2007). Overall, few studies suggest that these interventions are successful in achieving channel stability or habitat enhancement objectives (Thompson and Stull 2002; Shields et al. 2003; Thompson 2006). Here, a case study from the Richer Stream, located in southwestern Québec, is used to: 1) assess the impacts of channel straightening and dredging in an agricultural stream, and 2) determine which river management options would provide the most sustainable alternative at two scales: the watershed scale, and the stream reach scale in a residential sector which is particularly prone to bank erosion.

Background

Meandering rivers represent a stable channel pattern on shallow slopes with fine grain size and limited sediment supply (Church 1992), as is the case in the St. Lawrence Lowlands. The straightening of a meandering channel results in the simplification and homogenization of cross-sectional geometries and dimensions, stream planform, substrate type and flow patterns, and in the smoothing of bed topography (Brookes and Sear 1996; Frothingham et al. 2002). Straightened channels typically experience bed incision and river widening due to reduced bed friction, increased slope, increased velocity and stream power and associated bank failures (Hupp 1992; Frothingham et al. 2002; Lau et al. 2006; Simon and Rinaldi 2006). The elimination of floodplain storage and the increased hydraulic efficiency in straightened channels also generate increases in discharge, which may cause downstream flooding (Brookes 1988; Lau et al. 2006). Furthermore, dredging destroys bed armouring and gravel streambed internal structure, contributing to particle entrainment and channel instability (Wyzga 2001). Water and bio-physical quality are also affected by the increase in sediment transport capacity that follows the increase in drainage density and in maximum discharge peaks (Beaulieu 2007). In addition, the removal of streamside vegetation increases stream temperature and rarefies fish shelters (Frothingham et al. 2002). River management strategies in straightened streams typically imply a recurrent dredging procedure, although alternative solutions are increasingly being put forward to stabilize lowland agricultural streams or streams whose development is subject to space limitations (MAFFQ 2001; Piégay et al. 2005).

River management strategies that have been adopted to solve problems created by channel straightening range from restoration projects aiming at a complete recovery of former characteristics to the more recent concepts of river corridor, where the river is allowed to erode its banks, in a controlled "natural" state (Malavoi et al. 2002; Piégay et al. 2005). The incorporation of geomorphological principles into river engineering practices facilitates the establishment of sustainable long-term management strategies by understanding geomorphic processes at both the watershed and the reach scale (Rhoads and Herricks 1996; Kondolf et al. 2003). For example, several restoration projects of channelized rivers in Denmark which included some re-creation of meanders proved beneficial for macroinvertebrate density (Nielsen 1996). However, these projects require public support. In the case of agricultural streams, farmers may favor instead land drainage efficiency, as was the case in Illinois (Rhoads and Herricks 1996).

The implementation of management strategies may be supported by the installation of hydraulic structures, often referred to as hard engineering, or by the use of bioengineering techniques to enhance bank protection by increasing bank erosional resistance (Hey 1996; Kondolf et al. 2003). Hydraulic structures rely on the installation of in-stream physical components such as drop structures, energy dissipators, deflectors and bank revetments to alter river flow, or of revetments to improve bank protection. These structures were used widely during the recent decades to prevent or mitigate erosion problems, improve fish habitat quality, or both. However, there is still no agreement on their effectiveness, on the type of building materials and on the most appropriate design to use (Biron et al. 2004a). Furthermore, numerous cases of restoration failure have been documented following the implementation of instream structures (Downs and Kondolf 2002; Thompson and Stull 2002).

Bioengineering techniques to enhance river stability are recognized as soft-engineering methods because they do not change natural conditions such as the river planform, slope, and geomorphic units (Bennett et al. 2008). Instead, they assist the development of riparian vegetation that will eventually stabilize streambanks to a certain degree. For example, plant roots increase bank strength, preventing mass failure in lower reaches (Abernethy and Rutherfurd 1998; Millar 2000; Rey et al. 2004). In-stream vegetation decreases near-bank flow velocity and associated particle entrainment in mid-basin reaches by protecting soil particles against raindrops, trapping and retaining stream sediments, increasing infiltration rate, and decreasing erosion potential of runoff (Abernethy and Rutherfurd 1998; Millar 2000; Rey et al. 2004; Bennett et al. 2008). Wider riparian strips, i.e., the along-stream corridor adjacent to a river that is used to accomplish various natural functions, increase the overall catchment's response times to precipitation events and decrease peak discharges, and associated erosion rates (Anderson et al. 2006). The use of bioengineering to enhance bank stability is known to reduce the speed at which a bank erodes (Sudduth and Meyer 2006). More species are also observed in riparian habitats where trees are present (Boutin et al. 2003). Québec's provincial laws require at least 3 m of riparian vegetated strip in agricultural areas. This measure would be sufficient to capture fertilizers, pesticides and eroded soil particles, but insufficient for most plant and animal species requirements; plant species typically require a strip width of 10 to 30 m beyond high water mark whereas birds necessitate 75 to 175 m (Spackman and Hugues 1995; Boutin et al. 2003).

Methods

Study site

The Richer Stream is located in southwestern Québec near the municipality of Saint-Marc-sur-Richelieu, approximately 25 km east of Montréal (73.20°W, 45.68°N). This second order stream (using method of Strahler) is a tributary of the Richelieu River, which drains into the St. Lawrence River. The Richer watershed area is 17 km^2, with a main trunk of 6.9 km and 9 tributaries totaling 13.5 km in length. Two scales are considered in this study: the watershed scale (Figure 1a) and the reach scale which includes a section of the stream flowing between a residential area and an agricultural field (Figure 1b).

This Richer watershed is the subject of one of 10 pilot studies initiated in 2005 by the *Fondation de la Faune du Québec*[1] and *Union des Producteurs Agricoles du Québec*[2] on biodiversity and sustainability in agricultural streams. It represents a typical example of a southern Québec stream that was straightened to improve agricultural drainage, and where the riparian vegetated strip is very narrow. Due to the instability of the straight channel and the lack of bank protection, dredging must be performed on a regular basis in this stream to re-establish the channel's trapezoidal cross-sections and linear planform. Dredging is seen by many residents of the municipality and decision-makers as the main stream management strategy. Since the practice of straightening and dredging was widely used in North America in the twentieth century, this case study is representative of many agricultural watersheds.

