Integrating hydrogeomorphological concepts in management approaches of lowland agricultural streams in Quebec: Perspectives, problems and prospects

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ABSTRACT

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Alexandre Paradis

River management in agricultural settings has undergone profound changes in recent years, particularly in the Midwest. A better integration of hydrogeomorphological principles has led to novel approaches with the two-stage channel design for small agricultural streams being among the best examples. The applicability of these innovative techniques in Quebec remains to be tested. We conducted detailed analyses of streams in agricultural areas located in Montérégie (Quebec) to determine the impacts of a change in the trapezoidal channel profile. A particular emphasis was put on the subsurface drainage outlets which often limit the degree of adjustment of these small streams. These impacts were analyzed by hydrodynamic modeling (HEC-RAS) and a hydraulic geometry approach. Findings confirm the improvement of surface drainage for high magnitude floods, but also identify a potentially endemic problem in Quebec where, due to the rectangular shape of agricultural fields (an inheritance from French settlements), very deep subsurface drainage outlets are in conflict with natural floodplain generation within the straightened channels. Alternative measures to accommodate for natural fluvial adjustments while maintaining drainage efficiency were explored. One potential approach would be to create small pocket wetlands along the streams that would provide increased heterogeneity and limit the need to dredge agricultural streams over long distances. Lastly, crop yields within fluvial corridors were greatly influenced by flood connectivity, with markedly reduced yields in near-stream zones. This indicates that acquisition costs for critical riparian land could be greatly diminished for many of the critical areas needed for hydrogeomorphological processes to operate.

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The collaboration of several farmers in Montérégie, which allowed us to instrument streams and collect crop yield data, was also of great importance. Other providers of data include Info-Sols, MAPAQ, CEHQ, MRC Les-Jardins-de-Napierville and Ohio State University's Department of Food, Agricultural and Biological Engineering. Of this latter contributor I wish to thank among many others Jon Witter, Jessica d'Ambrosio, Mike Brooker, Professor Andrew D. Ward and Professor Larry Brown. I was extremely well received in the beautiful city of Columbus and very much impressed with the quality of the research being led in this grand university.

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Introduction

In agricultural fields, it is crucial for farm productivity to evacuate runoff as quickly as possible, particularly in Quebec where the growing season is short. In the 20th century, several governmental programs were established to straighten meandering rivers and to add human-made ditches to increase the evacuation capacity of agricultural watersheds. These modified streams were all designed using a trapezoidal, uniform shape, which is very different from the cross-sectional shape of natural streams. This thesis aims to expose the need for Quebec's agricultural stream management actors to consider more sustainable approaches than the traditional, ubiquitous trapezoidal ditch. To achieve this goal, a literature review of the various impacts of the ditch/subsurface drainage combination and of the potential alternatives is presented. Two of these alternatives are of particular interest because of their inclusion of fluvial geomorphology's key concepts – which in turn leads to more successful intervention in waterways: The two-stage channel design applied in agricultural environments (Powell et al. 2007a) and the self-forming stream concept (Landwehr & Rhoads 2003, Jayakaran et al. 2010). The research teams associated with those innovative techniques also developed freely available spreadsheet tools to help evaluate their implementation.

Drainage is a necessity in wet regions of the world to grow food more efficiently for an ever growing population. Restoration of the historically pristine environments of lowland regions is not a conceivable option, because of the economic importance attached to cultivated land, the nearly inexistent information on the preexisting conditions and the hydrologic alterations due to tremendous changes at the landscape scale (Rhoads et al. 1999). Still, each of the alternatives examined here strike a fascinating balance between the needs of the various actors concerned with agricultural streams and the hope of attaining sustainable management of this essential component of agricultural watersheds.

The literature review will first uncover the various impacts of the trapezoidal ditch design coupled with subsurface drainage. The second part exposes innovative solutions addressing those impacts with the following subsections:

-Self-formed stream using an over-wide ditch
-Two-stage channel design
-Disconnecting subsurface drainage outlets from streams
-Controlled drainage

1.1: Trapezoidal ditches and subsurface drainage: A problematic combination.

1.1.1 Historical Context

Ditch digging is said to have occurred as early as 9000 years ago in Mesopotamia (Beauchamp, 1987). But the most serious impacts on ecosystems undoubtedly started with the mechanization of the process and the arrival of subsurface drainage at the turn of the 20th century (Pierce et al., 2012). The state of Ohio provides one of the many striking examples of the extent of drainage networks construction during this period: 32 000 km of trapezoidal channels were dug from 1840 to 1980 (Dahl, 1990). Similar activity has occurred in Quebec's fertile lowland regions, although the exact numbers vary significantly between authors. Beaulieu (1999) states that nearly 30 000 km of channels were dug (either to channelize preexisting streams or to extend the drainage network), and an additional 20 000 km of works were performed in already channelized streams as of 2001. Boutin et al. (2003) mention 44,000 km of straightened watercourses while Biron and Rousseau (2009) separate this number in two: 30,000 km of straightened meandering streams and 14,000 km of new channels. Intertwined with channelization's expansion was the gradual appearance of subsurface drainage systems which were present in 44 million hectares of US agricultural land in 1985 (USDA, 1987). As for the province of Quebec, the most recent figures available are from 2003 (Table 1.1). More than 10 years later, those numbers can only have gone up as the popularity of such systems is undeniable and producers will not remove an existing drainage system. In fact, the recent trend is to double the number of lateral pipes (information taken from a soon to be published report by the Conseil pour le Développement de l'Agriculture du Québec). Straightened channels are mostly associated with improved drainage capacity and reduced channel migration objectives, but their greater depths also serve very well subsurface drainage outlets positioning (Jayakaran et al., 2010). As we shall see further, this combination is extremely problematic from both water quality and geomorphological standpoints.

Table 1.1: Subsurface drainage presence for every agricultural region of Québec[1]

Region	Subsurface drained fields (%)
Abitibi-Témiscamingue	24 ± 4
Bas Saint-Laurent	30 ± 4
Centre-du-Québec	47 ± 5
Chaudière-Appalaches	42 ± 5
Estrie	30 ± 5
Gaspésie-IDM	8 ± 3
Larentides/Laval/Montréal	45 ± 6
Mauricie	53 ± 5
Montérégie-Est	73 ± 5
Montérégie-Ouest	80 ± 4
Outaouais	26 ± 4
Québec-Capitale Nationale	37 ± 5
SaguenayLSJ/Côte-N/N-d-Q	58 ± 4
Province	**51 ± 2**

[1]Source: Drolet and Pigeon (2005).

1.1.2 Water quality impacts

Low order streams, representing head sources, will be the main focus of the proposed thesis mainly because of the easier implementation of management alternatives but also because of their ecological importance which was not always recognized along the continuum of river ecology's paradigms (Meyer et al. 2003; Finn et al. 2011). Headwater streams represent over two-thirds of the channel lengths encompassed in a typical drainage basin, making their alteration greatly responsible for the environmental depletion of bigger bodies of water downstream (Freeman et al., 2007). Strahler order 1-3 streams also show the greatest potential for large scale nitrogen treatment (Craig et al. 2008).

One of the major causes of agricultural stream deterioration is channel maintenance (Figure 1.1) being carried out in a recurrent way to unclog subsurface drainage outlets and restore the initially planned channel profile (Needelman and Allen 2007; Jayakaran et al., 2010). Freshly dredged banks have been confirmed as having very poor nutrient and herbicide retention capacities compared to non-perturbed banks (Smith et al., 2006; Pappas and Smith, 2007; Smith and Pappas, 2007). With an estimated average recurrence interval of 15 years for dredging activities in Quebec, soils are not allowed to develop the proper biogeochemical complexity needed to reduce pollutant runoff.

Figure 1.1: Clogged outlets (left) are a prime motivation to carry out dredging operations (right photo shows a recently dug ditch).

Improved drainage at the landscape scale led to considerable loss of floodplains and wetlands. A good example of this is the near disappearance of the Great Black Swamp, which used to cover 4000 km^2 in northwestern Ohio – now dominated by agriculture (Mitsch and Gosselink, 2007). Wetlands are widely recognized as hosting unique natural biogeochemical processes. Most notably, denitrification (Hunt et al., 2005) and particulate bound phosphorus sedimentation and phosphorus sorption (Dunne and Reddy, 2005) are absolutely essential to control the eutrophication of waterways. The loss of wetlands leads to the loss of those processes. This is particularly important when considering the very large amounts of fertilizers applied each year on agricultural land which are lost through both natural and artificial pathways.

Artificial pathways are embodied by subsurface drainage systems which completely bypass riparian vegetation (Osborne and Kovacic, 1993). This reduces the efficiency of the highly popular vegetated buffer strip technique in agricultural areas (Lemke et al., 2011). This management paradigm led to the adoption of environmental laws for minimal untouched vegetation widths along waterways of the province. NO_3-N is the main chemical lost this way because of its high solubility (Fraser and Fleming, 2001). Many authors have shown clear indication of significantly greater NO_3 exports from fields having subsurface drainage (Hill 1976; Skaggs et al., 1994; Thomas et al. 1995; Lemke et al., 2011). However, another clear scientific consensus is that subsurface drainage greatly reduces runoff volumes and consequently diminishes exports of sediment bound, poorly soluble nutrients like P, K, organic N and NH_4 (Baker et al., 1975; Hill 1976; Skaggs 1994). Overall, the same principle seems to apply to pesticides, although some are more soluble than others (Bastien et al., 1990; Kladivko et al. 2001). The dominant weight of headwater stream lengths in watersheds is even more important in subsurface drained areas because they receive the majority of drainage water. Figure 1.2 illustrates an example of the disparity between headwaters and more substantial downstream channels: 1-2 order streams in the Des Fèves watershed total approximately 250 km (80% of the watershed's entire channel lengths).

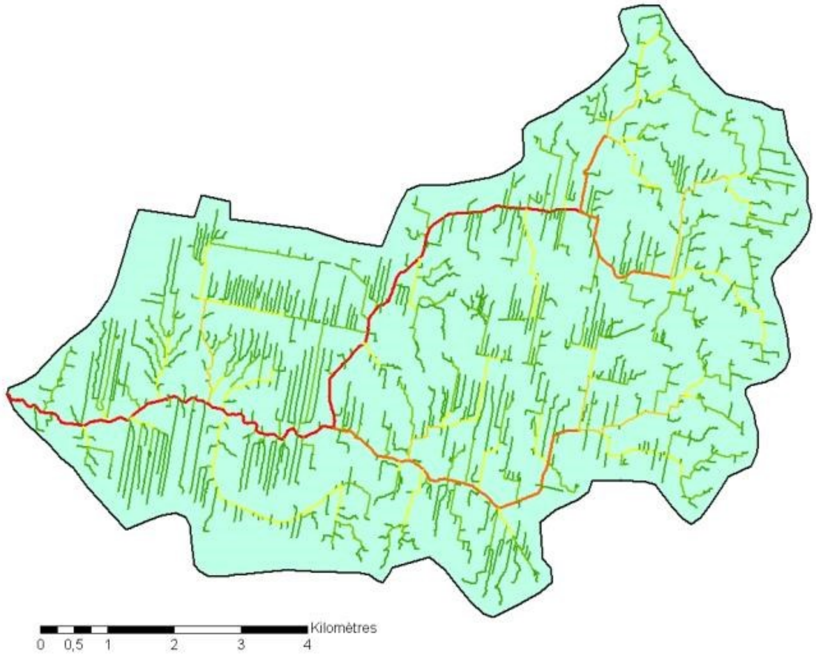


Figure 1.2: The des Fèves watershed's hydrological network, with low order (1-2) streams in green and higher order channels (3-4-5-6) shifting towards red.

Agriculturally dominated watersheds can also cause the deterioration of more fragile and complex downstream environments. The most publicized example is the Mississippi river basin which was identified as a major source of organic pollutants causing hypoxia in the Gulf of Mexico (Malakoff, 1998; Rabalais et al. 2002). At a considerably smaller scale, the lake Saint-Pierre (a Ramsar Convention wetland and UNESCO biosphere reserve fluvial lake near Trois-Rivières, Québec) is seeing comparable mechanisms responsible for the depletion of its ecological condition (Hudon and Carignan, 2008). The ecological effects of channelization will be developed in the next section, with a special attention given to physical habitat alterations.

1.1.3 Ecogeomorphological impacts

Channelization leads to increased velocities due to significantly greater channel dimensions, particularly depth since ditches are designed to hold a flood of a recurrence interval of approximately 10 years (Bukaveckas, 2007), while minimizing width in order to avoid loss of land.

In comparison, a natural channel can only hold a flood of a 1.5 to 2-year recurrence interval (Dunne and Leopold, 1978; Knighton, 1998). Another strong factor explaining higher energy in those fluvial systems is the increase in slope as a formerly meandering stream sees a considerable reduction in length when straightened. The combined effect of deepening the channel and increasing the slope results in considerable increase in bed shear stress (τ), defined as:

$$\tau = \rho g R_h S_0$$

where ρ is water density, g is acceleration due to gravity, R_h is hydraulic radius and S_0 is channel slope. Because shear stress is directly related to sediment transport, ditch designs result in increased bank and bed erosion in what used to be a low energy aquatic environment. A commonly used technique to mitigate bank erosion in the province is riprap – loose stone application on specific areas where erosion is observed (Figure 1.3). While this approach will mitigate erosion for shorter time scales, it will be ineffective for longer time scales as this hard structure can increase downstream erosion (Florsheim et al., 2008). Erosion is a natural process and restraining it leads to reduced ecological benefits (e.g. sediment source for diverse riparian habitats, modulation of stream morphology changes, etc.) (Florsheim et al., 2008). However, the erosional response of channelized streams isn't due to natural stream mobility, but rather to an adjustment process following a drastic change to the stream's morphology (Simon, 1992). Channel widening and mass-wasting are symptomatic of a fluvial adjustment to channelization, but are not acceptable processes to farmers as they lead to land losses. We are thus currently trapped in a system with highly modified fluvial systems deprived of any potential mobility towards dynamic equilibrium and optimal ecological functioning.

Although headwater streams in agricultural watersheds may not appear as suitable habitat for fish, a surprising range of species use them. For example, various fish species (ranging from minnows to adult northern pike) were observed at times in drainage ditch systems of Lake Erie tributaries (Tessler, 2012). On the other hand, Lau et al. (2006) found significant negative impacts of channelization on fish assemblage quality. Channelized streams and rivers also support lower fish abundance than their meandering counterparts (Frothingham et al., 2001). Both of those works attribute such an effect to lower habitat heterogeneity (mainly the lack of pool-riffle sequence).

Similarly, the presence of woody debris in streams is a strong explanatory factor of fluvial heterogeneity and ecological integrity (Benke and Wallace, 2003; Lester et al. 2007). In cultivated areas, riparian woody vegetation is mostly viewed as a nuisance compromising drainage efficiency and provoking aforementioned unwanted erosion (Ferrell et al., 2006). Such a perception is also present in Québec and this type of vegetation is subject to many treatments along agricultural waterways. Sweeney et al. (2004) also mention stream narrowing due to deforestation and a resulting loss of ecological services (mainly in-stream water pollutants treatment).

Figure 1.3: Bank failure due to erosion (left) and riprap applied to counter this phenomenon (right) in the des Fèves watershed.

More broadly, it is important to recognize ditches as the last remaining bastions of general biodiversity in intensively cultivated areas (Figure 1.4) (DEFRA, 2002; Herzon and Helenius, 2008). Although the focus has been put towards the ichthyologic importance of stream morphology, the riparian areas also support important land flora and fauna. Banks generally have steep banks due to channelization and cannot be properly cultivated. Also, even though producers don't always wholeheartedly embrace this rule, a 1 m vegetation strip has to remain untouched on the top of the bank slope. Reducing dredging operations that scrape bank vegetation would be beneficial to preserve what little remains of native vegetation in intensely agricultural settings.

Figure 1.4: The majority of the remaining fractions of natural vegetation are found mostly near streams (2009 photography of the downstream portion of the Des Fèves river – flow direction is N-W).

1.1.4 Economic impacts

Beaulieu (1999) provides insight to the order of magnitude of ditch digging costs for the ministry of agriculture from the moment they transferred intervention decisions to municipalities in 1994 (Table 1.2). From that year onwards, the MAPAQ (Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec) reimbursed 70% of the maintenance costs to the producers.

Table 1.2: MAPAQ dredging operation refunds from 1994-1998

Year	**MAPAQ refund**
1994	$664 000
1995	$1 022 000
1996	$1 558 000
1997	$1 365 000
1998	$1 937 000

More recent data on ditches in the Montérégie region reveal that for 2011 and 2012, 279km and 278km were dredged (Gravel, 2013). If we apply a very conservative construction cost of $15000/km, we obtain an average amount of $4,177,500 every year for that region alone. These data were provided by the ministry of Natural Resources and Fauna which receives pre-construction notices. Attempts to obtain information from the MAPAQ – which reimburses 70% of the construction cost to the producers – were so far unsuccessful, which is surprising since these are public funds.

Considering the large amounts of public money invested in this dredging activity, alternative designs that lead to more stable channels in the long term while maintaining drainage efficiency should at least be explored. Even if they generally present higher implementation costs than the maintenance of already constructed trapezoidal ditches, a longer-term analysis may reveal economic benefits if they result in reduced maintenance operations once built.

1.2 Innovative designs for enhanced stream integrity

1.2.1 The self-formed stream using an over-wide ditch

While the literature on the erosional response of streams to channelization is abundant (e.g. Shields et al., 1998; Wyzga, 2001; Shields et al. 2010), it is not the case for the depositional processes under constant sediment input conditions from the watershed (Landwehr and Rhoads, 2003). Many authors observed deposition within sand bed low-gradient channelized streams in the form of a meandering inset channel within the confines of a miniature floodplain (Figure 1.5) (Brookes, 1987; Rhoads and Herricks, 1996). Landwehr and Rhoads (2003) mention resemblance between those observations and the underfit stream concept (Dury, 1965). These two fluvial expressions are similar in terms of form, but are very different in terms of processes. A natural underfit river meanders within the confines of a former considerably bigger river channel generated by higher discharges from another climatic era (Figure 1.5). As for channelized streams, the inset channel isn't entrenched in a former channel's alluvium, but rather meandering through recently deposited sediment. This deposition is mainly explained by weaker stream capacity due to an imposed over wide channel (Landwehr and Rhoads, 2003). These self-formed channels are often referred to as unintentional since the primary purpose of ditches is drainage efficiency. By altering the initially planned profile, the drainage capacity of the constructed channel is necessarily changed. This is one of the prime reasons behind dredging operations. To account for this natural channel evolution while trying to maintain optimal planned drainage, the idea of a wider ditch was proposed as compromise (Jayakaran et al., 2010). This ditch would intentionally be over-wide in order to promote depositional processes and allow proper floodplain to inset channel width ratio. Powell et al. (2007a) mention a minimum of 3 times the inset channel's width at the bottom of the trapeze, 3-5 being the optimal range of ratios.