Data collection

The data used in this study were collected from August to November 2007, approximately 6 years after the last dredging operation occurred. Measurements of the stream bed and bank topography for the residential reach were taken with a Leica total station model [TC805L] at a density of about 0.4/m^2 for a 350-m long reach. This section includes two non-natural sharp bends where bank erosion is known to be problematic (Figure 1b). In general, 4 points were acquired on the bed and 4 on each bank at cross-sections spread apart by 3 to 5 m. Intermediate points were also taken to capture irregularities in the channel bed and banks. Samples of bed and bank sediments were collected at 4 cross-sections along that reach (Figure 1b). The laboratory analysis revealed that all samples consisted of fine silt and clay. As no gauging station is available for the Richer Stream, a staff gage was installed at a cross-section upstream of the residential sector to obtain daily water level measurements over a period of 41 days, which were then used to estimate parameters such as discharge, velocity, shear stress and stream power.

Some GIS data were already available at the onset of the project as the local agro-environmental organization, *Club Consersol Vert Cher*, agreed to share their GIS database with us. This database comprises topographic points, geo-referenced aerial photographs dating from 1932, 1964, 2000, 2004 and 2006, and land use, vegetation cover, water runoff and land erosion maps. The dataset include detailed metadata. Legal documentation concerning the stream dating from 1943 to 2006 was also provided by the regional municipality of county of *La Vallée-du-Richelieu*. Personal communications with local residents also helped in understanding and quantifying some of the historical aspects of the Richer Stream evolution.

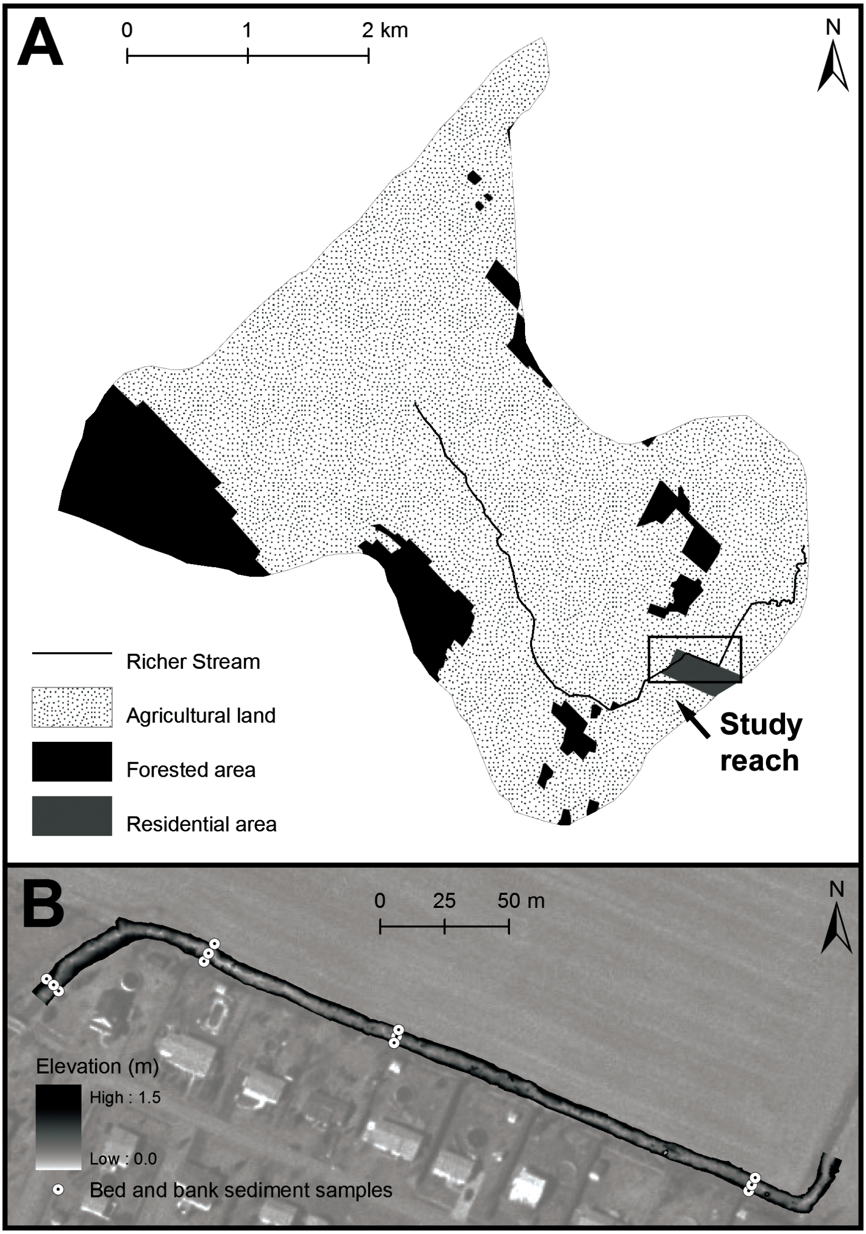

Figure 1. a) Richer watershed including the study reach near residential area. b) DEM of the residential area showing the four cross-sections where sediments were sampled. Flow is from left to right.

Data processing

Two digital elevation models (DEMs) were generated for this study: one for the residential reach and another for the entire watershed. The residential reach DEM was interpolated from the total station measurements using the Natural Neighbours method in the GIS software (ArcGIS version 9.2). This method was chosen after comparing it with other interpolation methods (Inverse Distance Weighting, Kriging, Spline) as it was more appropriate for the Richer Stream characteristics with rapid changes between shallow and deep sections. At the watershed scale, topographic points were extracted from stereoscopic pairs using photogrammetric software (DVP Vectorization). The DEM was built from the 3928 acquired topographic points using the Inverse Distance Weighting interpolation method in ArcGIS. The DEM was subsequently used to calculate the area of the drainage basin contributing to the flow discharge at certain cross-sections and to estimate the slope of the Richer channel.