Letting the fluvial system adjust in this way leads to a state of dynamic equilibrium, where virtually no more dredging is required. Unfortunately, no authors mentioning this approach have identified a potential conflict between stream deposition and deep subsurface drainage outlets, presumably because in their study areas the drain outlet was sufficiently high above the channel bed, which is often not the case in Quebec. This issue is developed in the third part of this chapter. Assuming subsurface drainage efficiency is not compromised and that the cross-sectional profile is sufficiently large to provide the desired water evacuation capacity, this would mean the end of cleanout operations with potentially large water quality benefits. Indeed, letting the stream adjust generates floodplain soil of higher carbon content and better structure than the subsoil composing the constructed benches of the two-stage channel design seen in the following section (Jayakaran and Ward, 2007; Jayakaran et al., 2010).

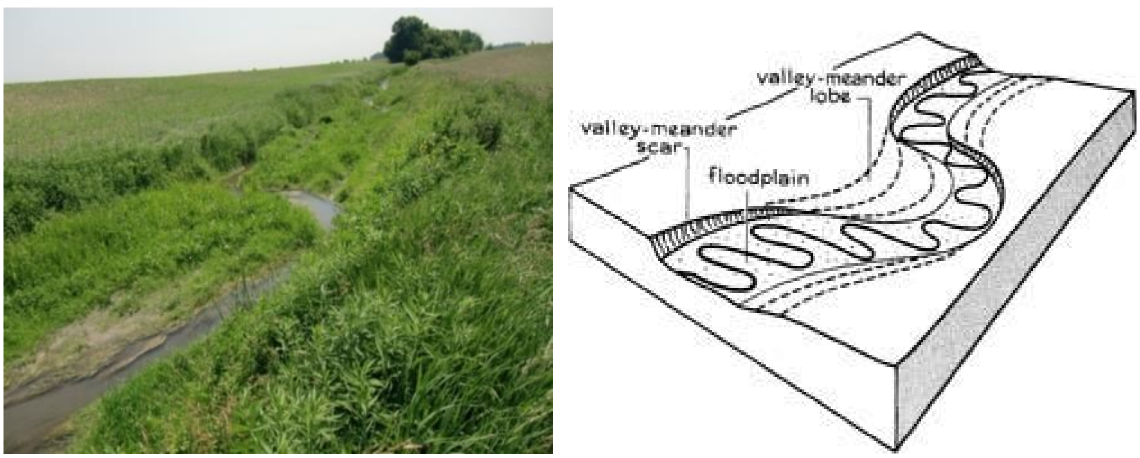


Figure 1.5: Left, an unintentional self-formed stream in the des Fèves watershed (pictured in the summer of 2012); Right, underfit stream meandering within a former bigger river channel (Springer Reference, http://www.springerreference.com/docs/html/chapterdbid/43380.html, 2014).

1.2.2 The two-stage channel design

The earliest mentions of a two-stage cross-sectional channel profile date back to Dobbie et al. (1971), Keller (1975) and Hinge and Dollis (1980). The main concern at the time was to reduce flooding frequency and severity while trying to avoid disturbing the natural channel with the typical channelization option (Sellin, 1990). This design was more recently recycled for agricultural low-gradient streams (Powell et al., 2007a). Quite similar to the initial versions, this approach aims at reducing human disturbances to a naturalizing channel. This technique is also highly similar to the self-forming stream. The main difference with the over-wide ditch is to build a dynamically stable naturalized state by widening the benches using machinery instead of simply promoting natural bench formation (Figure 1.6). This considerably accelerates the process of bench generation. The authors at Ohio State University focus on improved drainage capacity when presenting these bench widening concepts (Powell et al., 2007a). As previously mentioned, water conveyance is compromised when the trapezoidal cross-section profile is altered (by sediment accumulation, woody debris, etc.). This technique is therefore presented as a good balance between efficient open channel water evacuation and natural fluvial functioning.

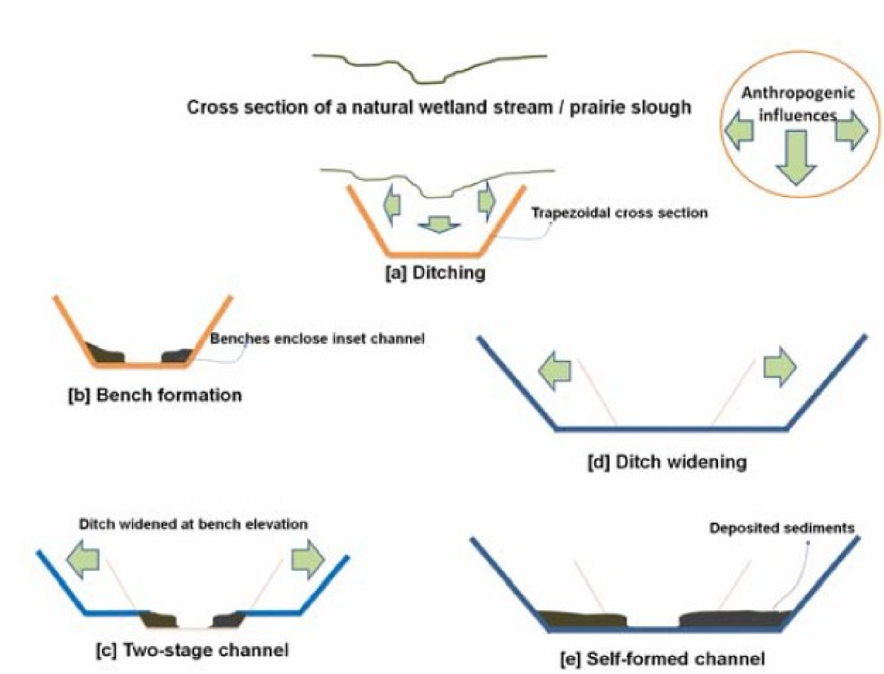


Figure 1.6: The self-formed channel (e) versus the two-stage channel (c), different construction operations that both lead to more stable fluvial systems (Jayakaran et al. 2010).

The reference reach approach to stream restoration is the theoretical background of this method (see Rosgen, 1996). The basic principle is to collect channel dimension data on a stable reach for a particular environment and use this information to restore similar conditions to a perturbed reach within a similar region. For the case of the two-stage channel design, regional curves of channel dimensions related to drainage area are used (Powell et al., 2007a). The so-called Rosgen classification approach is so popular in the United States that its sound knowledge is generally a requirement for being hired (Malakoff, 2004). Rosgen's school of thought has received criticism from renowned fluvial geomorphologists since the very beginning (Kondolf, 1995; Miller and Ritter, 1996; Doyle and Harbor, 2000; Simon et al., 2007). The stream classification system is essentially based on form, even though the discipline of river research has become formidably well equipped for quantitative analysis and thus process-based research. These processes are governed by uniform laws of physics, making them applicable in every existing environmental setting. Bankfull discharge measurements are central to the Rosgen approach. However, this can be particularly problematic as they are associated with stable channels (Simon et al., 2007) and not all the so-called reference reaches are stable. While they recognize the inconsistencies of the Rosgen theory, Jayakaran et al. (2010) argue that the self-forming stream or two-stage designs are proposed for low-energy slowly changing headwaters, also calling them very forgiving environments. In other words, low-order and low-gradient highly modified streams allow a lot of room for error without catastrophic results when trying to intervene as those systems have already been through drastic changes.

Because this design was only developed and promoted recently, ecological benefits remain mostly hypothetical, although many already advocate favorably for it because of the very poor state of trapezoidal channels (Pierce et al. 2012). One of the first major efforts in this regard indicates that connectivity to a floodplain is a major driver for macroinvertebrate and fish communities (D'Ambrosio et al., 2014). However, the studied naturalized ditches featured benches too small and/or intermittent for this conclusion to be confidently applied to two-stage ditches. Thus, much more work needs to be done in this regard.

As for water quality, the higher stability of the system is already a benefit as the dredging cycle could be definitely broken or at least see its recurrence interval increased substantially (Powell et al., 2007a). Even though the oldest agricultural two-stage channel project dates no more than 15 years ago, there are already peer-reviewed results of improved nitrogen retention over the trapezoidal ditch (Powell and Bouchard, 2010; Roley et al., 2012). In order to boost denitrification rates even more, horseshoe wetlands could be employed in conjunction with the two-stage channel design or the self-formed stream. This design will be explained in depth in the following section.

While this alternative channel design originated in the Midwestern US, it is interesting to note its emergence in other regions of the world. For instance, Finnish researchers examined cohesive sediment mobility through a two-stage channel constructed by a local water and environmental authority in southern Finland (Vastila and Jarvela, 2011; Vastila et al., 2015). The floodplain was constructed on only one side of the ditch which is not a recommended practice as bank failure was observed for such sites in the US (Dr. Jonathan Witter, Personal communication, July 20, 2014). Also, there does not appear to be any evidence for a regional curve approach for two-stage ditch sizing in Scandinavia. This might have some consequences on the stability and/or the water quality benefits of the system. Nevertheless, the presence of a floodplain element remains beneficial as long as water can easily rise up to that level. "Improvised" two-stage channels also exist, as illustrated in Figure 1.7. This unusual design was constructed by a producer in Montérégie without consulting any experts or asking for permits. Again, this was not executed according to the recommended steps established by Dr. Ward's team, but could help stabilise if sediment like sand and silt can easily access the bench and cover the exposed hard clay layer, thus allowing proper soil conditions for plant colonisation. Monitoring of this site could prove very interesting to see the evolution of a two-stage channel that was not constructed based on the regional curve of channel geometry approach.

Figure 1.7: “Improvised” one sided two-stage channel built by a farmer in the L’Acadie river basin.

1.2.3 Disconnecting subsurface drainage outlets from ditches

The depositional response to channelization mentioned earlier is probably what clogs deeper drain outlets. Surprisingly, the authors promoting the previous techniques recognize this blockage is what partly triggers dredging operations, but they don’t address the fact that the two-stage channel design or the self-formed stream could be encroaching subsurface tile drainage outlets because of their inclusion of those depositional features. As this problem is not highlighted in the scientific literature, there are consequently no alternative designs directly addressing this issue. However Petersen et al. (1990) proposed a horseshoe wetland design to address higher pollutant exports at drain outlets (Figure 1.8). These researchers also suggested this wetland design because they recognized woody vegetation roots could compromise drainage efficiency when implementing vegetated buffer strips.

While this setup was designed with water quality improvements in mind, it also offers potential as a method to laterally disconnect deep drains from streams, thus moving away from the traditional approach of linear dredging (generally over several kilometers) and providing opportunity for minimal disturbance with a punctual approach where only the wetland is dredged. Petersen et al. (1990) indicate that it should be at least 10 meters in length along the channel and 8 meters wide in the land. Subsurface drainage outlet length in the province average 5 meters (i.e. the distance between the stream and the lateral drains), thus limiting optimal horseshoe wetland dimensions (cutting part of the outlet pipe is easy, but encroaching on the rest of the tile drainage system would bring a lot of issues). This technique is designed firstly as an approach for stream naturalization promotion, but hard bank stabilization and/or periodical dredging of this small area could be considered as an option. This would result in less intervention than the current situation since it would only be punctual, instead of working on the entire stream's length.

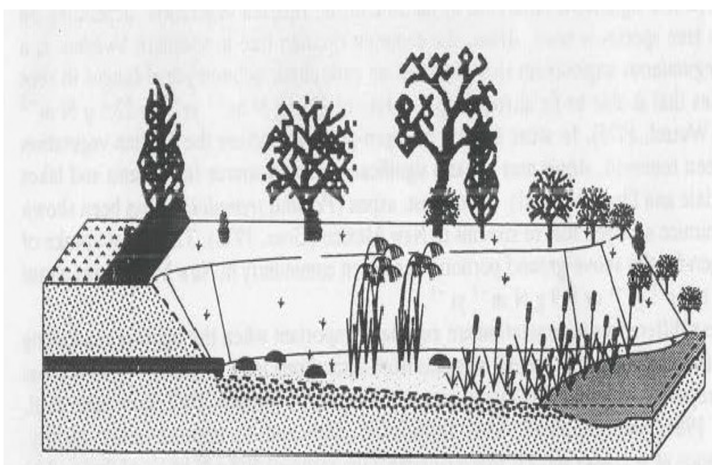


Figure 1.8: Small constructed horseshoe wetland to treat concentrated pollutants at subsurface drain outlets (Pertersen et al., 1990).

There is sometimes a lack of broader perspective in the field of restoration and managers tend to forget there is often the option to do nothing and let the watercourse adjust by itself towards dynamic equilibrium (Adam et al., 2008). The Petersen et al. (1990) approach of slightly disconnecting subsurface drainage outlets from the stream using a horsehoe wetland appears as a good way to support such school of thought in river restoration. However, it is important to examine the actual ditch width in relation to its drainage area, as it might not be wide enough to promote proper naturalization and bench to inset channel ratio.

1.2.4 Controlled drainage

While the alternatives exposed so far directly address channel morphology and ecological functioning, controlled drainage rather focuses strictly on modifying subsurface tile drainage. It could thus very well be employed in conjunction with the fluvial process centered alternatives.

The basic principle is to enhance control over the water table level by installing or removing flashboard risers in a box at the outlet's position depending on the weather and time of the year (Figure 1.9). Boards are completely removed during the springtime melt to bring the water table down quicker for a timelier sowing period.

Benefits mostly impact nitrate output reductions (Gilliam et al. 1979; Gilliam and Skaggs, 1986), but phosphorous reductions were also measured in some cases (Evans et al., 1995; Wesström et al., 2001; Wesström and Messing, 2007).

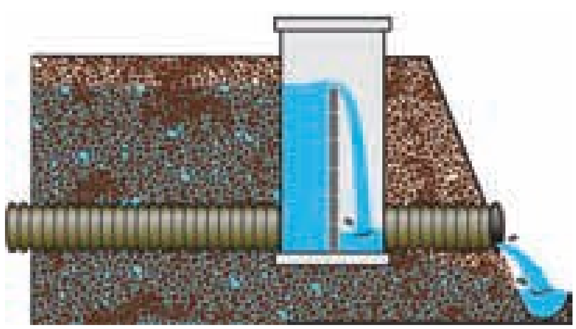
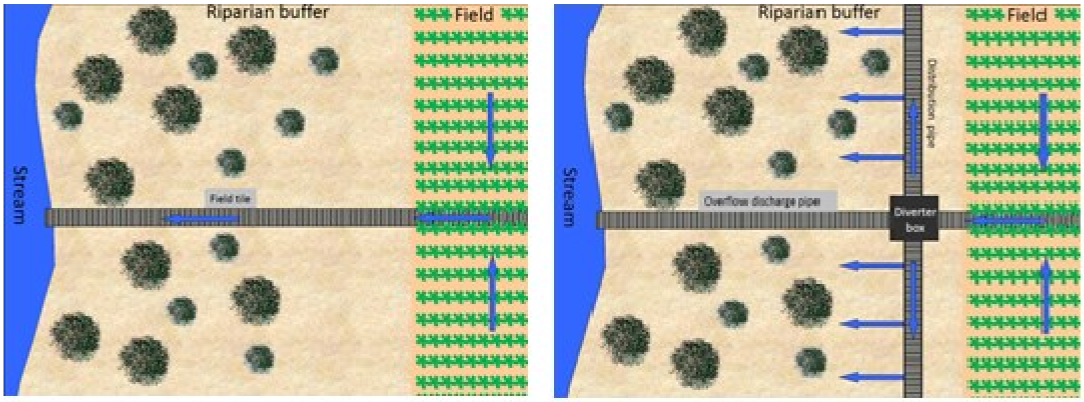


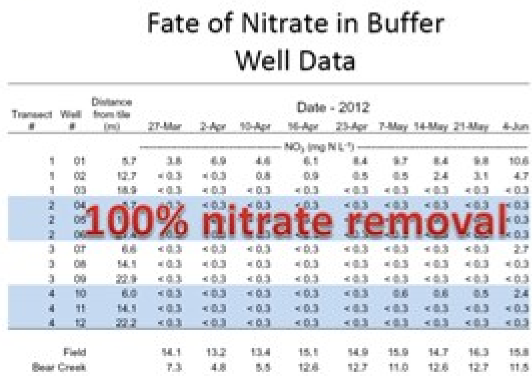
Figure 1.9: Controlled drainage structure (Frankenberger et al., 2006).

Besides the experimental work led by Chandra Madramootoo at the McDonald campus of McGill University (e.g. Madraamootoo et al., 2007), this design has not been applied in Québec so far.

This is certainly due to the fact there are very little benefits for the producers. Some criticisms were raised by scientists for truly efficient nutrient export reductions using this approach. First, raising the water table inevitably leads to more runoff water – thus more sediment bound organic pollutants and pesticides. Second, in Illinois the greatest amount of nutrients were measured during high to extreme discharges (Royer et al. 2006). The producers would be tempted to remove all the boards to have optimal drainage during those periods as a very wet field can lead to serious damage in terms of plant productivity (Torbert et al., 1993; Lauer, 2008). Nevertheless, having more control on the water table can still present interesting opportunities when employed properly. Considering potential stresses linked to climate change, this structure could help mitigate some of the potential future detrimental effects. It is also quite affordable at around $208/ha (Agriculture Canada, 2010), which is an important factor in a field where the social acceptance component is so crucial to successful projects.

A modified controlled drainage system, which re-saturates riparian buffers, was recently presented by Jaynes and Isenhart (2013). The basic functioning of this system is to run perforated pipes parallel to the stream and through a diverter box. This approach aims at restoring the connectivity between the underground water and vegetated buffer roots. Preliminary results show astounding remarkable 100% nitrate removal (Figure 1.10). This technique appears well suited for waterways bearing substantial buffer strips, but as outlined earlier, the majority of agricultural watershed streams are low order drainage waterways with a minimal 1 meter wide buffer required by the law. Not only is such a width insufficient to have good nitrate export reductions (Castelle et al. 1994), but farmers are not always respecting this limit.





Transect #	Well #	Distance from tile (m)	27-Mar	2-Apr	10-Apr	16-Apr	23-Apr	7-May	14-May	21-May	4-Jun
			Date - 2012								
			NO_3 (mg N L^{-1})								
1	01	5.7	3.8	6.9	4.6	6.1	8.4	9.7	8.4	9.8	10.6
1	02	12.7	< 0.3	< 0.3	0.8	0.9	0.5	0.5	2.4	3.1	4.7
1	03	18.9	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3
2	04	[illegible]	[illegible]	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3
2	05	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	< 0.3
2	06	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	< 0.3
3	07	6.6	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	2.7
3	08	14.1	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3
3	09	22.9	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3
4	10	6.0	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	0.6	0.6	0.5	2.4
4	11	14.1	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3
4	12	22.2	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3
Field			14.1	13.2	13.4	15.1	14.9	15.9	14.7	16.3	15.8
Bear Creek			7.3	4.8	5.5	12.6	12.7	11.0	12.6	12.7	11.5

Figure 1.10: Re-saturating buffers is an interesting addition to a traditional controlled drainage system for major nitrate export reductions (Jaynes and Isenhart, 2013).

Finally, the vegetated buffer strips in Jaynes and Isenhart's experiment comprised woody vegetation, which provides greater nitrate uptake than grasses (Osborne and Kovacic, 1993). In Quebec, wood is rarely present along agricultural ditches because of the erosion the debris may cause. This technique is well suited for larger vegetated buffer strips, but is likely not effective in cases where the buffer strips are much smaller, as is the case in Quebec.

1.2.5 Modelling tools for agricultural water management

Models are very useful tools to help evaluate various management alternatives prior to their actual implementation. A very large number of modelling tools are available to examine various problems in agricultural watersheds. Only the most relevant to this project are presented here.

According to Borah and Bera (2003), the most complete watershed scale non-point source pollutant models are the Soil and Water Assessment Tool (SWAT), Hydrological Simulation Program – Fortran (HSPF), Annualized Agricultural NonPoint Source pollution (AnnAGNPS) and MIKE SHE. These models all include the option of incorporating a subsurface drainage component, which is essential in agricultural watersheds. They are numerical tools known to perform very well for catchment scale nutrient export estimations, but they require large amounts of input data to capture the complexity of watersheds. According to Ahmed et al. (2007), the most popular models at the individual field crop scale include: the Root Zone Water Quality Model (RZWQM), DRAINMOD, Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) and Leaching Estimation and Chemistry Model (LEACHM). These models are mainly used for the analysis of controlled drainage systems effect on water quality.

The agriculture-oriented models mostly focus on groundwater and pollutant dynamics at the field or watershed scales. However, open channel hydraulics is a non-negligible aspect of agricultural water management because of the typically highly extended surface drainage networks and the impact of flooding on crop yields. The Hydraulic Engineering Center's River Analysis System (HEC-RAS) is a free 1D hydraulic modelling tool developed by the US Army Corps of Engineers allowing simple and efficient analysis of open channel flow dynamics. One of the most popular uses of this model is flood mapping (e.g. Tate and Maidment, 1999; Knebl et al., 2005). This model is perfectly suited for channelized watercourses because of the simplicity of the hydraulic parameters governing flow conditions. In contrast, 2D and 3D hydraulic models require more detailed data which may not be required for flooding analysis considering the fairly simple cross-sectional shape of the channel (Syme, 2011).

1.3 Summary and Research Objectives

Despite a growing popularity in the Corn Belt of the USA, the aforementioned alternatives have not so far been considered in Quebec. Although recurrent dredging is costly and causes strong negative environmental impacts, it remains the dominant, if not the only, way of managing agricultural streams in Québec, with very little questioning from the concerned actors. Sustainable alternatives based on sound geomorphological principles were presented above, but their applicability in Quebec remains to be tested. The two-stage channel design and the self-formed stream using an over wide ditch were developed in regions with highly similar climatic and geologic contexts to Quebec's lowlands, providing initial confidence in their implementation potential. However, the presence of deep subsurface drainage outlets could compromise the development of natural fluvial features (mainly benches) in channelized streams. This issue isn't clearly underlined in the scientific literature even though drain clogging is sometimes identified as a major reason for initiating ditch dredging operations.

The first objective of this research is to assess the feasibility of implementing the two-stage channel or the self-forming channel designs in reaches representative of the agricultural landscape of Quebec. Specific research questions related to this objective are:

1. How much additional space is required to implement alternative ditch management approaches for selected reaches in southern Quebec?
2. Is there an impact of alternative approaches on drainage efficiency?
3. How do alternative approaches compare with traditional management from an economical point of view?

The second objective is to investigate the design of subsurface drainage systems in Quebec in comparison to those of Ohio, which is the state that hosts the largest number of two-stage channel projects. In Ohio, deep drain outlets do not seem to present a conflict with the implementation of alternative approaches. Two hypotheses will be tested for this part of the project.

1. That there could be a flaw in the design of subsurface drainage systems in Quebec, resulting in deeper than necessary drain outlets.

2. That the colonial heritage of land division in Quebec could be responsible for the deeper drain outlets. Indeed, the basic shape of current farm fields in Quebec is inherited from the rectangular *seigneuries* in New France, whereas elsewhere in North America fields are organized in a more squarely fashion. The distance between upstream and downstream subsurface drainage tiles is therefore potentially much greater, imposing more constraints on the design in order to maintain sufficient slopes.

The third objective is to evaluate what changes could be made to subsurface drainage systems to solve the problem of outlets being too close to the river bed, and thus accommodate naturalization processes.

2.1 Study areas

Three sites which fit within the suggested drainage area limits for two-stage channel applications (between 1 mi ^{2} and 10 mi^2 – Powell et al., 2007a) were identified. The project targeted the Des Fèves, Lacolle and L'Acadie watersheds in the Montérégie region of Québec. Additionally, three other sites were chosen for crop yield analysis near streams (Figure 2.1). The Montérégie region accounts for a little over 7000 farms, accounting for a quarter of all agricultural land in the province, mostly dominated by vegetable, corn and soybean crops, which respectively represent 65%, 62% and 48% of the provincial production (MAPAQ, 2014). Intensive channelization occurred in this agriculturally dominated region during the 20th century. The earliest aerial photographs (dating back to 1930) show that the conversion of forested areas to agricultural land was already very advanced in the early 20th century. Some historical photos show areas with even less forest than today. As for channelization, many meandering streams were already straightened by 1930, but a few meandering channels can be observed on some of the higher order river sections (Figure 2.2). The resolution of the 1930 aerial photos does not allow for a proper assessment of the state of channelization in headwater channels, but it is highly likely that the majority of the ditch network was already dug, while the more energy demanding high order streams and rivers were completed later on when machinery became available.

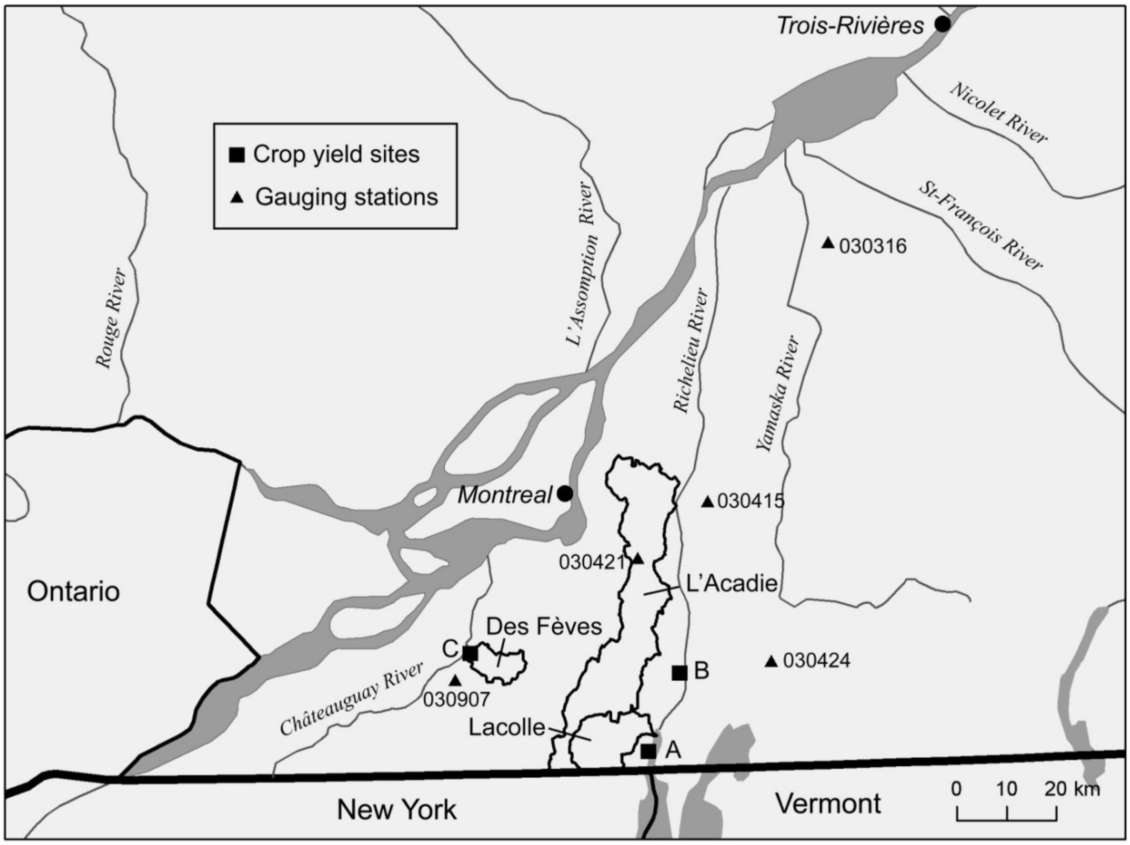


Figure 2.1: Location of the Des Fèves, Lacolle and l'Acadie watersheds, the crop yield analysis sites and the nearest CEHQ gauging stations.

Figure 2.2: A meandering reach of Strahler stream order 5 on the Des Fèves watershed in 1930 (left), channelized later (photo on the right from 2009).

2.1.1 Geomorphological analysis sites

In order to work on research objective #1, a representative study reach was chosen in each watershed for more intensive analysis. Criteria for site selection were the following: a lower order tributary, but with perennial flows; a channelized pre-existing stream; the presence of subsurface drainage that matched typical drainage systems in the province; ongoing dredging activities; and openness of farmers. In order to ensure the selected reach was a natural stream before human intervention, a detailed analysis of a high-resolution (1 m pixel size) LiDAR Digital Elevation Model (DEM) was conducted to verify the presence of fluvial features such as depressions indicating oxbow lakes (former meander loops). This was combined with an analysis of the 1930 aerial photos to see the presence of unperturbed streams nearby.

The Des Fèves river branch number 53 was already straightened in 1930, but the LiDAR DEM showed clear signs of former meandering in the landscape (Figure 2.3). This 4.09 km stream drains approximately 327 hectares with the majority of surrounding corn/soy fields having subsurface drainage systems emptying into it. The downstream portion of this reach is the only zone that has not been straightened and that still has a sinuous layout (see Figure 1.5). A dredging operation was carried out on most of this study-reach length during late summer or early autumn of 2013.

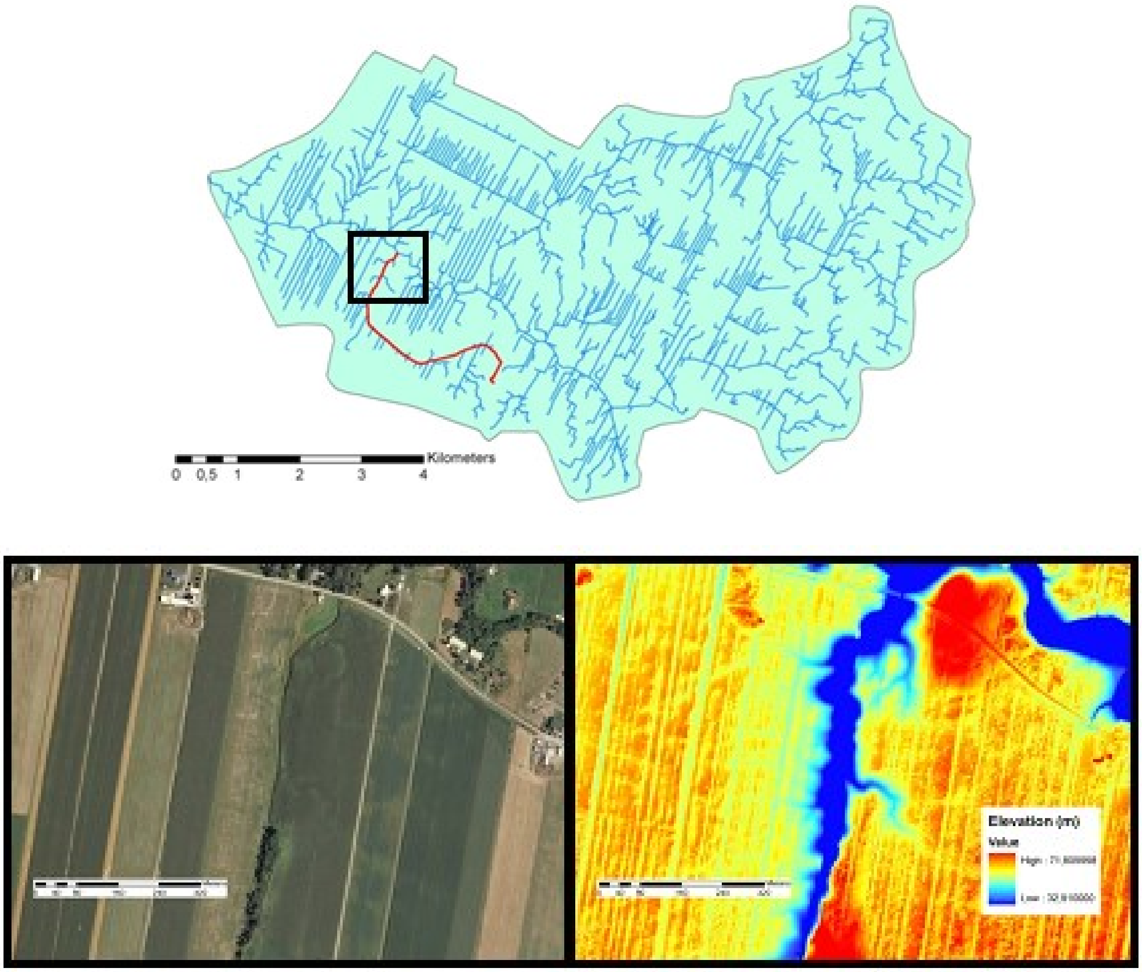


Figure 2.3 Top: the Des Fèves watershed with the selected reach in red; Bottom left: aerial photography shows an apparently standard agricultural ditch but LiDAR DEM (bottom right) reveals a clear imprint of former meandering in the landscape.

The Cours d'eau Barrière in Lacolle River's watershed showed partial meandering in the 1930 photography and the ~697 ha drainage area leaves little doubt about it being a natural pre-settlement stream. The surrounding field are all on corn and soy rotations with the vast majority featuring subsurface drainage. The 1930 photographs feature some meander scars near the present-day channel, but the resolution is not sufficiently high to confirm this. Since it is a fairly large stream this study focused on the downstream section, between Pleasant Valley Road and the Lacolle River, which is 3.9-km long (Figure 2.4). A dredging operation was conducted during the summer of 2013.

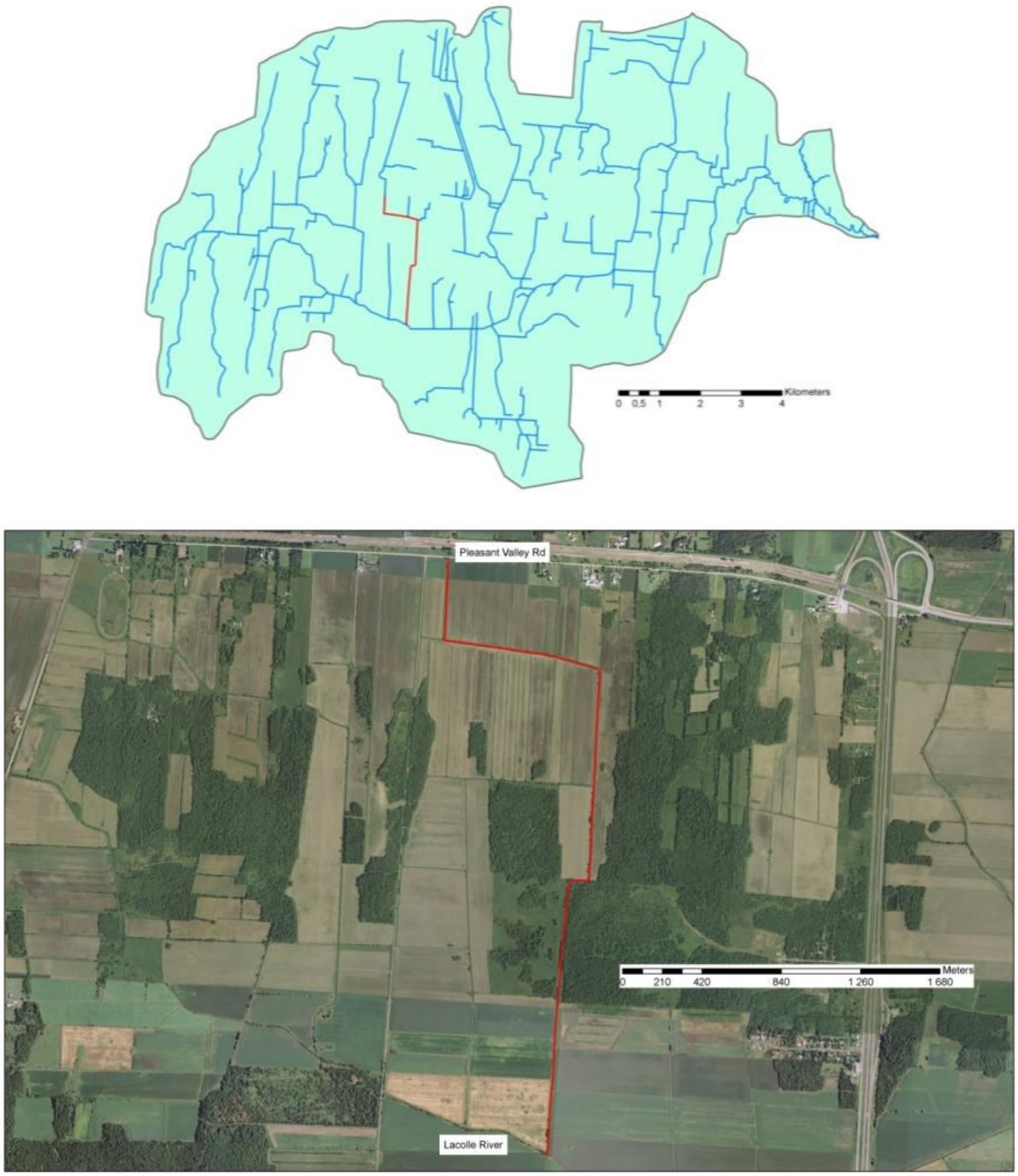


Figure 2.4: Top, location of branch number 16 within the Lacolle watershed; Bottom, aerial photography of the downstream portion between Pleasant Valley road and the Lacolle River.