At the cross-section where daily flow depth was measured, the cross-sectional area (m^2) and wetted perimeter (m) is calculated based on the known topography. The hydraulic radius is then calculated using:

$$R = {}^{A}\!/_{P} \qquad (1)$$

where R is the hydraulic radius, A is the cross-sectional area, and P is the wetted perimeter. The Manning equation is used to compute velocity at this cross-section:

$$V = \frac{R^{2/3} \,.\, S^{1/2}}{n} \qquad (2)$$

where V is the velocity (m/s), S is energy slope (estimated here with the channel slope), and n is the Manning roughness coefficient (dimensionless), estimated at 0.029 for the reach. The discharge (Q) is then calculated using:

$$Q = V \cdot A \qquad (3)$$

The watershed area ratio method was used to compute bankfull discharge from a near-by gauging station on the Hurons River, located 20 km away and with a similar land use (Newbury and Gaboury 1993). The watershed ratio between the Hurons and Richer streams is 23. Assuming a recurrence interval of 1.5 years, the Hurons' bankfull discharge is 77.7 m^3/s, which results in an estimated bankfull discharge of 3.33 m^3/s for the Richer Stream. A correlation coefficient of 0.91 is obtained between the Richer discharge estimated using equations 2 and 3 and the watershed ratio estimate. Bankfull width (7 m) and depth (0.92 m) at the staff gage are estimated from bankfull discharge, equations 2 and 3, and channel cross-sectional topography. The stream power per unit width (at bankfull discharge) ω (W/m^2) is estimated from:

$$\omega = t_0 \cdot V \qquad (4)$$

(Simons and Richardson 1966) where t_0 is the bed shear stress (N/m^2), given by:

$$t_0 = \rho \cdot g \cdot R \cdot S \qquad (5)$$

where ρ is water mass density (kg/m^3) and g is the acceleration due to gravity (m/s^2).

Changes in sinuosity, amplitude, and slope are the main parameters used to quantify the impact of human interventions on the Richer channel. Sinuosity is defined as the length of the meandering channel divided by the length of the channel valley, whereas the amplitude corresponds to the average width of the meander loops. Changes in channel dimensions and pattern along the Richer Stream were reconstructed on the basis of geo-referenced aerial photographs dating from 1932, 1964 and 2006, of legal documentation dating from 1943 to 2006 and of personal communications with residents of the municipality of St-Marc-sur-Richelieu. The temporal evolution of the Richer channel cross-sectional area was traced by reading all legislative Acts regulating channel modifications and maintenance processes (1943 through 1987). For instance, the Act of 25 August 1958 specified that the Richer Stream should have both bed width and depth set at 5 feet (1.52 m) with bank angles at 45 degrees. The Acts of 8 September 1987 specified that the bed width should be increased to 6 feet (1.83 m). This suggests that the cross-sectional area was increased by at least 9.9 percent. However, initial channel dimensions remain unknown.

Natural changes to the straight channel since the latest dredging operation are much easier to assess for the residential reach since both the initial and current cross-sectional shape and dimensions are known. The initial shape is assumed trapezoidal and uniform, with dimensions corresponding to those mentioned in the most recent Act (1987) regulating the Richer Stream management strategy. The current dimensions and shapes are obtained from the interpolated DEM.

The current Richer channel shape in the residential area is examined at 44 cross-sections spaced on average 8 m apart using the topographic map created with the total station surveyed data. Erosion is divided into four types: negligible (little erosion), incision (mainly bed erosion), mass failure (mainly bank erosion), and combined (bed and bank erosion). For each cross-section, the area and the thalweg (position of the deepest point in a cross-section) are measured. Bed shear stress values are calculated between each adjacent cross-sections using equation (5) and mapped to determine the spatial distribution of low and high bed shear stress values.

Results

Watershed scale

The current land use of the Richer watershed is agricultural at 85 percent, forested at 14 percent and urbanized at 1 percent. Spatial analysis using GIS reveals that the distribution and area of each land cover type remained relatively stable since 1932. The only exception to this is the development of a residential area south of the stream. Overland flow into the stream may have been reduced due to the interception of precipitation by municipal sewerage. Similarly, the urban infrastructure and vegetation may have prevented sediment from entering the channel. Since the municipality is located in the downstream part of the watershed, the impact of urbanization on water and sediment supply is limited. In middle and upper reaches, bank vegetation consists mainly of grass with isolated trees and shrubs. A wider vegetation strip with greater plant species diversity is present in some of the lower reaches where a few of the original meanders are still in place (Figure 1a).

In 1932, most of the reaches appear in a natural state. Only a few abandoned meander belts are visible near roads on the aerial photographs dating from that year, suggesting that straightening may have begun before this date near roads and bridges. This section discusses how the channel has evolved in terms of length, sinuosity and slope between 1932 and 2006 and discusses the potential consequences of these changes. Since no accurate topographic representation of the Richer watershed exists prior to 2006, the assumption is made that land morphology has remained relatively stable since 1932, thus that the 2006 DEM can be used to compute channel slope for 1932, 1964 and 2006 planforms. This assumption, based on the fact that land cover has remained fairly stable from 1932 to 2006 (with the exception of the limited urban development), may lead to some error in slope calculations, which is unfortunately not possible to quantify.

On the 1932 aerial photograph, the length of the Richer Stream in its assumed natural state (without considering its tributaries) is 9.1 km, with an average sinuosity of 1.44 and an average slope of 0.094 percent. The average amplitude is 34.3 m (Table 1), with a stream width of approximately 8 m. In 1943, the first Richer Stream Management Act was signed to straighten some sections located in the upper to middle reaches. A part of the lower reach was also straightened, although most of it remained in a relatively pristine state considering the inevitable influence of upstream channel modifications. In 1964, the channel is shortened by about 966 m; as a result, sinuosity decreases and slope increases on average by 12 percent (Table 1). Straightening continued until 1986. After this date, maintenance works were performed in order to counter the channel's natural tendency to retrieve a sinuous shape. An aerial photograph taken in 2006 reveals that the channel is then almost completely linear. However, two downstream sections

Year		**Length (m)**	**Sinuosity**	**Slope (%)**	**Amplitude (m)**
1932		9079	1.44	0.094	34.3
1964		8113	1.28	0.105	34.0
2006		6863	1.09	0.124	7.4
1964 vs. 1932	1964 - 1932	-966	-0.15	0.011	-7.5
	1964/1932	0.89	0.89	1.12	0.99
2006 vs. 1932	2006 -1932	-2216	-0.35	0.030	-26.9
	2006/1932	0.76	0.76	1.32	0.21

Table 1. Evolution of the Richer channel length, sinuosity and slope for the entire stream.