Branch C of the L'Acadie watershed is a tributary located east of the village of Hemmingford, close to the small headwater US portion of the watershed (Figure 2.5). The year of the last dredging operation remains unknown. This site was chosen because of its organic soils, which in this region covered an estimated 4300 ha in 1972 (BMI, 2005). Many producers are cultivating these rich soils within the l'Acadie basin, with a particularly strong concentration of vegetable crops that see optimal growing conditions in this type of substrate. The first field from the junction with L'Acadie river features potatoes while the rest are on corn and soy rotations. Previously outlined management alternatives focus primarily on mineral soils. Further investigation on their applicability in regions dominated by organic soil is thus needed. The studied reach has a drainage area of ~253 ha and is a significant contributor of the upstream portion of the l'Acadie River which flows towards the Chambly basin. The total stream length is around 1.4 km, but there is contact with cultivated fields only for 480 meters. The upstream forested area is included because it could represent a good reference reach for naturalization processes. The straight longitudinal profile of the stream is a good indicator of earlier agricultural activity.

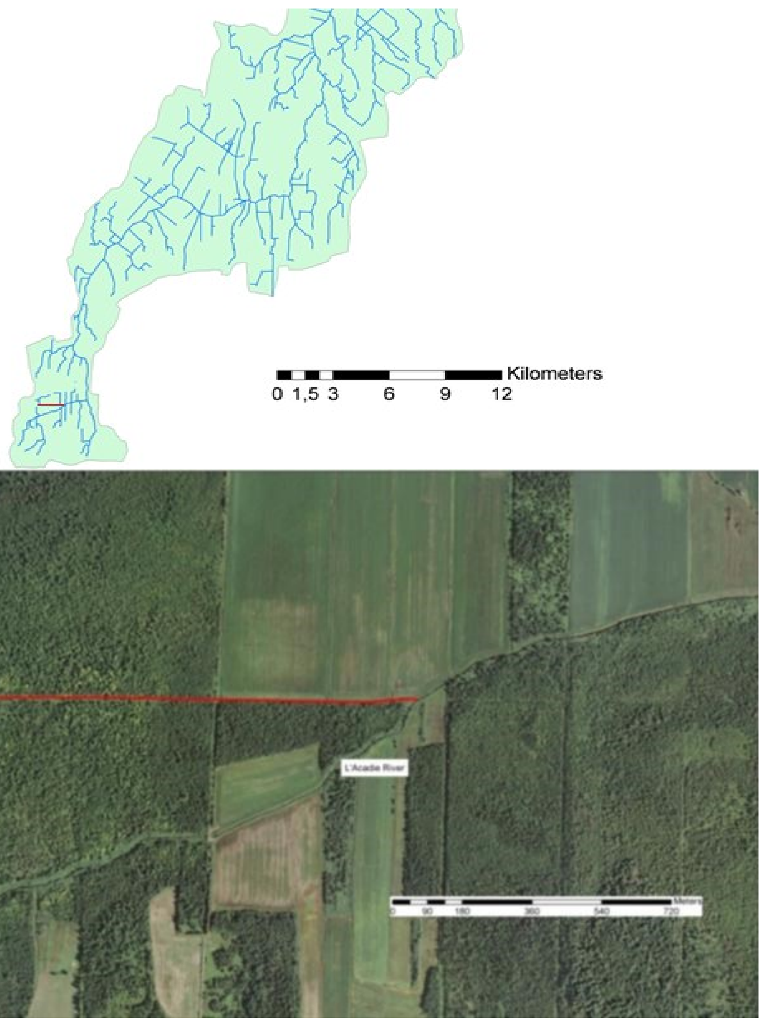


Figure 2.5: Top, location of the studied reach within the southern half of the l'Acadie watershed; Bottom, aerial photography of the studied reach, a small tributary of the l'Acadie River.

2.1.2 Crop yield sites

Additional sites were required to conduct a crop yield analysis near streams as the previous 3 sites did not present enough connectivity between field and stream or did not have the appropriate crop (some areas are so wet that only grass may grow). The main objectives of this analysis were to assess the extent of the effect of flooding on crop yields and compare impacted yields with reference values for the province. Maize and soy were the target crops as they dominate the landscape and are fairly easy to collect and analyze. Samuel Comtois, an agronomist with 9 years of experience at PleineTerre, selected sites where he was already aware of some yield problems near streams. Section 2.2.2.2 provides more detailed information on the experimental design.

The first site is located south of Lacolle, near the Richelieu River (Figure 2.1). The stream that flows through the area is a very small tributary of this mighty River and drains approximately 2 km^2. The second site is also drained by a small Richelieu tributary, but further North as part of the municipality of Saint-Paul-De-L'île-Aux-Noix. It is important to mention that these two streams may be subject to backwater conditions during spring as the Richelieu drains an immense territory and is well known for frequently inundating riparian areas. This special context is discussed in more detail in chapter 4. The third and final site is located on the north bank of the Des Fèves River, approximately 1.25km from the junction with the Chateauguay River (Figure 2.1). A site adjacent to a bigger watercourse was chosen to examine crop yield near a more dynamic system.

2.2 Data collection and analysis

2.2.1 Available data

Several datasets for this project were provided by PleineTerre, an agro-environmental consulting group based in Napierville QC, which is a close partner in this project funded by an NSERC/FRQNT industrial scholarship. The company provided LiDAR DEMs (1 meter resolution) and aerial photographs (ranging from 1930 to 2009). The available LiDAR DEM was used to extend the cross-sectional profiles to the floodplain zone (areas above the water surface) and the water surface slope of the study reaches was obtained from LiDAR data using the hydrogeomorphological GIS tools developed by Biron et al. (2013). Also, the agronomers and agricultural engineers who work for PleineTerre have an extended network of farmer contacts which was very useful for this project. For example, site identification was partly guided by their knowledge of the degree of openness of certain farmers. This perception factor is essential to the success of proposed solutions. The Pleineterre employees were also available to answer more general, agronomy related questions.

Info-sols.ca, a website created from a MAPAQ (Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec) and Géomont (GIS company) partnership, offers readily available spatial data relevant to agricultural studies such as subsurface drainage plans. Although the plans themselves are not georeferenced, their approximate location is indicated in the form of a point feature. It is important to note however, that the most recent plans available from the website are from 1993, corresponding to the last year the ministry of agriculture would directly overview agricultural water management projects. Having PleineTerre as a partner allowed us to retrieve directly from the producers any missing plans from later years. The two main types of graphic information available on those plans are in two dimensions. The first one is a bird's eye view of the drainage network with information like drain spacing, length and diameter. A longitudinal view of the collector drain and the first lateral drain connecting constitutes the second form of information provided (Figure 2.6). This profile often includes a vertical distance between the outlets and ditch bottom, which is a variable particularly important in this study.

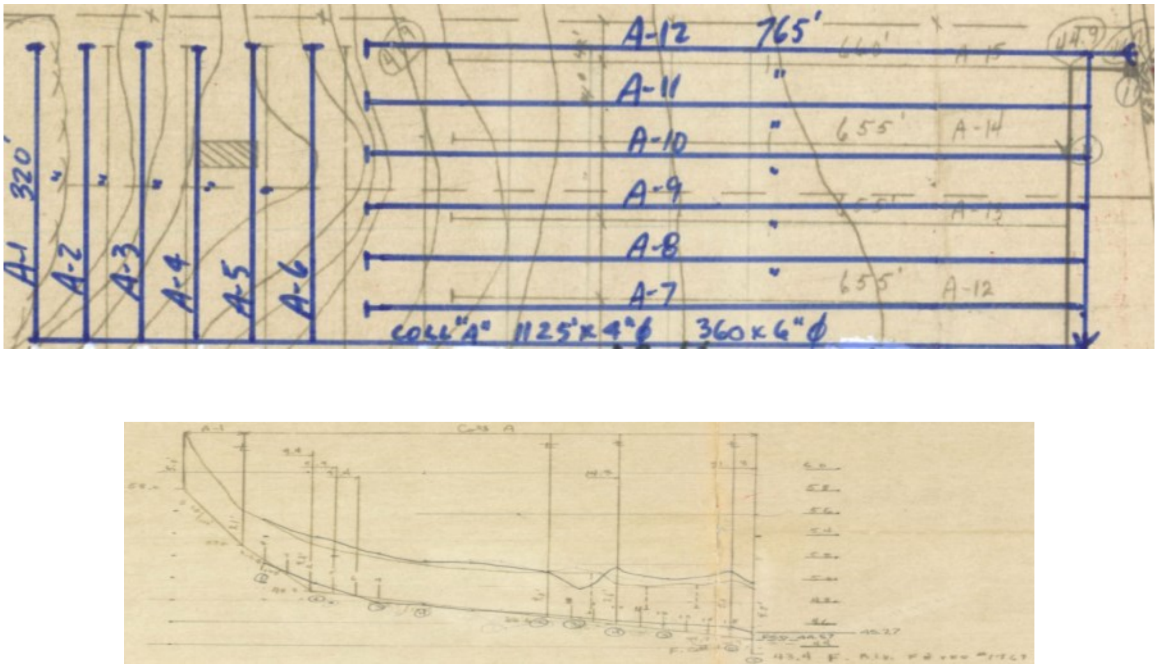


Figure 2.6: Example of a standard subsurface drainage plan for a field located in Montérégie, Québec where bird's eye view (top image) and associated long profiles (bottom image) are provided.

Discharge data from different gauging stations managed by the Centre d'Expertise Hydrique du Québec (CEHQ) were available in the study region (Figure 2.1).

Finally, a research internship to Ohio State University's department of Food, Agricultural and Biological Engineering was conducted during the summer of 2014. Dr. Andy Ward's research team (most notably Drs. Jonathan Witter and Jessica d'Ambrosio) is at the forefront of the research on alternative management designs in agricultural streams, such as two-stage and self-forming channels. This internship was used to document case studies and provide insights into the implementation process of alternative management approaches. Researchers at the Ohio State University department of food, agricultural and biological engineering developed readily available *Excel* spreadsheets for easier data storage and analysis regarding two-stage or over-wide ditch designs (Mecklenburg and Ward, 2004). They can be retrieved from this website:
http://soilandwater.ohiodnr.gov/water-conservation/stream-restoration#SPR

It was also used to document the question of drain outlet depths to compare the situation in Ohio and in Quebec. Dr. Larry Brown, a subsurface drainage expert in this department also took some time to discuss the problem of the very deep subsurface drainage outlets we often observe in

Quebec. Dr. Brown managed to provide 2 physical copies of subsurface drainage plans for Ohio fields during the internship. Those plans are very similar to Quebec plans. Dr. Matthew Helmers, professor at Iowa State University's College of Agriculture and Life Sciences also provided us with a sizeable report on controlled drainage (Agricultural Drainage Management Coalition - ADMC, 2011), where bird's eye view plans are provided along with topography and approximate drainage depth for several fields located in Ohio, Iowa, Minnesota, Illinois and Indiana.

2.2.2 Collected data

2.2.2.1 Regional curves of channel geometry

As highlighted in the literature review, the two-stage channel design is based on the reference reach approach. This requires a thorough characterization of the hydraulic geometry of the bankfull discharge related to drainage area. The Enhanced Ditch Design tool includes such empirical formulas, but since it was developed for Ohio, the regional curves will likely need to be adapted for Quebec. Data was thus collected in the studied watersheds to build such curves. Identifying reference reaches throughout the region was a relatively complex task since very few watercourses escape the cleanout operation cycle. Photo-interpretation using Google Earth proved an efficient method to search for potentially natural two-stage profiles before heading on the field. A weight-of-evidence approach developed at the Ohio State University was then used to analyse the suitability of sites of interest (i.e. that presented a natural floodplain). The most critical information to this weight-of-evidence approach for regional curve site selection is the time elapsed since the last dredging operation. The most likely source of information in this regard are Quebec's Municipalités Régionales de Comté (MRC) which usually have a watercourse manager responsible for all the ditch dredging projects on their territory. These key actors have all the historical dredging records allowing us to investigate the amount of time passed since the last cleanout operation of a given site. The longer the time since last cleanout, the closer the fluvial system is to a complete two-stage profile worthy of a field survey. Upon identification of proper reference reaches, measurements of the bankfull geometry dimensions (width and depth) were taken using a tape and a Spectra model LL100N precision laser level (Figure 2.7). Also, the drainage areas were extracted from LiDAR DEMs in ArcGIS. Naturalized ditches leave very little room for error during those measurements as inset channels are extremely well defined – several sites featured a very sharp drop from the top of the bench to its foot (Figure 2.7). The width measurement is particularly important as two-stage channel dimensions are recommend to have a minimum width at bench height of 3 times the inset channel width. Because of the scarcity of undisturbed naturalised sites, we included streams from all over Montérégie, which has the potential of lowering the linear model's strength. There were a total of 8 selected streams with drainage areas ranging from 0.17 km^2 to 60.6 km^2.

Figure 2.7: Channel dimensions field measurements using a laser level and a tape (notice the sharply defined inset channel).

Finally, width at the bottom of the ditch was measured to assess the ratio between inset channel width and total width available. This ratio is critical as below a certain threshold, floodplain synthesis cannot occur.

The second source of bankfull geometry measurements was gauging station data from the CEHQ. The selected stations were the following: #030907 – Des Anglais River; #030415 – Des Hurons River; #030421 – L'Acadie River; #030316 – David River; #030424 Aux Brochets River (Figure

2.1). These gauging stations are associated with large drainage areas (between 323 and 642 km^2) – well over the typical range for ditches. Still, researchers at OSU often include rivers in their curves when they fit well in the regression (Dr. Jonathan Witter, personal communication, July 20, 2014). The bankfull discharge was considered to correspond to a 1.5 year recurrence.

In order to produce a rating curve, the CEHQ technicians measured velocity in the core of the river section at their gauging stations using a velocimeter combined with a GPS. Velocities for parts of the river that are too shallow (e.g. near banks) or too close to the river bed are interpolated using *WinRiver*. Therefore, there is no precise survey of the full river profiles at the stations, resulting in limited geometric precision for this project (especially for width). CEHQ bathymetry for the selected rivers was available with files compatible with the *WinRiver* software (freely available online) (Figure 2.8).