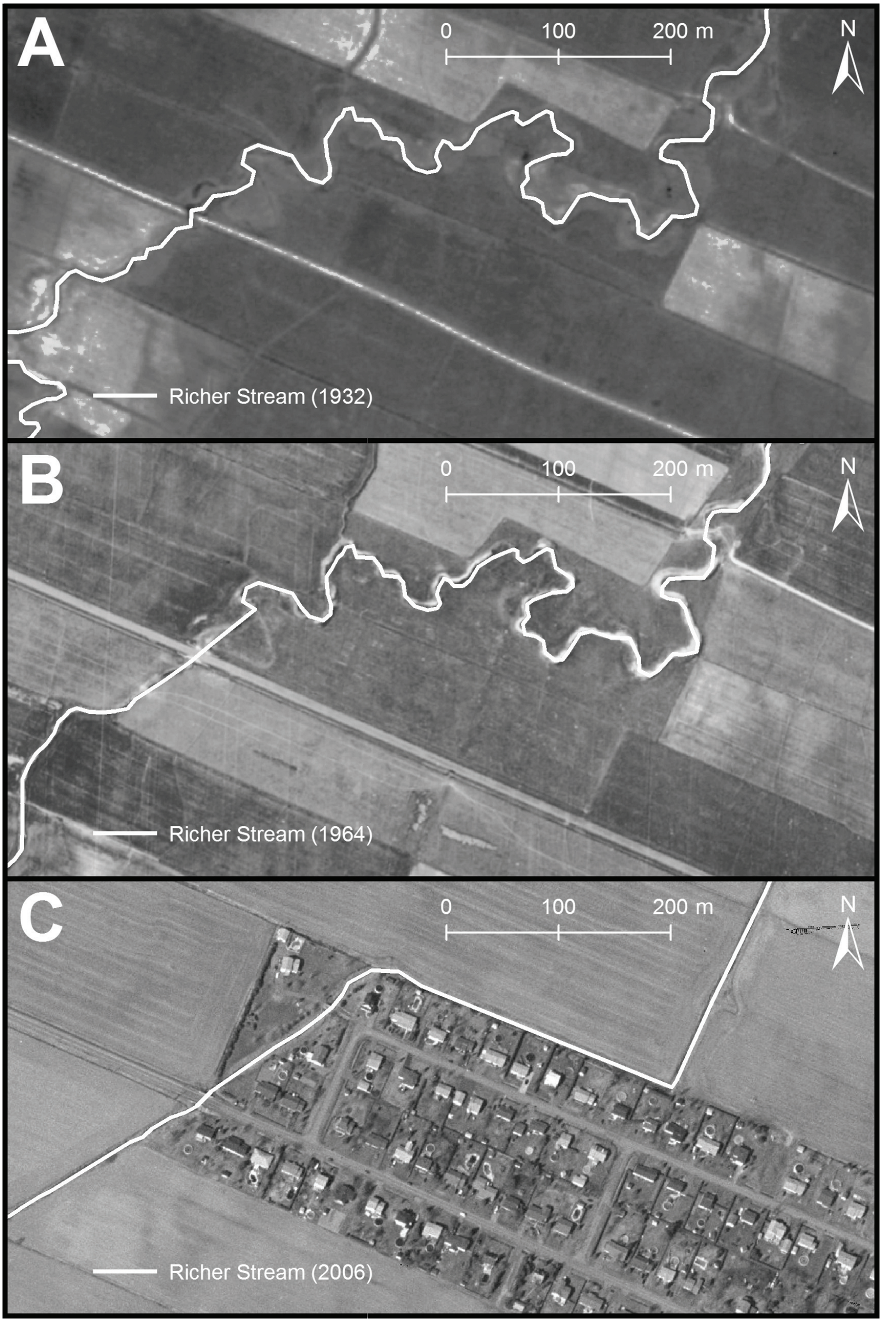

Figure 2. Aerial photographs of the residential reach in a) 1932, b) 1964 and c) 2006.
Flow is from left to right.

still retain their natural meandering planform since adjacent landowners always refused to modify the stream. Between 1964 and 2006, the channel length decreased by 2.2 km, resulting in a 32 percent increase in slope (and a corresponding decrease in sinuosity), while the amplitude is dramatically reduced by close to 27 m since 1932 (Table 1).

Residential reach scale

Year		Length (m)	Sinuosity	Slope (%)	Amplitude (m)
1932		898.4	1.76	0.112	57.0
1964		884.2	1.73	0.114	52.1
2006		551.6	1.08	0.183	5.1
1964 vs. 1932	1964 - 1932	-14	-0.03	0.002	-4.9
	1964/1932	0.98	0.98	1.02	0.91
2006 vs. 1932	2006 -1932	-347	-0.68	0.071	-51.9
	2006/1932	0.61	0.61	1.63	0.09

Table 2. Evolution of the Richer channel length, sinuosity and slope in the residential area.

At the residential reach scale, changes in the evolution of the Richer Stream are even more drastic (Figure 2), with an increase in slope of 63 percent, and an amplitude decrease of 91 percent between 1932 and 2006 (Table 2). Since bed shear stress is directly proportional to flow depth and channel bed slope (eq. 5), a major physical consequence of straightening is to increase significantly bed shear stress and stream power values. Assuming a bankfull discharge of 3.33 m^3/s, a bankfull velocity of 0.60 m/s, a trapezoidal channel with 45-degree bank angles, it is estimated that the bed shear stress values have increased from 3.0 to 4.0 N/m^2 (32 percent) on average for the entire Richer Stream and from 3.6 to 5.9 N/m^2 (63 percent) in the residential

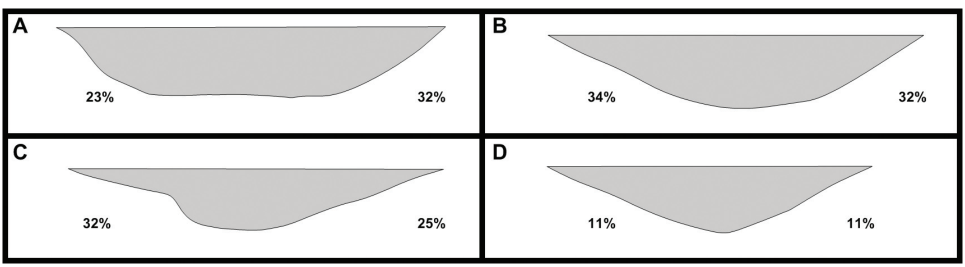

Figure 3. Erosion types in the residential area: a) negligible, b) combined mass failure and incision, c) mass failure and d) incision. Percent values indicate the frequency of left and right banks observed with this type.