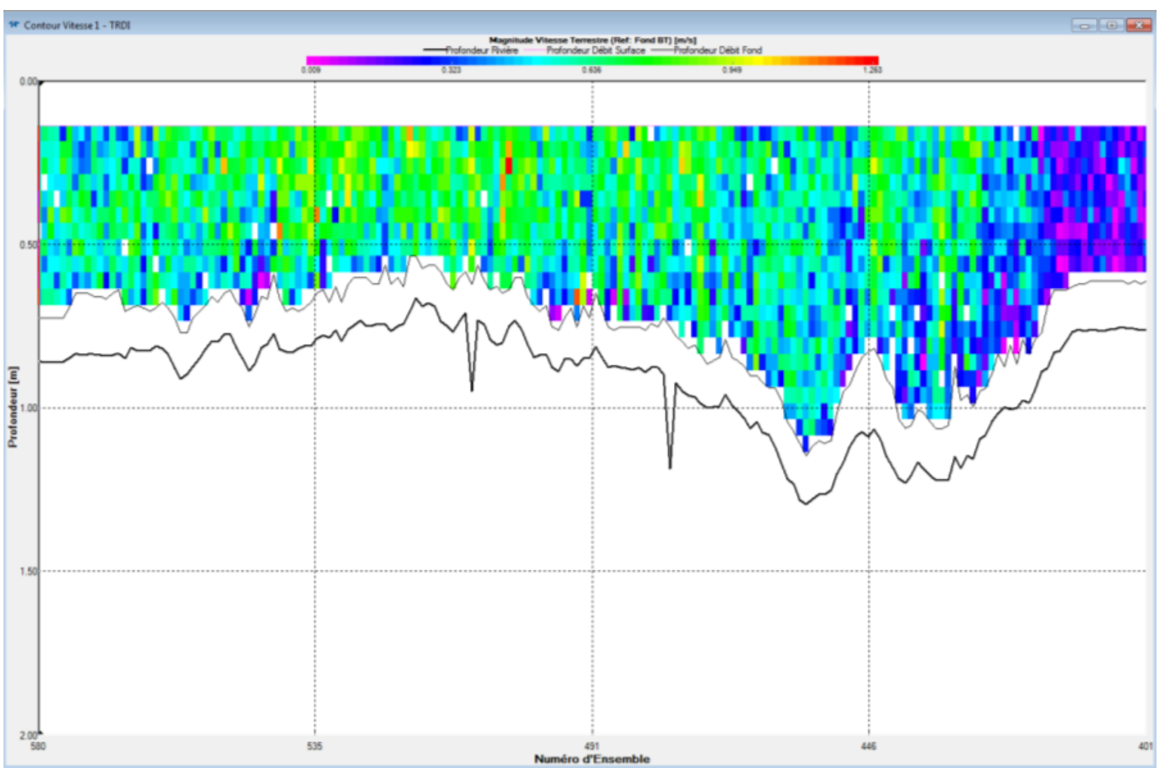


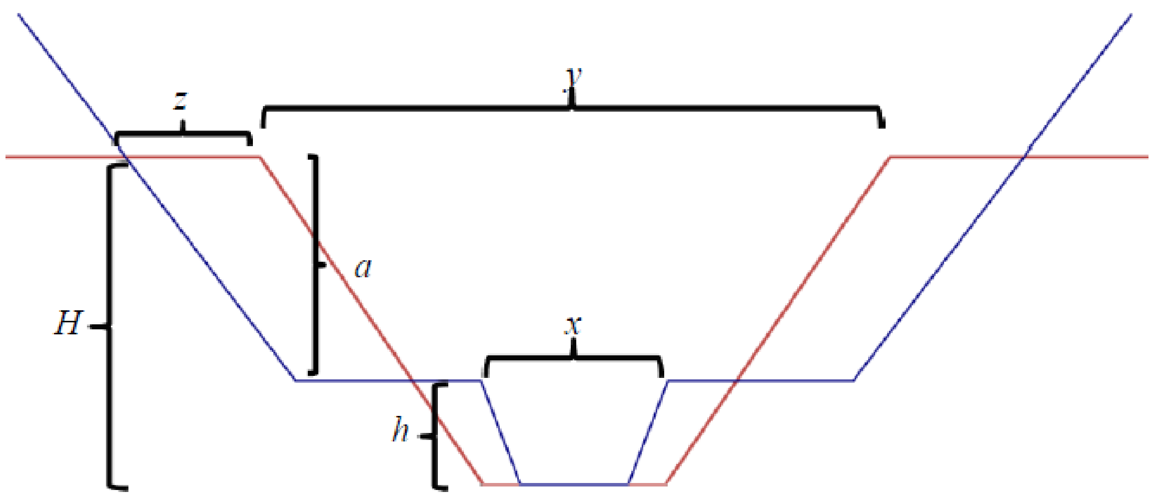
Figure 2.8: Example of a cross-section in WinRiver (colored rectangles represent velocity cells of the surveyed cross-sectional area and are at a minimum height above the river bed which is represented by the thicker black line).

The files which were provided to us by the CEHQ (one set per station) each corresponded to a precise date, but they were not for bankfull discharge events. Discharge events of a 1.5-year recurrence (assumed the bankfull recurrence interval), using the Weibull method, were calculated for every station from the CEHQ website to identify dates which corresponded to a bankfull discharge. Since water levels were not available online because they are based on an arbitrary 0 datum, CEHQ was contacted to retrieve this information for the identified dates (WinRiver file and bankfull discharge). The last step to obtain precise depth information was to calculate the difference between those arbitrary water levels and add them to the depth of water obtained from the WinRiver profile.

Width estimates were more problematic as the shallower sides of the channel are not included in the WinRiver profile. However, using the geographical position of the gauging stations allowed bankfull width estimation using the hydrogeomorphological GIS toolset with a LiDAR DEM (Biron et al., 2013).

In order to use the *Enhanced Ditch Design* tool from Ohio State University, longitudinal and cross-sectional bathymetry surveys, as well as water surface levels, were required. The bathymetry information was collected for the three selected watershed reaches using a *Juniper Systems Archer XF101* DGPS (Differential GPS) provided by PleineTerre. This data was also used in the HEC-RAS modelling part of this project.

Generating regional curves allows testing of the required space for optimal two-stage ditch dimensions. As stated in Chapter 1, optimal two-stage channel dimensions are 3-5 times the inset channel width at bench elevation (Powell et al., 2007a). Regional curves allow us to retrieve the inset channel width for any site by extracting the drainage area. The selected reaches have considerable lengths, meaning drainage area is very different from the upstream to downstream limits. This has to be taken into account for more progressive and appropriate cross-sectional profiles than the current trapezoidal design where the cross-section remains constant over long distances. Drainage area was thus extracted using LiDAR DEM at approximately 500 meter intervals along the reach. A simplified geometry (ditch bottom and top widths and heights of the banks) was extracted from every point where drainage area was retrieved as the variation in the micro-topography of the banks was deemed negligible, and such a simplified geometry allowed for easier calculations. Combining it with two-stage profiles estimated from regional curves, the simple geometry was applied to estimate critical spatial information such as additional width at the level of the field (Figure 2.9). These widths were also essential to evaluate the volumes of spoil between every cross section. Assuming bank slopes remain constant, a parallelogram shape represents the area of earth to be removed for a given cross-section. The volume of spoil can then be obtained by multiplying the area by the stream's length between cross-sections. Volumes were calculated for the two main alternative channel approaches: the two-stage channel (which assumes benches are already present within the ditch) and the over-widened ditch (which corresponds to a wider trapezoidal profile that will allow bench formation in the long run). The difference between the two thus rests in the height of the parallelogram. The two-stage channel's height is provided by subtracting the height of the benches (given by the regional curves) from the height of the actual banks. For the over-widened ditch, the current bank height is used.



*Additional width [z] = (Ratio * Inset channel width [x] – Top width of ditch [y])/2*
Height of parallelogram [a] = Height of bank [H] – Height of bench [h]
*Area of left parallelogram = Height of parallelogram [a] * Additional width [z]*
*Volume of spoil = (Area of left parallelogram + Area of right parallelogram) * length between cross-sections*

Figure 2.9: Illustration and calculations of the additional width and parallelogram area for a two-stage channel of 3 times the inset channel width at bench elevation.

2.2.2.2 Economic analysis

2.2.2.2.1 Estimating the implementation cost

The first part of the economic analysis which will be presented in Chapter 4 is the estimation of the difference in implementation cost between three alternative approaches and the trapezoidal ditch design for Québec. The most passive of those alternatives is not to intervene and to let the stream adjust by itself towards equilibrium (generally consisting of a fully natural two-stage profile). The 2 major costs related to this self-formed channel approach are land acquisition and tile drainage outlet stabilisation as bank erosion will enlarge the stream corridor. An estimate for land acquisition was calculated using an average agricultural land price of 19 387$ per hectare for western Montérégie (FADQ, 2014a) and multiplying it by the additional area required for every study site (based on the minimum width of 3 times the inset channel width found in chapter 3). The other two alternatives – the two-stage channel and over-widened ditch designs – include these costs, but also require construction costs. The first step for construction is to obtain all the permits and to design construction plans with field surveys and computer-aided design (CAD) software. Using PleineTerre's estimates for these pre-construction steps as well as the supervision of construction sites for several streams in the MRC Jardins-de-Napierville, a total estimate of 4500 $ per kilometer was obtained.

The construction costs of the two-stage channel design in the Midwest vary from $33 per linear meter to $218 per linear meter (Powell et al., 2007b). This high variability is mainly linked to the overall amount of earth to be removed but also whether or not the dug materials are to be transported away from the adjacent field. Trapezoidal ditch cleanout operations typically leave the dug earth atop the banks and producers eventually spread the material over their field, but mineral horizons cannot simply be pushed over fields as it would considerably weaken crop yields. There are no readily available figures for the cost of traditional ditch dredging operations in the province of Quebec. Renée Gravel, a biologist working for the Fauna sector of the provincial government has reviewed a large number of dredging operation requests and provided through personal communication a cost averaging 25$ per meter. This value was selected for the traditional approach component of the economic analysis.

As for the constructed alternative approaches, spoil volumes calculated in chapter 3 are used to estimate the cost in chapter 4. To avoid repetitiveness it was decided to proceed with only one width scenario: a ditch that provides the minimal lateral space requirement of 3 times the inset channel width at the bottom (Powell et al., 2007a). The first step was to separate fertile horizons (which can be pushed over the field) from predominantly mineral layers, but only for the Lacolle and Des Fèves sites since the l'Acadie site has deep organic deposits. Since no soil assessment was conducted for those sites, a rough estimate of 0.3 m is used for fertile soil thickness (this corresponds to the average Ap horizon, the critical agricultural soil layer towards which most tillage, cover crops and fertilizer applications are targeted – e.g. Kundu et al. 1996; Raper et al. 2000; Ogbodo 2005). Also according to Mr. Déziel, a good mechanical shovel operator will dredge approximately 600 meters per day of bed and banks for the traditional trapezoidal ditch maintenance work, at an hourly rate of 170$/hour (making it 1360$ for an 8 hour day). These figures apply for a dredged material thickness lower than 0.3m and it is obviously hard to provide a precise number due to site conditions variability. According to Mr. Déziel's experience, an average thickness of sediment to be removed by dredging corresponds to roughly 6 inches, or 0.15 m (about half of the 0.3m). It was thus decided to use a value of 300 meters per day for the rate of fertile soil removal for both over-widened and two-stage ditch designs. It could be expected that two-stage channel would be dug at a faster rate as less material is removed, however the difference should be negligible considering a bench height has to be respected (it takes significant time to make sure digging is being conducted at the right bench elevation). For the organic soils present at the l'Acadie river's Branch C, we use the average additional width required per bank (1.5 meters). According to the average dredging thickness of 0.15 m, it would thus take roughly 10 times longer to remove the material (60 meters per day).

The same approach was used for the two other sites' mineral horizons, but a second phase had to be taken into account: transportation of the material. This issue is rarely encountered with trapezoidal ditch dredging as most of the dug sediment is sourced from the top of the fields (i.e. fertile soil). Mr. Déziel again provided insight as he encountered these issues on a few projects. An important particularity to soil transportation from agricultural fields is that the trucks are loaded to half (~15 tons) of their capacity to avoid soil compaction. Also, the MRC pays for this operation as long as the material is transported no further than 3 kilometers away (beyond this distance, farmers have to pay). Time constraints unfortunately did not allow us to evaluate realistic scenarios to estimate such distances for every site. A 3 km value was used for both sites as we anticipate the MRC to still require farmers to find the nearest possible areas to dump the spoil. This obviously brings a lot of uncertainty for this part of the estimation, but it is a realistic number as farmers will tend to find the nearest dumping sites to avoid extra cost. A few companies that provide this kind of transportation service were contacted and an average rate of 10$ per metric ton was estimated from the gathered information. All that remained was estimating the density of the mineral fractions so that volumes could be transformed into mass. According to soil maps of both areas, silty clay was the dominant fraction to consider and has an average density of 1.75 tons/m^3 (Jones Jr, 1986).

Lastly, subsurface drainage outlets will need to be adjusted to the new channel width. Québec's ministry of Agriculture provides grids to help estimate the cost of materials and labor for the various agricultural water management works for which they provide subsidies. This includes the renovation of old subsurface drainage outlets. For this specific work, materials (riprap and geotextile) and labor (mechanical shovel and supervision) add up to a total cost of around 800$ per outlet. This value was used for the 3 analyzed alternatives.

Chapter 6 comprises a small economic analysis for the implementation of the horseshoe wetland at deep drains. The methodology is identical for every aspect except land acquisition. Because the surfaces to be retrieved were so small (~10 m^2), they were not included in the costs surrounding construction. Cost was converted to \$/m in order to provide a fast mean to compare it with other alternatives.

2.2.2.2.2 Crop yield analysis

Bernhardt et al. (2005) attempted to classify much of the recent stream restoration projects in the US in terms of their primary objectives. Cost associated with each primary goal was then computed. The median value for land acquisition goals was by far the highest of all expenditures (\$812,000), followed by floodplain reconnection goals at \$207,000. Thus, land acquisition is expected to be an important part of the implementation costs for the two-stage channel and over-wide ditch techniques as they are typically wider than trapezoidal channels. An assessment of the value of cultivated riparian land must be undertaken in order to provide a fair compensation price. Thus, the second component of this economic analysis was to evaluate crop productivity along selected agricultural streams. It is hypothesized that lower yields was found near streams because these zones are regularly flooded or affected by bank erosion. If this is the case, it can provide convincing arguments for producers to concede riparian land at more affordable prices.

For the first year, crop yield was estimated for a corn field at three distances intervals (0-10 m, 10-20 m and 20-30 m) at three cross-sections 20 meters apart. For every interval, all corn cobs present along one row were collected by hand. The 0-meter mark in the resulting figures corresponds to the limit of the cultivated land, which is normally 1 m away from the ledge of the bank (minimum vegetated buffer strip width requirements for agricultural streams in Québec). Following the analysis of the results, it became clear that limiting data collection to 30 meters was problematic and that larger distances from the stream were required. Therefore, data collected in the second year was extended to 30-40m and 40-50m intervals. For the second year, two of the three corn fields were changed to soy production.

Finally, an analysis of the geomorphic setting was conducted for those sites to help identify factors which may affect crop productivity within stream corridors (bank erosion and flooding). Fluvial scars which are often observed on recent photography and LiDAR DEMs, combined with an extensive historical sequence of aerial photography (starting in 1930) allows delineating precisely the river's lateral migration corridor. However, since most of the sites have stabilized banks, river mobility plays a negligible role in crop productivity on a year-to-year basis (which is the critical timescale for those analyses). By contrast, flooding – the other main space of focus when delineating fluvial corridors (Biron et al., 2014) – is of great importance at this short timescale. It was thus decided to focus mainly on this component when delineating stream corridors. LiDAR DEMS are an important tool as they provide a rapid insight into the areas more prone to flooding in a given field. Spring 2014 aerial photographs were also used as they illustrate very clearly the wettest parts of river corridors (darker areas).

2.2.2.3 Hydraulic Modelling

Hydraulic modelling is used to determine how a change in cross-sectional channel shape impacts the channel's water evacuation capacity and field flooding. The 1D hydrodynamic model HEC-RAS requires the following data to simulate flow stage for various discharge values: bathymetry of the bed and floodplain (obtained from field surveys and LiDAR DEM), discharge recurrence, roughness coefficient (Manning's n) and culvert positions.

A rating curve was established for the Lacolle and Des Fèves sites by using pressure transducers and a thin plated 90° V-notch weir (Figure 2.10). The first pressure transducer was used a few meters upstream of the V-notch. The measured water heights at this station were transformed into water height from the bottom of the V notch, and discharge was then calculated using this formula (Rantz, 1982):

$$Q = 1.38*h^{2.5}$$

where Q is discharge in cubic meters per second and h is the measured height of water passing through the V-notch in meters.

A second pressure transducer was installed far downstream to avoid any effects of the weir on water height and thus allowed relating discharge to water height. Water heights associated with discharges of higher magnitudes were thus precisely estimated. This precise data collection also permitted model calibration by modifying Manning's roughness coefficient.

4 levels of flow were tested in this analysis: low, medium, high and very high. The very high flow corresponds to the maximum in-channel discharge, i.e. the drainage capacity when the trapezoidal channel is completely full. Note that using the term "bankfull discharge" would be confusing as it typically corresponds to a 1.5-2-year recurrence interval, whereas human-made channels are designed to withhold much higher flows in order to limit flooding in agricultural fields (for a complete study of bankfull discharge and high frequency events in agricultural streams read Kallio,

2009). This discharge was estimated using the model HEC-RAS by progressively raising the discharge until the water surface corresponded to the top of the trapezoidal channel.

The high level corresponds to a 10-year recurrence interval discharge. This was computed based on the 42-year record of the nearest CEHQ gauging station (rivière Des Anglais, station #030907). The drainage area method was then used to determine the corresponding discharge for the 3 study sites, i.e.:

$$Q_{ditch} = Q_{station} * DA_{ditch} / DA_{station}$$

where Q_{ditch} is the scaled discharge of the gauging station ($Q_{station}$) using a ratio of the drainage areas of the experimental site (DA_{ditch}) and the gauged watercourse ($DA_{station}$).

Low and medium flow discharges were selected according to field measurements for the 2 sites equipped with a V-notch weir. The corresponding discharges for the third site (Branch C of the l'Acadie River) was computed using the drainage area ratio method

Manning's *n* was estimated visually from field visits and was used as a sensible starting value for model calibration. Various components of roughness (grain size, presence of obstacles, variable cross-sectional dimensions, and sinuosity) were estimated to compute an overall value for both the bed and the floodplain (Dingman, 1984). Culverts were also identified and their diameters measured. The roughness coefficient obtained this way for medium flow during calibration was applied to high and very high flows since no direct measurements of those rarer events could be taken during the course of this project. It is also important to note that no model validation was conducted in this project, principally due to a lack of time. Had hydraulic modelling been more central to this project, more effort would have been deployed towards that important step.

Stream naturalization approaches are expected to change Manning's *n* due to lower dredging recurrence resulting in vegetation development and some channel sinuosity. A sensitivity analysis of Manning's *n* values was conducted in HEC-RAS to measure the impact on water level of increasing resistance.

Figure 2.9 ABS pipe installation for a pressure transducer (left picture) and V-notch weir installed at a culvert – the ABS pipe can be seen in the back on the left bank (red arrow in the right picture).

For the third objective, HEC-RAS was employed to evaluate one-dimensional flow dynamics for the horseshoe wetland type alternative. Integrating such a form in the model was done by establishing horseshoe cross-sections very close to the normal ditch cross sections (Figure 2.10). This forces the creation of the cavity when using cross-sectional interpolation. Since this project already covers a large array of analyses, it was decided to leave more advanced modelling aside. For instance 2D modelling could have been used to evaluate water recirculation and sediment deposition rates within the horseshoe wetland. It would be interesting for a follow-up project to further investigate this topic. For this management approach to become more popular, it is important to assess the reaction of main actors (farmers, stream managers, mayors, etc.), as suggested in the following section.