Year		Bankfull flow velocity (m/s)		Bed shear stress (N/m^2)		Stream power (W/m^2)	
		Entire stream	Resid. reach	Entire stream	Resid. reach	Entire stream	Resid. reach
1932		0.50	0.55	3.0	3.6	1.5	1.8
1964		0.53	0.55	3.4	3.6	1.8	1.9
2006		0.58	0.70	4.0	5.9	2.3	3.4
1964 vs. 1932	1964 - 1932	0.03	0.00	0.4	0.1	0.3	0.1
	1964/1932	1.06	1.01	1.12	1.02	1.18	1.07
2006 vs. 1932	2006 -1932	0.08	0.15	1.0	2.3	0.8	1.6
	2006/1932	1.15	1.28	1.32	1.63	1.52	1.87

Table 3. Estimated bed shear stress and stream power in the Richer Stream in 1932, 1964 and 2006.

area, between 1932 and 2006 (Table 3). Using equations (4) and (5), the stream power per unit width has increased from 1.5 to 2.3 W/m^2 (52 percent) on average in the entire stream and from 1.8 to 3.4 W/m^2 (87 percent) in the residential reach. These values suggest that the average erosive potential has significantly increased at both scales, but especially in the residential reach.

The analysis of the erosion types encountered in the residential reach reveals that only 27 percent of the 88 banks analysed (two banks per cross-section) are minimally eroded (Figure 3, Table 4). The most common observed erosion type in this analysis is a combination of mass failure and incision (33 percent), followed by mass failure only (28 percent) then by incision only (11 percent). Failed banks are more frequent on the left side (looking downstream) while banks with negligible erosion are more common on the right side, indicating a greater potential for erosion on the left side.

	Negligible			Incision			Mass failure			Combined incision and mass failure			Total
	L	R	Tot.	L	R	Tot.	L	R	Tot.	L	R	Tot.	
Frequency	10	14	24	5	5	10	14	11	25	15	14	29	88
Frequency (%)	23	32	27	11	11	11	32	25	29	34	32	33	100
L = left; R = right; Tot. = total													

Table 4. Erosion types in the 44 sampled cross-sections of the residential area.

Calculations of the average channel dimensions in the residential area reveal that although the channel cross-sectional area has remained relatively stable over time, a marked decrease

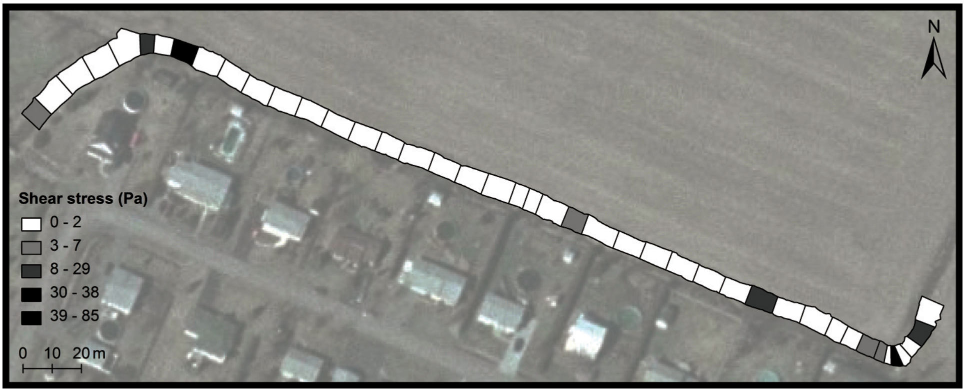

Figure 4. Estimated bed shear stress values in the residential reach. Flow is from left to right.

in depth (24 percent), increase in width (43 percent) and decrease in bank angles (up to 50 percent) are visible. The thalweg position has also shifted by 12 percent of the channel width towards the left bank (looking downstream). This is consistent with the observations that more erosion is occurring on the left bank. The magnitude of the changes and the speed at which they operated suggest that a trapezoidal channel lacking protection is unstable and that the channel naturally adapts by adjusting all dimensions and migrating to the left.

The analysis of individual cross-sections also revealed that bed shear stress distribution is not uniform in the residential reach (Figure 4). Although the average calculated bed shear stress is around 4.0 N/m^2 in 2006, a twentyfold increase in estimated shear stress values is observed in the cross-sections immediately downstream of the two bends, suggesting a high potential to erode bend banks. High bed shear stress values are also visible upstream of the second bend which is a zone with a massive failure of the right bank that constricts the channel cross-sectional area.

Discussion

Our results indicate that an important consequence of channelization in the Richer Stream is the decrease in length resulting in a corresponding increase in channel slope. At the scale of the watershed, the increase in channel slope (32%) corresponds well to observations in Indiana (33%; Brookes 1988) and Illinois (23%; Rhoads and Herricks 1996). However, the increase in the residential sector is markedly larger (63%) than previous observations. Such an increase results in higher bed shear stress values, which were found to be abnormally high in a bend located in the residential area where bank failures were observed and where the channel is in general unstable.

The detailed analysis of cross-sections in the residential reach of the Richer Stream provided useful information about the nature and evolution of the straightened channel adjustments.