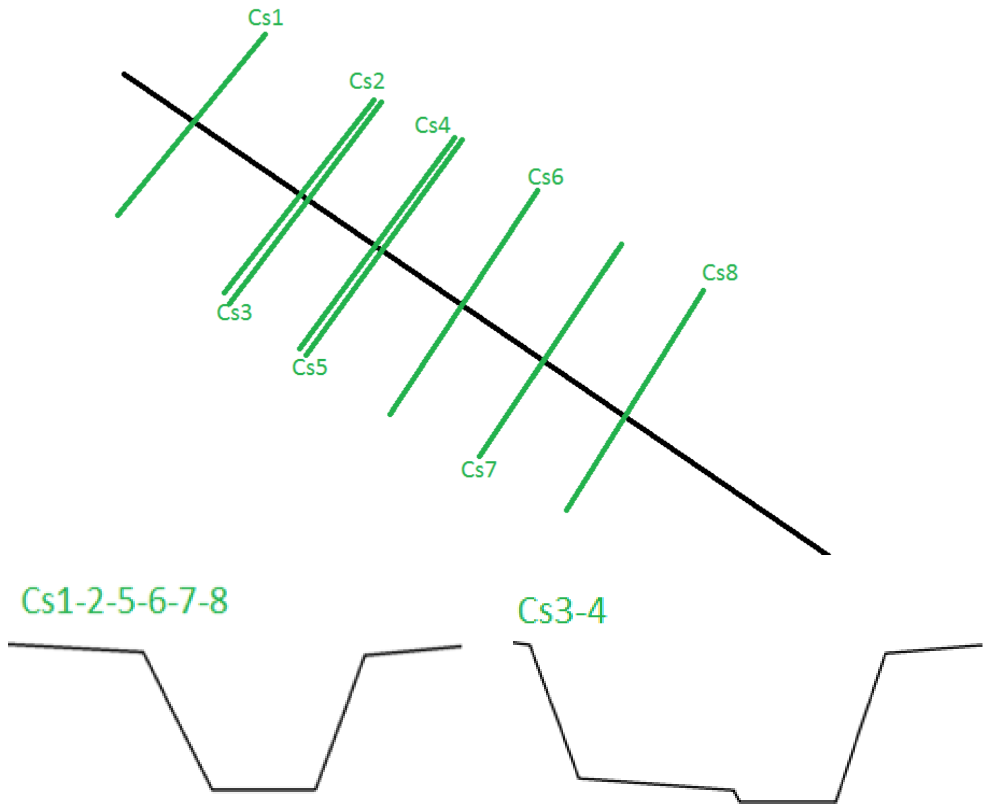


Figure 2.10: Integration of horseshoe wetland cross-sections in HEC-RAS.

2.2.2.4 Subsurface drainage design comparison

The first step taken in this section was to try to identify potential design anomalies in subsurface tile drainage in Quebec. The surveyed longitudinal profiles of several Montérégie streams to be dredged were retrieved in a pdf format. These plans generally provide the depth of the drain outlets along the streams (Figure 2.8). Retrieving the subsurface drainage plans corresponding to outlets of various depths allowed for a thorough assessment of the quality of subsurface drainage design in Quebec without requiring time-consuming field work to determine the drain outlet depth. However, a limitation of this approach is that there is no indication on which bank those outlets are making it harder to identify the corresponding drainage plan when more than one symbol was present along a stream. Outlets were thus only selected when it was obvious on which side of the bank they was located (e.g. forest on the other side).

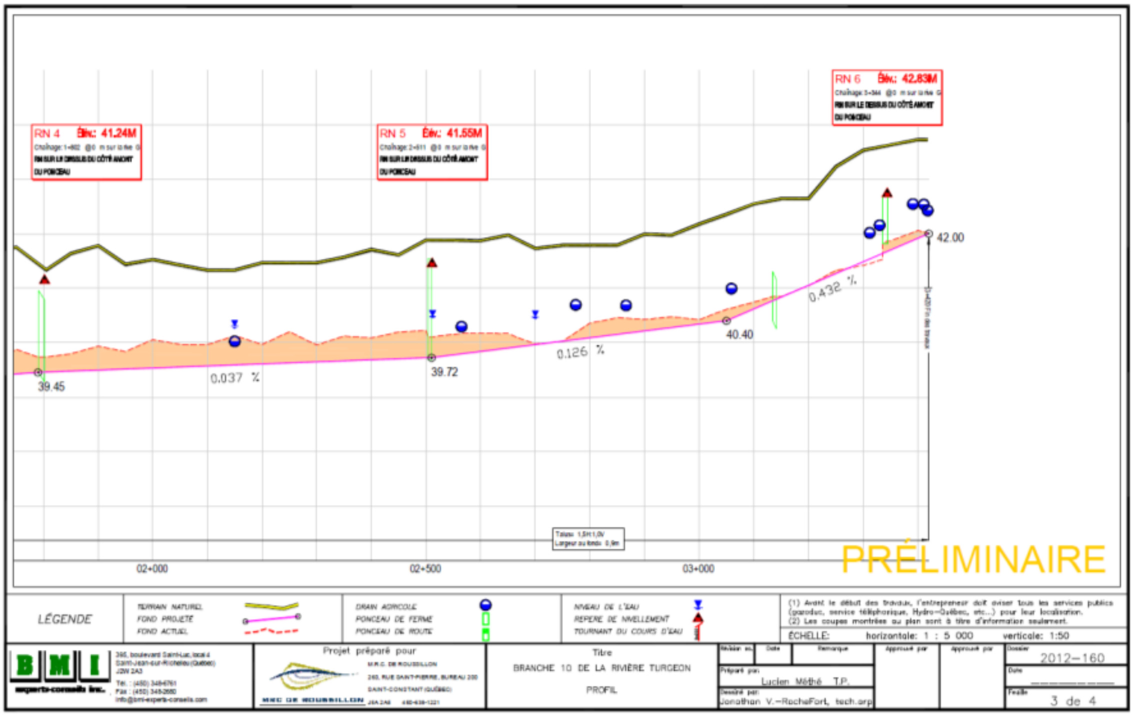


Figure 2.8: Example of a longitudinal stream profile plan – drain outlets are symbolized with half-filled blue circles.

The second step in this analysis was to assess the differences in the shape of subsurface drainage systems between Quebec and the rest of North America. Most Ohio fields are closer to a square shape than Quebec fields, due to the *seigneurie* cadastral layout. However, some subdivisions within broader squared plots are rectangular in Ohio as well. Conversely, the overall picture is a predominantly rectangular agricultural landscape in Quebec, but some square subdivisions exist within fields. This complexity alone justifies such a quantitative analysis between the two regions instead of a simple visual assessment.

Using ArcGIS's minimum bounding geometry tool (Figure 2.9), rectangular shapes can be generated out of more complex polygons or polylines to treat the field *shapefiles* uniformly. This operation allows the simple extraction of dimensions that was used to calculate a length to width ratio. A subsurface drainage system with a square shape will have a ratio close to 1 while this ratio will be much greater for narrow rectangular fields. From the Pleineterre GIS database, 15 polygon shapefiles representing fields were randomly selected. For the Ohio fields, 15 polygon shapefiles of fields were digitized in Google Earth. A Student t-test for these two independent samples was run in R for length, width and the length to width ratio. Boxplots of the two samples for the 3 tested attributes revealed that the variance was not equal (this is the default setting for the t.test command in R).

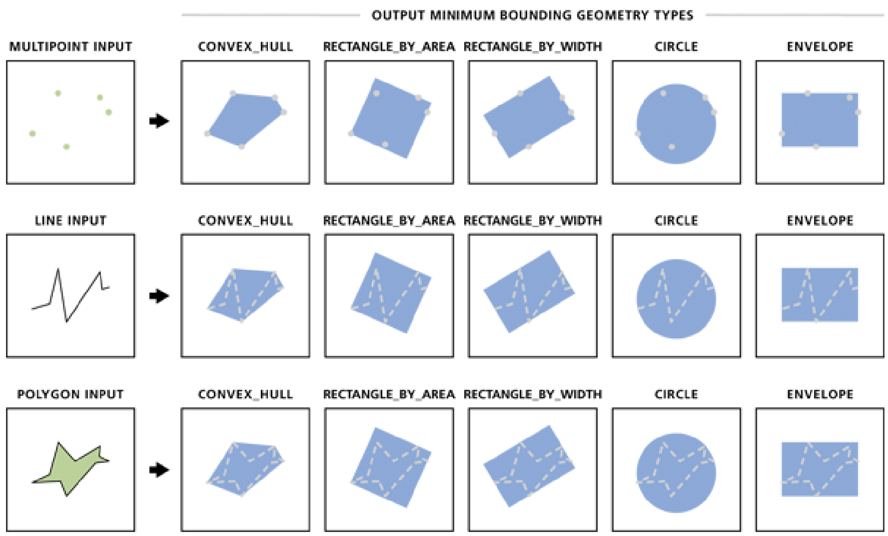


Figure 2.9: Minimum bounding geometry outputs will generate a simplified field form that will allow uniform extraction of width and length. From ArcGIS help.

In addition to the field shape comparison,, drain outlet depth was also examined since this is a critical factor preventing Quebec agricultural streams from being naturalized. Quebec plans almost always include long profiles of the collector drain and the first lateral drain. For the rest of North America, little information was readily available as the ADMC report does not include detailed long profiles. However, the two hard copies of drainage plans provided by Dr. Brown did include such profiles and were analysed separately. The ADMC report plans were used for a more extensive but less precise analysis of the relationship between drain depth and topography (drain depth is defined in this report as a single average value for the entire drainage system).

2.2.2.5 Perception of the explored alternatives

As many of the alternatives presented here have never been used in Quebec, it was essential to explore initial perceptions of the main actors concerned with agricultural water management. Especially important are the farmers who are the first concerned by any proposed project. PleineTerre's deep connections in the milieu facilitated the dissemination of sketches and ideas through agronomic consultation meetings with producers or during meetings like the Journée Grandes Cultures in St-Rémi. An illustrator was hired in the project to produce a unique and realistic figure of the horseshoe wetland applied to very deep drain outlets as very little scientific literature is available on this concept which promotes both naturalization processes and subsurface drainage efficiency. Several meetings with farmers, agronomists and stream managers were held to discuss the implementation potential of various alternatives.

Researchers at Ohio State University have developed and used regional curves of bankfull geometry extensively for their research on two-stage channels as well as a guideline for planners wishing to implement this alternative management approach in their area. It was decided to use the same approach to evaluate alternative channel dimensions for our 3 study sites as the great majority of the constructed two-stage channels built under this approach in the Midwest have so far proven very stable (D'Ambrosio et al., 2012). The following sections provide the results of the first attempt at establishing regional curves for the St-Lawrence lowlands as well as the estimated two-stage channel dimensions derived from them. These dimensions ultimately provide critical information to assess the cost of implementing alternatives that incorporate natural fluvial processes.

3.1 Regional Curves

Table 3.1 summarizes the date of the last cleanout operation of the reference streams which were surveyed in the field and included in the regional curves. Most of the selected streams had not been dredged for a long time (if at all) on the measured reaches. Considering the amount of time that was put in the search of undisturbed ditches (several weeks), the fact that very few recurrently dredged reaches were identified is symptomatic of a relatively short-cycled practice throughout the region.

Table 3.1: Last cleanout operation date of the lower-order streams selected for regional geometry analysis

Name	Coordinates	Year of last cleanout
No name- Small tributary ditch draining into l'Acadie river	(45°09'02.43''N; 73°47'14.44''W)	Unknown
Small tributary of Norton Creek	(45°02'00.64''N; 73°34'13.88''W)	Unknown
Ruisseau Richard-Gervais (Lacolle)	(45°04'38.65''N; 73°21'06.93''W)	No dredging – aerial photographs of 1930 show nearly the same stream path.*
Branch 53 of the Des Fèves River (Sainte-Martine)	(45°12'39.92''N; 73°47'09.11''W)	2013 - Downstream portion left undisturbed
Ruisseau Morin (Napierville)	(45°13'34.38''N; 73°24'29.61''W)	2000 – benches left intact.
Ruisseau Zénophile-Primeau (Très-Saint-Sacrement)	(45°09'15.33''N; 73°49'44.99''W)	1985
Ruisseau Atkinson (Très-Saint-Sacrement)	(45°08'55.51''N; 73°48'22.92''W)	1996
Des Fèves River**	(45°13'10.66''N; 73°47'34.37''W)	None

*The fluvial corridor is highly incised for a few kilometers - this section was thus not included in channelization projects during the 20th century.
**Unlike the other sites this one was selected because of its more substantial drainage area, allowing us to reduce the scale gap between naturalized ditches and gauged rivers.

Most of the forest clearing and stream channelization in the region was already completed by 1930 (as confirmed by the analysis of 1930 aerial photographs). This means that a considerable amount of time has passed since any major watershed disturbances occurred for those selected streams. This further strengthens the confidence in their stability and the relevance of including them in the regional curves analysis. Also included are 5 gauged agricultural rivers (Figure 3.1).

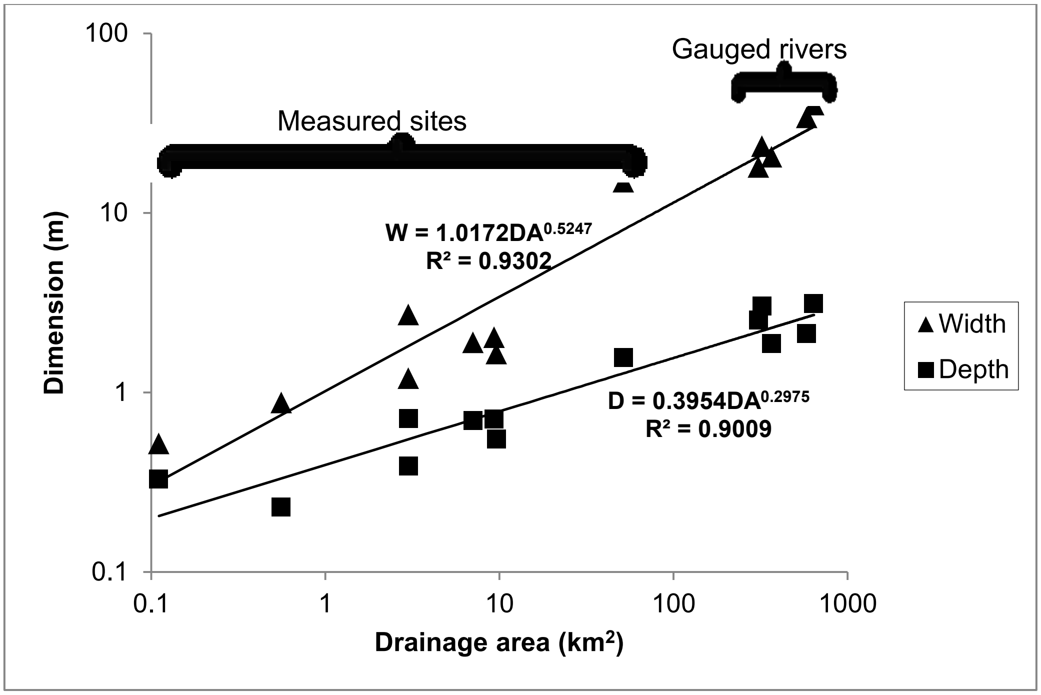


Figure 3.1: Regional curves of bankfull channel geometry (Montérégie)

Coefficients of determination (R^2) values are very high (0.98 for width and 0.93 for depth), considering the size of the covered territory (Montérégie has an area of ~12,000 km^2). Indeed, as you enlarge the territory, you normally encompass more varied geologies and reliefs leading to an increase in geometry variability for alluvial streams. In the Midwest – where numerous regional curves have already been established – this high degree of correlation is generally associated with much smaller areas – e.g. watershed scale.

The closest regional curves from the Midwest for a comparable scale are those of the Northwestern Ohio drainage ditches, which are defined as such (Mecklenburg and Ward, 2004):

$$W = 1.35*DA^{0.4}$$

$$D = 0.31*DA^{0.2}$$

The proximity of both regional curves is not surprising when considering the surface deposits of both regions. Indeed, nearly all of the selected sites are located within the Champlain's sea maximal extent where clay deposits are a common feature (Gadd, 1988). Extensive clay deposits are also a dominant physiographic unit in Northwestern Ohio, in the region of the Maumee Lake Plains, which comprises among other sub-units the Paulding clay plains (Brockman, 2007).

Table 3.2 summarizes the main physical properties of the naturalized reaches included in the regional curves. These properties are important as they can help delineate minimums and maximums when planners consider conducting a two-stage channel construction project.

Table 3.2: Physical properties of the selected reaches for regional geometry assessment

Name	Drainage area (km^2)	Reach Slope	Bottom width of the ditch (m)	Ditch bottom width to inset channel width ratio
No name- Small tributary ditch draining into l'Acadie River	0.17	0.0013	2.3	4.4
Small tributary of Norton Creek	0.56	0.0033	22.2	25.2
Ruisseau Richard-Gervais (Lacolle)	2.90	0.0026	38.0	22.0
Downstream portion of Branch 53 of the Des Fèves River (Sainte-Martine)	2.91	0.0020	6.1	4.2
Ruisseau Morin (Napierville)	7.06	0.0023	6.3	3.3
Ruisseau Zénophile-Primeau (Très-Saint-Sacrement)	9.49	0.0022	7.2	3.6
Ruisseau Atkinson (Très-Saint-Sacrement)	9.90	0.0016	5.1	3.1

No minimal slope assessment was found in the scientific literature, which is surprising as a minimum of energy is required for a stream to be able to maintain itself within the confines of a ditch. A maximum slope of 0.5 % is mentioned in a Great Lakes Regional Water Program information booklet (Ward et al., 2011). A range of 1 to 10 square miles (2.59 – 25.90 km^2) is also provided in this short report. Considering that no detailed and peer-reviewed analysis exists on this issue, these values appear approximate, with suspiciously round numbers to give them too much credibility. It is thus important that a more extensive analysis of appropriate slope and drainage area be developed in future projects as the two-stage and over-widened ditch designs are quickly gaining popularity. Out of all the sites presented in table 3.2, the small ditch tributary of the L'Acadie River happens to feature minimum values for both drainage area and slope. However, delineating minimum values based on a single site would be very presumptuous. Furthermore, this particular site is in a predominantly organic soil environment, whereas all the other sites are found in mineral soil environments. Clearly, more site assessments will be needed in the future to better define the optimal slope and drainage area ranges when selecting sites. This work is essential to ensure project success for planners who wish to integrate natural fluvial processes in agricultural streams. In the meantime, sites with clear fluvial features already present may be targeted as the risk for failure is very low.

The recommended minimal ratio of ditch bottom width (inset channel and benches) to inset channel width is estimated to be 3 (Powell et al., 2007a). This ensures the stability of the floodplain as well as providing enough space for high denitrification rates. All of the naturalized sites which were selected for regional curve establishment are above this minimum – Ruisseau Morin being the closest at 3.3 (Table 3.2). On the other hand, when looking at the 3 study sites, this minimum ditch width required for stable stream naturalization is never met. For instance, the bottom width at the mouth of the Cours d'eau Barrière is approximately 3 meters whereas the regional curve returns a width of 2.82 meters for the inset channel alone. In other words, the current ditch bottom width to inset channel width ratio is around 1 for this site (Table 3.3). This is not surprising considering no benches were observed when surveying those 3 sites (several outings over 2 years). Additional space is thus required for naturalization processes to occur and floodplain centered alternatives to be sustainable at the study sites.

3.2 Additional space required

The strong relationships found in the regional curves strengthen the confidence in the ability to precisely estimate the amount of work needed in terms of earth removal. However, it is important to start by comparing the physical properties of the 3 study sites to the naturalized streams selected for regional curve establishment. This can help determine whether they are fit for the application of the two-stage or over-widened ditch designs. The only "abnormal" value found is the Cours d'eau Barrière's slope of 0.0011 which is slightly lower than the minimal value of 0.0013 (Table 3.2 and Table 3.3). Two-stage channel and over-wide ditch scenarios are still tested for this watercourse, but additional investigation would be needed if this site was ever to be seriously considered for projects of this nature. For instance, sediment transport analysis could be conducted to assess the ability of the stream to sustain itself with a two-stage profile.

Table 3.3: Physical properties of the selected watershed sites

Site	Drainage area (km^2)	Reach Length (km)	Slope	Ditch width to inset channel width ratio
Des Fèves River Branch 53 (Upstream)	2.41	2.84	0.0027	0.8
Cours d'eau Barrière	6.97	3.93	0.0011	1.0
Rivière L'Acadie Branch C	2.53	0.48	0.0021	1.1

Using a simplified geometry approach (see section 2.2.2.1), the additional widths at the field's level as well as the volumes of earth to be removed were estimated. Table 3.4 provides the additional widths required and their associated volumes of spoil while Figure 3.2 complements these numbers with the visual representation of one cross-section.

Table 3.4 : Additional width required per bank and corresponding volume of spoil to be removed from the 3 watershed sites for two-stage channel and over-wide ditch designs

Name	Additional width (m) for a ratio of 3X		Additional width (m) for a ratio of 5X		Volume of spoil (m^3) for two-stage channel		Volume of spoil (m^3) for over-widened ditch	
	Min	Max	Min	Max	3X	5X	3X	5X
Des Fèves River Branch 53 (Upstream)	0.55	1.94	1.15	3.73	6 907	12 600	10 022	18 763
Cours d'eau Barrière	2.00	3.50	4.34	6.50	30 916	90 458	45 775	119 956
Rivière L'Acadie Branch C	1.23	1.75	2.72	3.58	1414	2991	2148	5100

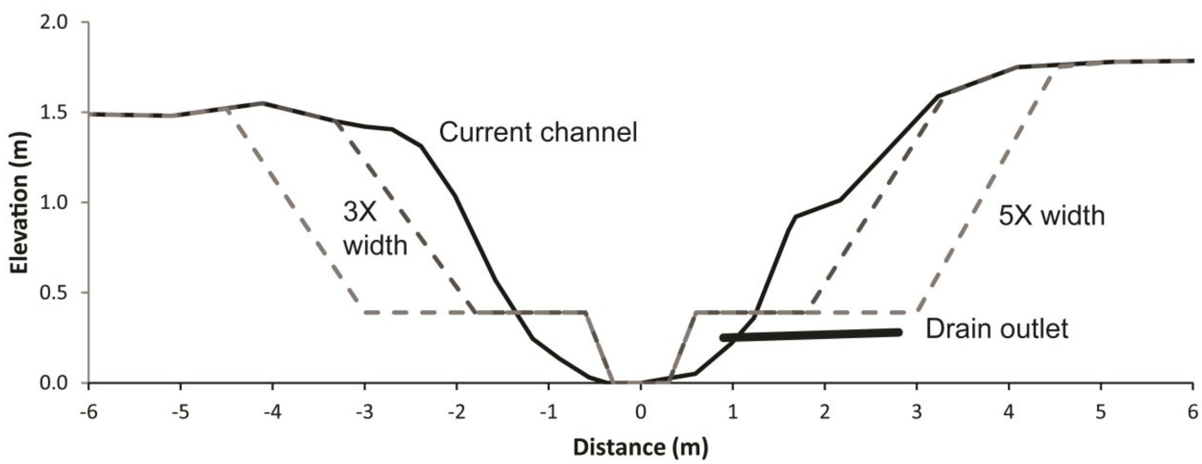


Figure 3.2: Visual representation of a two-stage channel design in blue (3X and 5X widths) over the actual Branch 53 of the Des Fèves River in red – the bold black line represents a deep subsurface drainage outlet measured in the field.

While the alternative channels were progressively smaller in the upstream reaches (as drainage area diminishes), the actual profiles didn't show such a progressive shrinkage. Consequently, all of the minimum additional widths were found in the most upstream parts. This highlights one of the problems with the traditional design of ditches, i.e. they do not follow hydraulic geometry concepts, where width and depth should increase from upstream to downstream. Instead, current designs use a constant trapezoidal shape for extensive distances (some of the straightened channels can be several kilometers in length).

3.3 Conclusion

The strongly correlated regional curves of channel dimensions were used to precisely quantify the additional space required for alternative channel management techniques which incorporate natural fluvial processes. By extracting the drainage area of chosen sites we obtain the inset channel width, which allows us to overlay the optimal two-stage channel dimensions (3-5 times the inset channel width at bench elevation). From this, a simple geometry was used to deduce width at the level of the field and volumes of spoil. The main finding from this analysis is that additional horizontal space is required for all 3 sites (between 0.55 and 6.50 meters for each bank). Since those sites were selected because of their representative nature for the province, it can be expected that most two-stage channel projects undertaken elsewhere will also face this issue. However, the wide array of widths is also indicating there would be a varying degree of discontent from producers: 0.55 meters doesn't have a considerable impact on cultivated areas compared to 6.50 meters. However, in all cases there remains a sizeable amount of earth to be removed.

The following chapter uses the findings of this chapter (mainly the spoil volumes) to first estimate the construction costs of the two-stage and over-widened ditch designs and to compare those prices with traditional approaches. In the second part, the agricultural productivity of those critical riparian areas is examined. Finally, the vertical space required for undisturbed water evacuation from subsurface drainage outlets is also a critical component regarding the implementation potential of floodplain centered alternatives (Figure 3.2 is a good illustration of the conflict between stream naturalization and deep outlets). However, an economic analysis doesn't address this problem entirely. The various facets of this issue are examined in chapter 6.

Analyzing environmental management decisions using an economic analysis is an essential component as arguments founded on science alone are often not powerful enough to induce change of practice. The first part of this chapter examines overall implementation cost of the two-stage channel design, over-wide ditch design and the self-formed stream and discusses the differences with the traditional dredging approach. The second part examines crop productivity in critical riparian areas which often are targeted by alternatives that require additional lateral space. Both of those parts are expected to help provide economic arguments for the implementation of the aforementioned alternatives in a long term perspective.

4.1 Construction cost

4.1.1 Results

Table 4.1 summarizes the expected cost for land acquisition for the 3 study sites as they all require additional lateral space. Table 4.2 includes this number alongside the rest of the before and after construction costs: permit application, plan designing and site surveillance.

Table 4.1: Land acquisition cost using average agricultural land prices for Montérégie in 2014 for 3 times the inset channel width

Site	Area of land to acquire (ha)	Price ($)
Des Fèves River branch 53	0.85	16 479
Ruisseau Barrière (Lacolle)	2.22	43 039
L'Acadie River branch C	0.15	2 908

Table 4.2: Pre and post construction costs for the 3 study sites
(two-stage and over-wide channel designs)

Site	Permits ($)	Plans ($)	Site surveillance ($)	Land Acquisition ($)	Total ($)
Des Fèves River branch 53	1 000	10 240	1 620	16 479	29 339
Ruisseau Barrière (Lacolle)	1 500	13 755	2 430	43 039	60 724
L'Acadie River branch C	500	1 680	1 020	2 908	6 108

As mineral horizons need to be treated differently, it is important to assess the percentage they represent for the 2 study sites located in mineral soil environments (Table 4.3). These numbers helped increase the precision in the construction cost for those sites while the Branch C of the l'Acadie River only fits in the fertile organic soil columns of Table 4.4.

Table 4.3: Estimated proportions of mineral soil layers in the total spoil volumes for the 2 study sites located in mineral soil environments

Site	Total spoil volume for 2-stage channel (m^3)	Mineral spoil volume for 2-stage channel (m^3)	Total spoil volume for over-wide ditch (m^3)	Mineral spoil volume for over-wide ditch (m^3)
Des Fèves River branch 53	6 907	3 866 (56.0%)	10 022	6 276 (62.6%)
Ruisseau Barrière (Lacolle)	30 915	21 808 (71.5%)	45 775	35 072 (76.6%)

Table 4.4 : Estimated construction cost of two-stage channel and over-wide ditch designs for the 3 study sites

Site	**Subsurface drainage outlet adjustment**			**Fertile soil removal**			**Mineral horizons removal**			**Mineral horizons transportation**			**Total ($)**
	Rate ($/out)	*Nb of outlets*	*Cost ($)*	*Rate ($/day)*	*Nb of days*	*Cost ($)*	*Rate ($/day)*	*Nb of days*	*Cost ($)*	*Rate ($/t)*	*Mass (tons)*	*Cost ($)*	
TWO-STAGE CHANNEL													
Des Fèves River branch 53	800	27	21 600	1360	9.5	12 920	1360	28	38 080	10	6 766	67 655	140 255
Ruisseau Barrière (Lacolle)	800	21	16 800	1360	13.5	18360	1360	65	88 400	10	38 164	381 640	505 200
L'Acadie River branch C	800	1	800	1360	8	10880	N/A	N/A	N/A	N/A	N/A	N/A	11 680
OVER-WIDE DITCH													
Des Fèves River branch 53	800	27	21 600	1360	9.5	12 920	1360	28	38 080	10	10 983	109 983	182 583
Ruisseau Barrière (Lacolle)	800	21	16 800	1360	13.5	18 360	1360	65	88 400	10	61 376	613 760	737 320
L'Acadie River branch C	800	1	800	1360	8	10 880	N/A	N/A	N/A	N/A	N/A	N/A	11 680

Table 4.5 combines all costs for the implementation of the two-stage design, over-wide ditch design and the self-formed stream as well as the current management approach of ditch dredging.

Table 4.5: Comparison of total cost for a traditional dredging approach, the two-stage channel design and the over-widened ditch design

Stream	Traditional dredging cost ($)	Self-formed stream cost ($)	Two-stage channel design cost ($)	Over-widened ditch design cost ($)
Des Fèves River Branch 53 (Upstream)	71 000 (25 $/m)	38 079 (13 $/m)	169 594 (60 $/m)	211 922 (75 $/m)
Cours d'eau Barrière	98 250 (25 $/m)	59 839 (15 $/m)	565 924 (144 $/m)	798 044 (203 $/m)
Rivière L'Acadie Branch C	12 000 (25 $/m)	3 708 (8 $/m)	17 788 (37 $/m)	17 788 (37 $/m)

4.1.2 Discussion

The same high variability of costs mentioned by Powell et al. (2007a) for the two-stage channel design is observed in this analysis (between $37 and $144 CAD per meter). Despite several factors that were harder to quantify precisely (e.g. distance of transportation of mineral spoil), two broad conclusions can be drawn with confidence about the two-stage and over-wide ditch designs: 1) cost varies greatly according to factors such as drainage area and soil type and; 2) these alternatives will always be more expensive to implement than the traditional ditch dredging operations, especially in mineral soil areas. However, comparing the traditional dredging approach with the tested alternatives is questionable since one is a maintenance operation (traditional ditch dredging) and the other requires the design of a new channel. Strictly speaking, the comparison should be made with the creation of the traditional ditches, but it is a rather difficult endeavor to go back to the years of channelization at the turn of the 20th century and compare costs with potential alternatives that would be applied a century later. Furthermore, it is important to not limit the analysis to the additional cost highlighted in Table 4.5, but to also consider that a two-stage profile is expected to greatly reduce the need for recurrent maintenance (Powell et al., 2007a), thus greatly reducing cost in the long term. A longer lasting channel means that multiple dredging operations are avoided. For example, assuming a maintenance recurrence of 50 years for alternative management options and a current recurrence average of dredging between 15-20 years, there would normally be 2 or 3 dredging operations conducted in that span (assuming agricultural practices remain the same). This means a cost of 50-75$/m, which narrows enormously the cost gap between conventional and alternatives approaches. Also, the current environmental management paradigm of including ecological services in economic analysis could improve the social acceptability of the these alternatives. For example, one of the most important benefits associated with the floodplain-integrated management options is the marked reduction of nitrate concentrations in water which improves downstream water quality and aquatic habitat (Roley et al. 2012). Despite these arguments, the fact that a long term vision to stream management has yet to be well anchored in the milieu constitutes a big obstacle to modifying the management approach. The most interesting finding of Table 4.5 is in fact the very low cost of the self-formed stream – a passive approach to stream management which doesn't get as much attention as the two-stage channel design despite providing the same end result with minimal human intervention. A major reason for this is the relatively low cost of land acquisition for all 3 study sites (average of 10% of the total cost of the constructed alternatives – Table 4.1). This goes against our expectations, which were partly supported by Bernhardt et al. (2005) who had a far broader perspective than the agricultural world alone, in which extensive floodplain restoration might be more difficult to sell to stakeholders. Despite this relatively low cost, it remains important to examine in more detail yields in the critical riparian space which would no longer be available for crops. This is relevant in a broader stream management perspective which could include self-forming channels (where no soil removal cost would be involved) as well as other approaches requiring giving more space to rivers (e.g. freedom space for rivers – Biron et al. 2014).

4.2 Crop yield analysis near streams

4.2.1 Saint-Paul-de-l'Ile-Aux-Noix

The LiDAR DEM for this area reveals a substantial depression corridor parallel to the Richelieu (Figure 4.1). The spring 2014 aerial photographs show this entire corridor filled with floodwater from the Richelieu (Figure 4.1a). The exact nature of this depression is hard to define as no stream (channelized or natural) currently lies at its bottom (this is due to an interpretation error for site selection). However, on the 1930 aerial photographs a few curved scars appear within this boundary, which could be traces of a former meanders, but the resolution of the photography limits confidence in this hypothesis. The crop yield analysis was conducted along a small drainage ditch (approximatively half a meter in depth), but the field's boundary is also connected to the bigger corridor and sensitive to flooding from the Richelieu. The flooding space presented in Figure 4.1 extends 14 meters in the field for the 3 cross-sections as seen in the following figures (Figures 4.2 – 4.4).

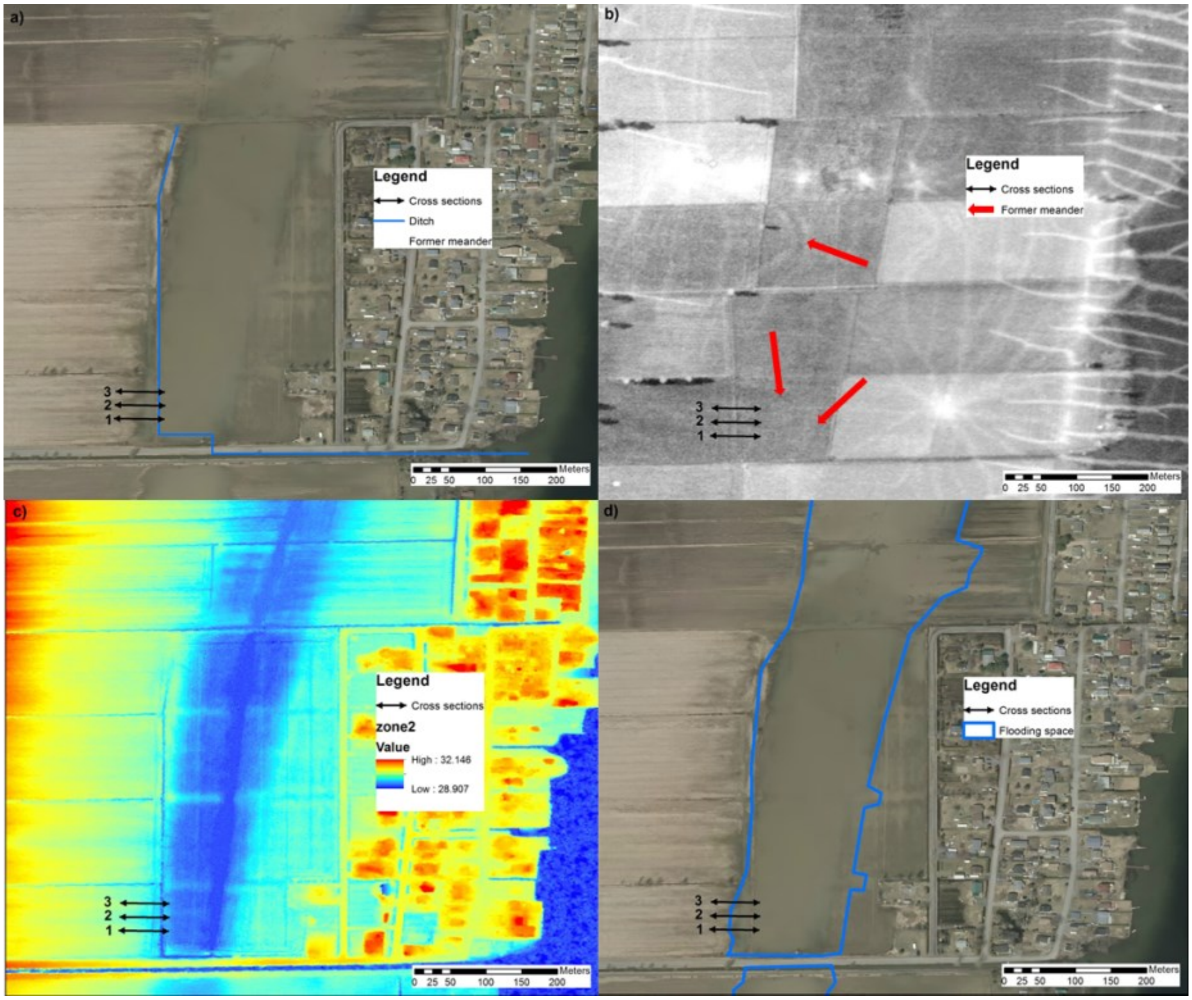


Figure 4.1: a) Spring 2014 aerial photograph showing the Richelieu floodwater filling the depression; b) 1930 aerial photograph which does not reveal the presence of a natural stream within the corridor; c) LiDAR DEM highlighting the extent of the depression; d) Flooding space defined using a combination of aerial photography and LiDAR.