Firstly, erosion types show that both incision and bank failures occur. The observed channel`s widening and sediment accumulation on the bed suggest that incision may cause bank failure which itself leads to sediment accumulation on the bed as the sediment forming the collapsed banks are dispersed. Secondly, the development of a sinuous thalweg was observed while the channel also became slightly more sinuous. Similar changes were observed in the Big Pine Creek, Indiana, a watershed that is similar to the Richer Stream in terms of watershed area, soil type and sinuosity (Brookes 1988). Six years after its construction, the Big Pine channel experienced incision, bank slumping, widening and the development of higher sinuosity. Our observations in the Richer Stream follow the sequence of adjustments following river straightening described by Brookes (1988), namely bed degradation (followed by bank slumping), armouring, development of a sinuous thalweg, sinuosity recovery, and the development of a sinuous course by deposition.

Bank failures were found to be more common on the left bank. This may be attributed to the fact that the agricultural land on the left bank is more vulnerable to mass movement than the residential land on the right bank, which is protected by roots, stems and leaves from deciduous and coniferous trees, shrubs and grass species throughout the year. Failures may also be related to heavy machinery used on the agricultural side which promotes bank damage.

The findings concerning the evolution of the dredged channel in the residential reach are derived from a single sequence of topographic data acquisition. The main limitation of this procedure is its inability to detect the temporal and spatial connections between erosion types, thus to capture the detailed channel evolution following disturbance. A potential improvement in the understanding of the re-meandering processes could be achieved by acquiring topographic data in the study reach several times during a period of several months, particularly following flood events. An alternative could be to install erosion pins along the stream banks and measure the rate of erosion on a regular basis (Lawler 1978; Couper et al. 2002). However, the method used here remains a useful first approach in stream management to highlight potential problems and elaborate solutions in the short term.

In this study, average bed shear stress values are estimated for each uniform section of the channel using Equation 5. Other methods to compute bed shear stress using mean velocity or turbulence fluctuations are available (Biron et al. 2004b; Tilston and Biron 2006), which may have been more accurate than the basic equation used here. However, the latter requires only topographic data, which are easily available.

Our findings suggest that the removal of riparian vegetation associated with recurrent dredging activities decreases the Richer channel stability. The fact that the channel naturally adjusted to disturbance by decreasing bank slopes by half while decreasing its depth and maintaining a constant cross-sectional area suggests that bank angles were too steep and points to a lack of bank cohesion. This was also observed by Micheli et al. (2004) who found agricultural floodplains to be 80 to 150 percent more susceptible to erosion than riparian forest floodplains. Soil strength could be increased compared to bare soil by maintaining a riparian vegetated strip consisting of woody and grass species. The net effect of this approach was found to vary with plant species assemblage and moisture content (Simon and Collison 2002; Simon et al. 2006). However, a riparian strip constituted from a combination of shrubs and trees is expected to enhance vegetation colonization and channel narrowing (Malkinson and Wittenberg 2007).

River management options

Several solutions to bank instability exist, however their use is not always desirable or possible in an agricultural context and under all circumstances. Furthermore, potential solutions are not necessarily the same at the watershed and residential reach scales because of the different contexts and objectives to attain in each case. For instance, the elaboration of solutions for the residential reach must take into account the very limited available space for the installation of vegetation and hydraulic structures. A wider range of modifications is possible at the watershed scale due to the low density of roads and buildings, but they must be affordable and implementable at a large scale. In this study, two assumptions were made. Firstly, the residential area cannot be moved or reduced in size due to the important costs and efforts that such options would require. Secondly, the agricultural field could be slightly modified in size in exchange of potential financial subsidies from the provincial government to the land owners. These assumptions imply that either the solution must be implemented with significant space constraints or the channel has to be moved.

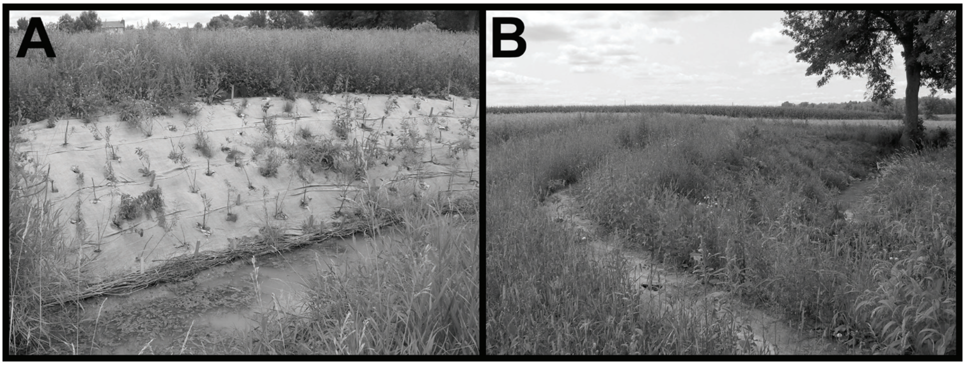

Figure 5. Examples of channel bank stabilization with vegetation and bioengineering implemented in a downstream reach of the Richer Stream in 2007. a) Flattening of the over steepened bank slopes, installation of cardboard-coco mat and plants to protect banks, and installation of trellised branches to prevent bank toe erosion. b) Rows of trees planted to promote bank cohesion with root reinforcement in the long term.

The agro-environmental group *Club Consersol Vert Cher* has implemented bioengineering solutions in May 2007 in one of the few meanders located in the lower reaches of the Richer Stream (Figure 5). Bank inclinations were reduced from 1:1 to 1:1.5 to decrease mass failure potential. A jute or coco mat was used and placed over a cardboard mat in a few channel bends. The former type was entrained by spring flood while the latter resisted. The establishment of plants on the cardboard-coco mat was more successful than on the cardboard-jute mat. Although some of these results are encouraging, only time will confirm whether the techniques used are sustainable in the long term.

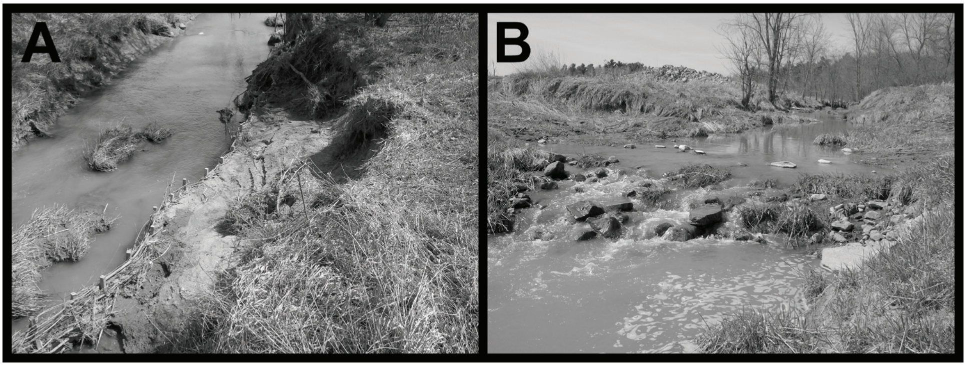

Figure 6. Hydraulic structures currently being used in the Richer channel to improve bank stability.
a) Vertical pillars installed in 2007 and used to reduce bank toe erosion. Flow is towards the top.
b) Block ramp installed by a farmer in 1997. Flow is towards the bottom.

Some hydraulic structures such as vertical pillars have been in place in the Richer Stream and have proved successful so far (Figure 6a). Not only did flow velocity decrease near the bank, but the area between pillars and the right bank (looking downstream) was filled with sediments that otherwise would have eroded into the stream. This adjustment, also observed by Abam (1995) helped the channel maintain its depth. However, in the long term, the area between the pillars and the right bank would probably become completely filled and this technique would not be able to trap any sediment. Also, the pillars may collapse and release previously trapped particles (Abam 1995). A block ramp was also installed during the summer of 1997 and seems helpful in dissipating energy and decreasing flow velocity at low discharge (Figure 6b). Block ramps increase flow resistance while reducing shear stresses on the base material (Pagliara and Chiavaccini 2006). However, the fact that significant bank failures occurred 50 m downstream of the ramp suggests that this method alone cannot solve bank erosion problems. An environmental limitation of using this structure in the Richer Stream is that it completely obstructs fish migration at low flow (Thompson and Stull 2002). A general limitation of installing any structure is that increasing resistance to erosion without modifying flow energy usually results in increasing erosion downstream, therefore displacing the problem to another location (Jueyi et al. 2006). Also, the impact of these structures varies with flow stage. For example, three-dimensional numerical simulation was conducted to test the effect of five bendway weirs on bank toe protection in Sugar Creek, Illinois (Abad et al. 2008). This study revealed an increase in shear velocities on the bed in the lee of these structures and along the outer bank above the top of the structures at medium- and high-flow stages.

Naturalization, or controlled natural state, consists in limiting human interventions in the channel structure and letting the river self-adjust within a certain reserved riparian area, which also has the benefit of increasing ecosystem structural (physical) diversity and quality, and heterogeneity in vegetation community (Toth 1996; Larsen and Greco 2002, Piégay et al. 2005). Naturalization can be implemented with dechannelization, the relocation of a stream inside its historical channel and ecosystem; this solution helps restore geomorphic features, diversity and functions quickly (Toth 1996). However, the Richer Stream cannot be relocated inside the 1932 channel in the residential area as the channel has been filled for agricultural purposes and as the municipality of Saint-Marc-sur-Richelieu was established over the former planform. Instead, the channel could be altered to exhibit historical stable planform, shape and dimensions, knowing that the resulting channel would also be relatively stable. Since the municipality of Saint-Marc-sur-Richelieu was planning to expand its residential area next to the river (upstream and downstream), a naturalization solution was proposed to its Administration Council in January 2008 to prevent eventual land losses and damages to infrastructure and future dwellings, and environmental degradation associated with dredging practices. Using aerial photographs, it was estimated that the historical stable channel-pattern amplitude (exhibiting negligible lateral or downstream migration rates and having a 10-m wide channel) occupied a zone with an amplitude of 44 and 42 m upstream and downstream of the residential area, respectively. A suggestion was thus made to use 17- and 16-m wide riparian areas on both sides of the stream respectively for the northern and southern development sites (Figure 7). These values correspond to the amplitude less the channel width (10 m), divided by two. Although it was felt that leaving such a corridor undeveloped would limit future needs for stabilization and notwithstanding that no long-term comparison of costs was completed, this solution was rejected by the council for financial reasons. Instead, the administration council maintained their idea of establishing a 13-m wide corridor, which is 3 m larger than what is required by the provincial law.

Figure 7. Potential solution consisting in the naturalization of two parts of the Richer channel that are located near future residential developments. The width of the riparian zone for the two proposed development is based on the natural (1932) meander amplitude for each zone.

During the meeting with the municipality council, solutions involving planform and morphology alteration were discussed. The council proposed to move part of the channel so that its natural adjustment in shape and dimensions would become less problematic for current and future residential land owners. The characteristics of the desired stable meandering channel pattern can usually be determined from historical measured geometrical parameters such as sinuosity, slope, amplitude, wavelength and width (Shields et al. 2003). However, it is not possible to proceed that way for the current solution since the mean slope would be increased significantly as a result of the valley length being shortened by 28.4 percent with respect to the 1932 planform. In order to maintain the 1932 slope, a sinuosity of 2.34 would be required in the shorter valley. Such a high value of sinuosity is undesirable in this reach as it would drastically contrast with much lower values in adjacent reaches, creating potential backflow problems when the faster upstream flow would enter this high sinuosity reach. A new combination of amplitude and wavelength was determined to design a channel having a sinuosity of 1.29, i.e., the sinuosity required to keep the 2006 slope in this section of the stream. In this solution, channel planform is elliptical and its wavelength is derived from Ramanujan's (1914) first approximation of an ellipse perimeter (P):

$$P \approx \pi \left\{ 3(a+b) - \sqrt{(3a+b)(a+3b)} \right\} \qquad (6)$$

where a and b are the lengths of the semi-minor and -major axes, respectively. The relation between channel amplitude (A) (m) and wavelength (L) (m) for a specific sinuosity is then described using a linear equation:

$$L = m \cdot A + y \qquad (7)$$

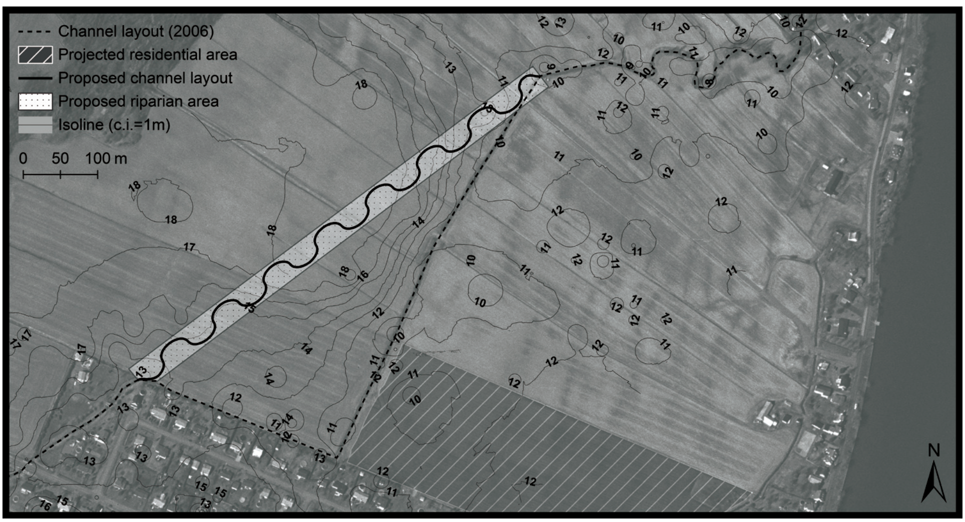

Figure 8. Potential solution relying on the migration of part of the Richer channel from the residential area to an agricultural zone to limit bank erosion and flooding problems in the residential sector.

For instance, m is equal to 3.26 and y is equal to $6.19 \cdot 10^{-15}$ in a channel exhibiting elliptical planform if the sinuosity is 1.29. The value of parameters m and y was determined knowing that L is equal to four times the length of the semi axis that is parallel to the valley and A is equal to twice the length of the semi axis that is perpendicular to it.

Using this equation, a compromised planform between the 1932 amplitude and wavelength would include a 26-m amplitude and an 86-m wavelength. This situation would result in a mean channel width of 9 m, based on the relationship with the distance between two consecutive pools (5 to 7 channel widths). The total riparian vegetated strip width would be 35 m (Figure 8). Note that uniform planform geometries or channel width, depth and slope should not be employed; the calculated values should only be used as average values for the designated reach (Shields et al. 2003). Since the elevation near the projected channel bank tops is on average 4 m higher than it is near the current channel, approximately 0.5 million cubic meters of soil would need to be moved in order to level the terrain and establish the stream in the lowest elevation zone.

An intermediate solution consists in combining the establishment of a riparian vegetated strip and minor planform and shape modifications (Figure 9). The curved planform in the area downstream of the residential area decreases flow impact at the location where bed shear stress values were estimated to be the highest. The riparian areas stabilize banks and provide the channel with enough space to adjust laterally.

Figure 9. Potential solution relying on planform and shape alterations, stabilization with vegetation and bioengineering techniques, and naturalization.

Other stabilization solutions for the residential area require the channel to be minimally shifted towards the agricultural side. For instance, reducing the Richer bank angles by half would imply that the channel is approximately 3-m wider than it currently is.

Conclusion

This study aimed at improving our understanding of the impacts of channel straightening and dredging in a small agricultural watershed, but also at identifying some sustainable solutions that could be implemented in a reach flowing between a residential area and agricultural lands to reduce the problems associated with bank erosion in a way that is ecologically acceptable.

River straightening had a marked impact on the Richer Stream, with an increase in slope of 32 percent at the watershed scale, and a corresponding decrease in sinuosity. At the residential reach scale, the increase in slope is even more dramatic (63 percent), resulting in a marked increase in bed shear stress and stream power. Only six years after the last dredging operation ended, the channel was found to have adjusted naturally to compensate for its unstable condition with a 100 percent reduction in the angle of over-steepened banks, a significant shift in thalweg position towards the left bank, a 6 percent increase in sinuosity, and an equivalent reduction in channel bed slope.

The geomorphological characterisation of the Richer Stream allowed the identification of solutions that could improve channel bank stability. Using the geometrical parameters of the 1932 Richer planform, an increased riparian vegetated strip width in which the stream would be "free" to re-initiate meanders is suggested upstream and downstream from the current residential area, where more space is currently available but where new residential developments are planned in the near future. This solution should be combined with a planform alteration in the artificially-maintained sharp bends to implement a more natural and sustainable channel.

Often, in the public's mind, erosion is regarded as a problem. This conception ignores the fact that rivers are dynamic; lateral migration of meanders and floods are natural and inevitable processes. Efforts should be placed on understanding these natural processes and considering them in the planning phase of various projects involving rivers instead of trying to control them. Also, stream management should be analysed from different perspectives; cooperation among experts from different domains (geomorphology, engineering, agronomy, policy makers, and municipal representatives) and the community is needed in order to implement more sustainable solutions for agricultural watersheds.

YANNICK ROUSSEAU is a M.Sc. student in the Department of Geography, Planning and Environment at Concordia University, Montreal. Email: yanrousseau@gmail.com. Areas of current research include the geomorphological impacts of river straightening in lowland agricultural watersheds and the assessment of management strategies using sediment transport and flow hydralics modeling .

PASCALE BIRON is an Associate Professor in the Department of Geography, Planning and Environment at Concordia University, Montreal, QC Canada H3G 1M8. Email: pascale.biron@concordia.ca. Areas of current research include stream restoration for fish habitat, sustainable management of agricultural rivers, and numerical modeling of river dynamics.

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Notes

1. The Fondation de la faune du Québec was created in 1986 by the Government of Québec to mitigate loss of wetlands and to fight aquatic and land habitat degradation by supporting wildlife initiatives (http://www.fondationdelafaune.qc.ca).

2. The Union des Producteurs Agricoles du Québec was created in 1972 to promote, defend and develop the professional, economic, social and moral interests of Québecís farm producers. In addition, it seeks to improve living conditions of rural communities at the social, economic and cultural levels (http://www.upa.qc.ca).

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