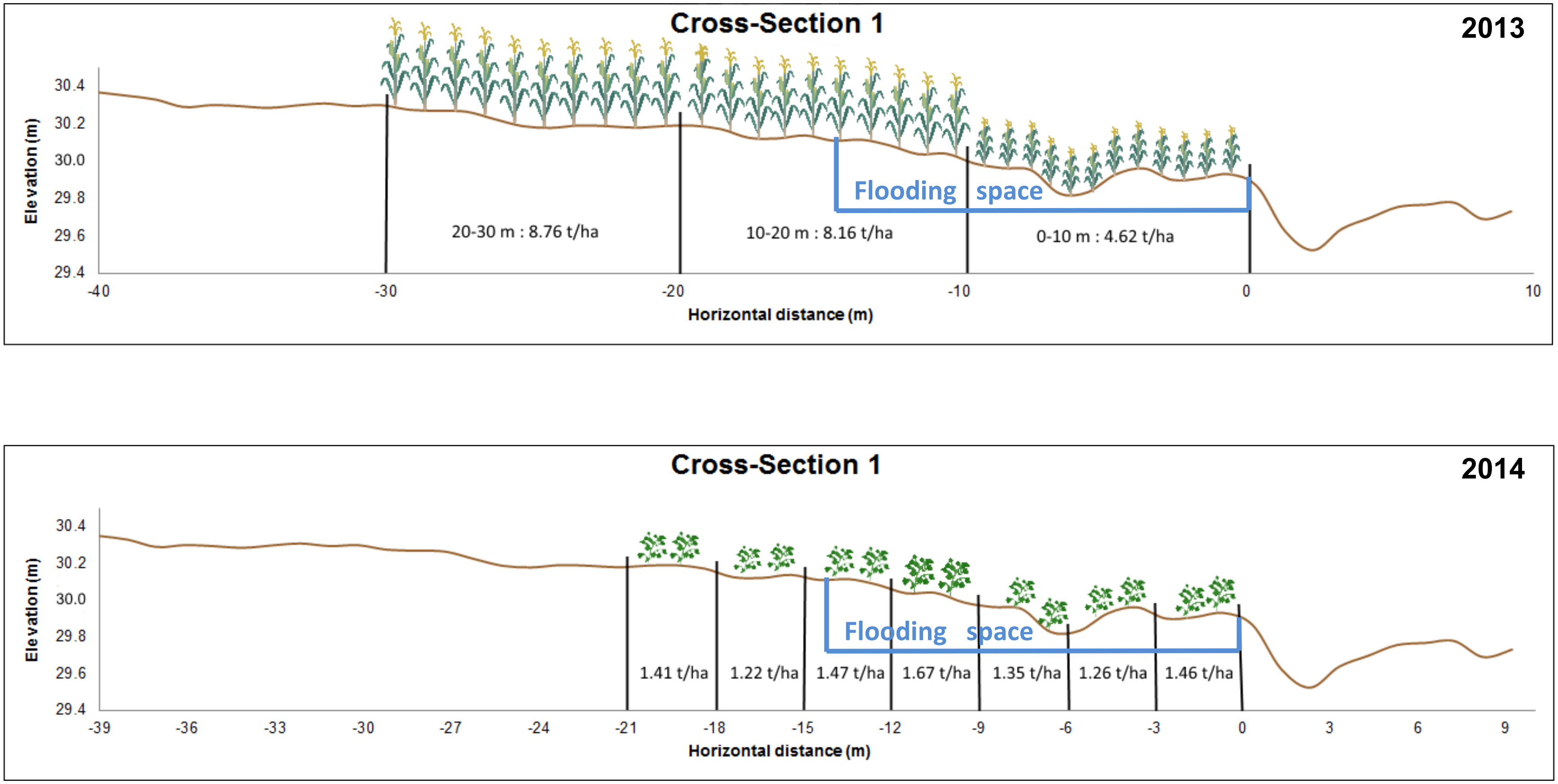


Figure 4.2: Cross-section 1 of the Saint-Paul-de-l'Île-aux-Noix site and the measured yields for 2013 and 2014.

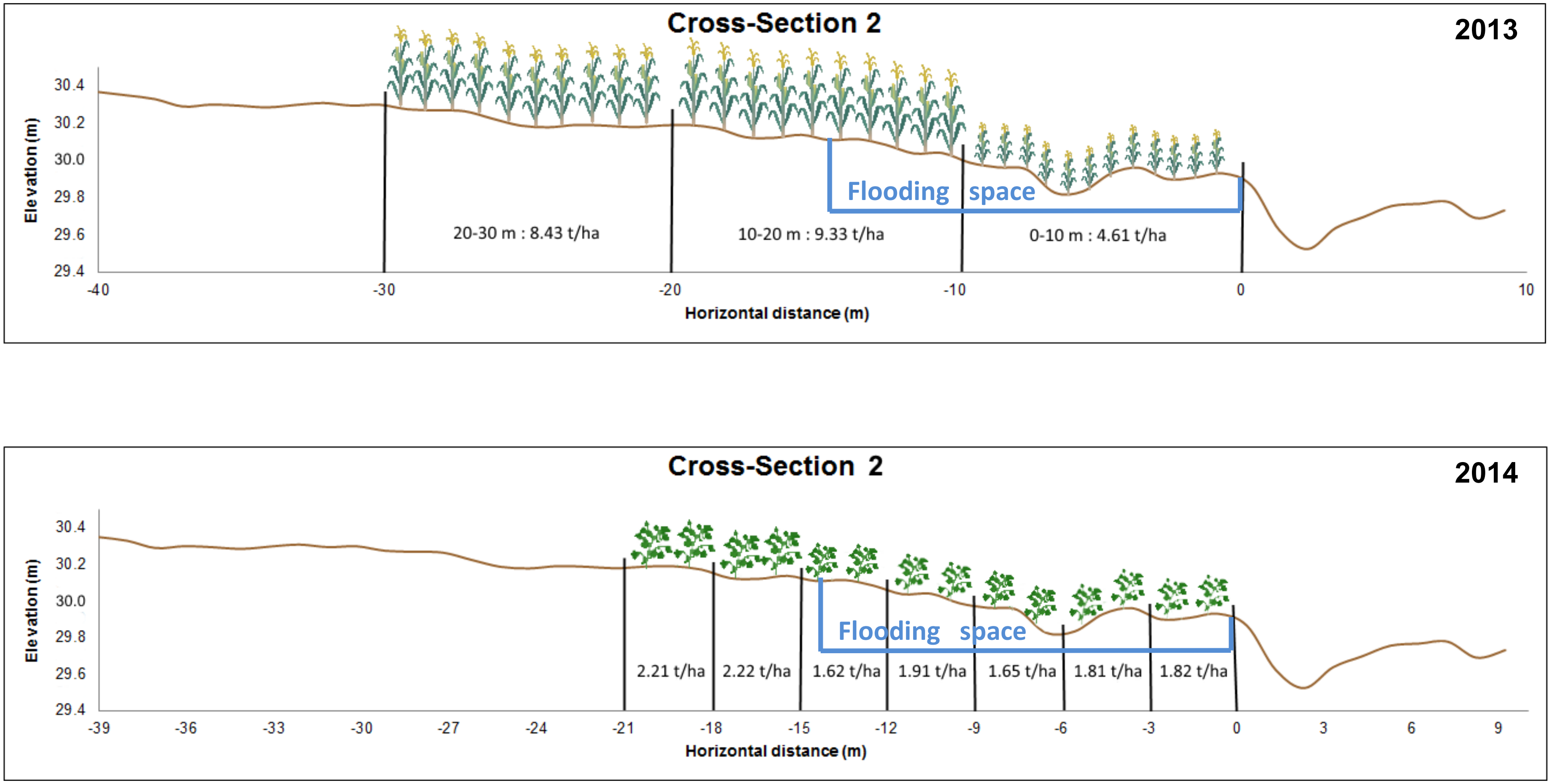
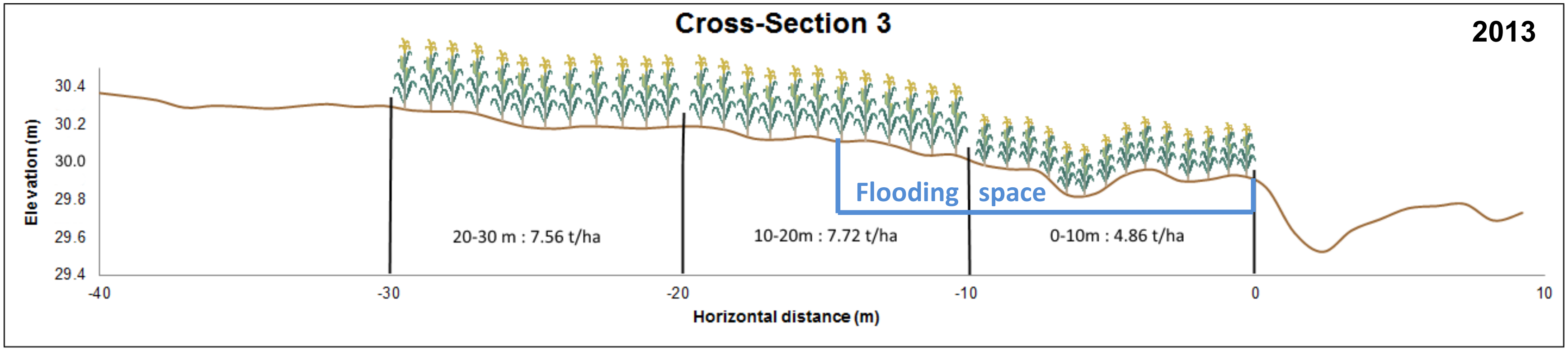


Figure 4.3: Cross-section 2 of the Saint-Paul-de-l'Île-aux-Noix site and the measured yields for 2013 and 2014.



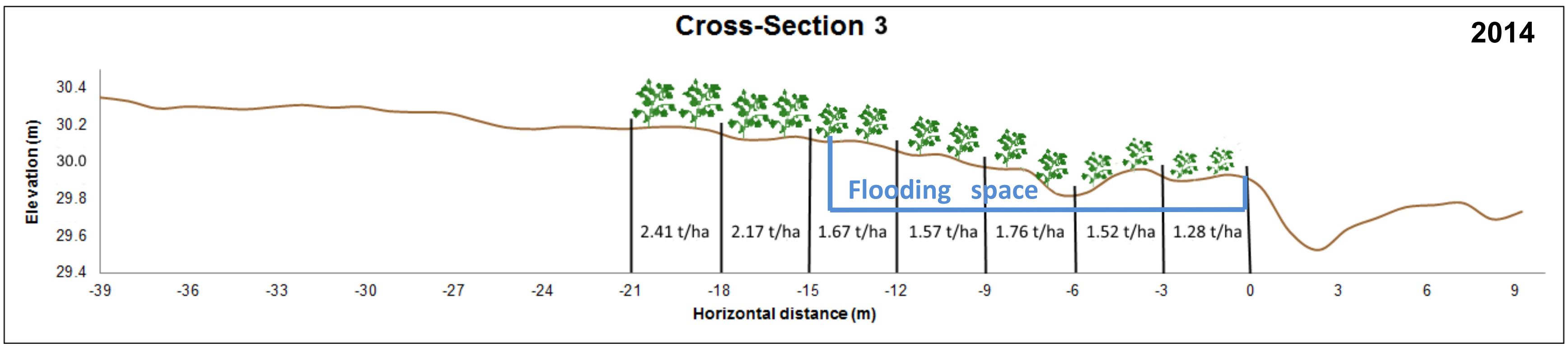


Figure 4.4: Cross-section 3 of the Saint-Paul-de-l'Île-aux-Noix site and the measured yields for 2013 and 2014.

In 2013, there were very low yields for the 0-10 m interval and a plateau afterwards (Figure 4.5). The 10-20 m interval is partly within the flooding space, but flooding in this case doesn't seem to have had an effect on productivity. For 2014, the shorter 3 m intervals required for soy analysis reveal a slightly larger effect – up to the 12-15 m interval, if cross-section 1 is excluded (yield did not increase within the 15-21 m interval as was the case for the two other cross-sections). When considering only cross-sections 2 and 3, the average yield between 15 and 21 meters is 37% higher than in the 0-15 m interval. The Richelieu hydrograph (station 030430) provides some explanation for the observed differences between 2013 and 2014 (Figure 4.6). Peak discharge was 0.27 m lower in 2013, which when looking at the topography roughly shortens the reach of the flood to 9 meters for that year compared to 15 m in 2014.

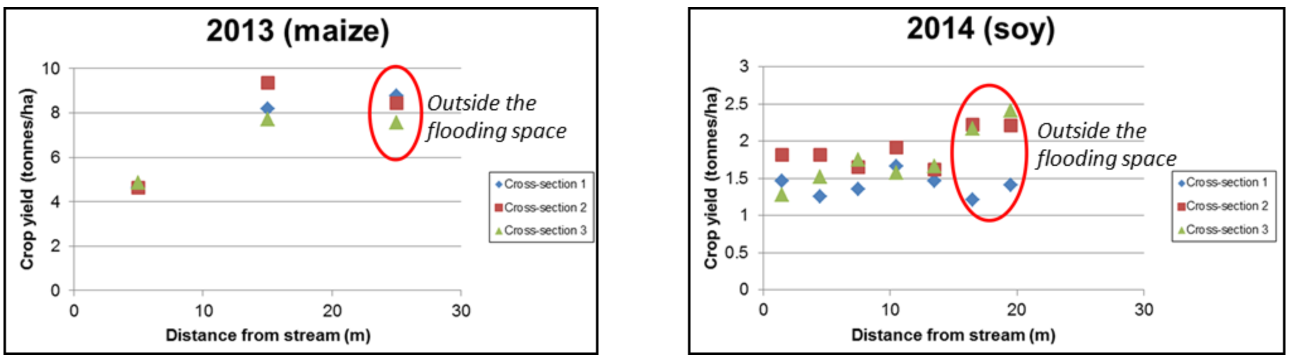


Figure 4.5: 2013 and 2014 crop yields for the Saint-Paul-de-l'Île-aux-Noix site.

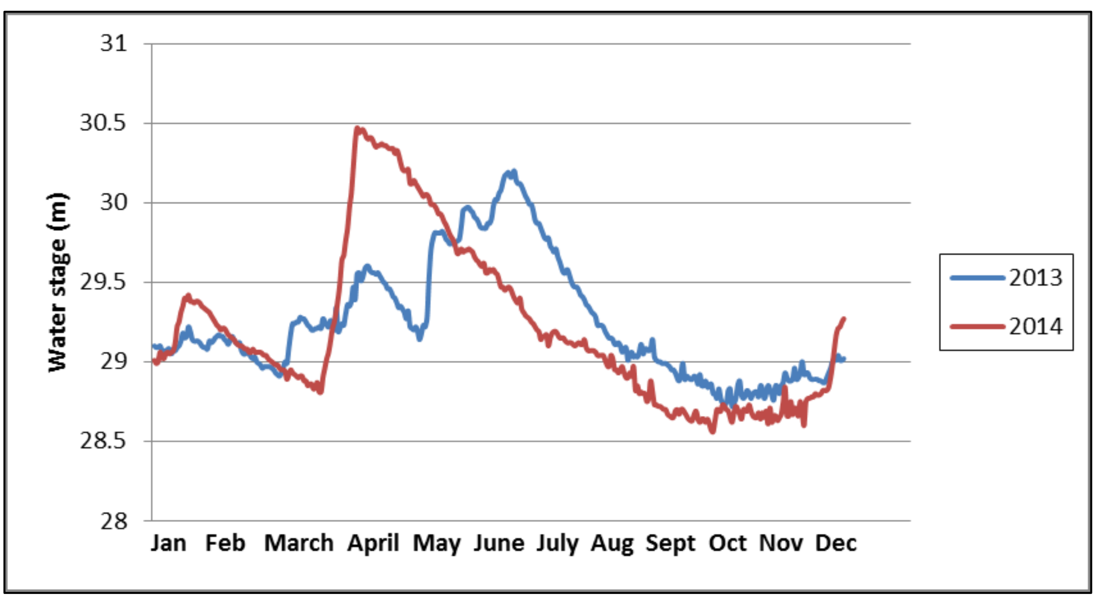


Figure 4.6: Richelieu river's flood hydrograph at Saint-Paul-de-l'Île-aux-Noix for years 2013 and 2014.

4.2.2 Lacolle (Ruisseau Bisaillon)

This study area is also part of a large corridor parallel to the nearby Richelieu River. Here, however, a perennial stream (Ruisseau Bisaillon) is present (Figure 4.7). This stream appears to be under-fit, with a ratio of valley width to stream width of approximately 40. Note that it was not possible to calculate meander wavelength ratio as the stream was straightened over its entire length. The analysis of the 1930 aerial photos indicated that the stream was already straightened by that time and no meander scars were visible.

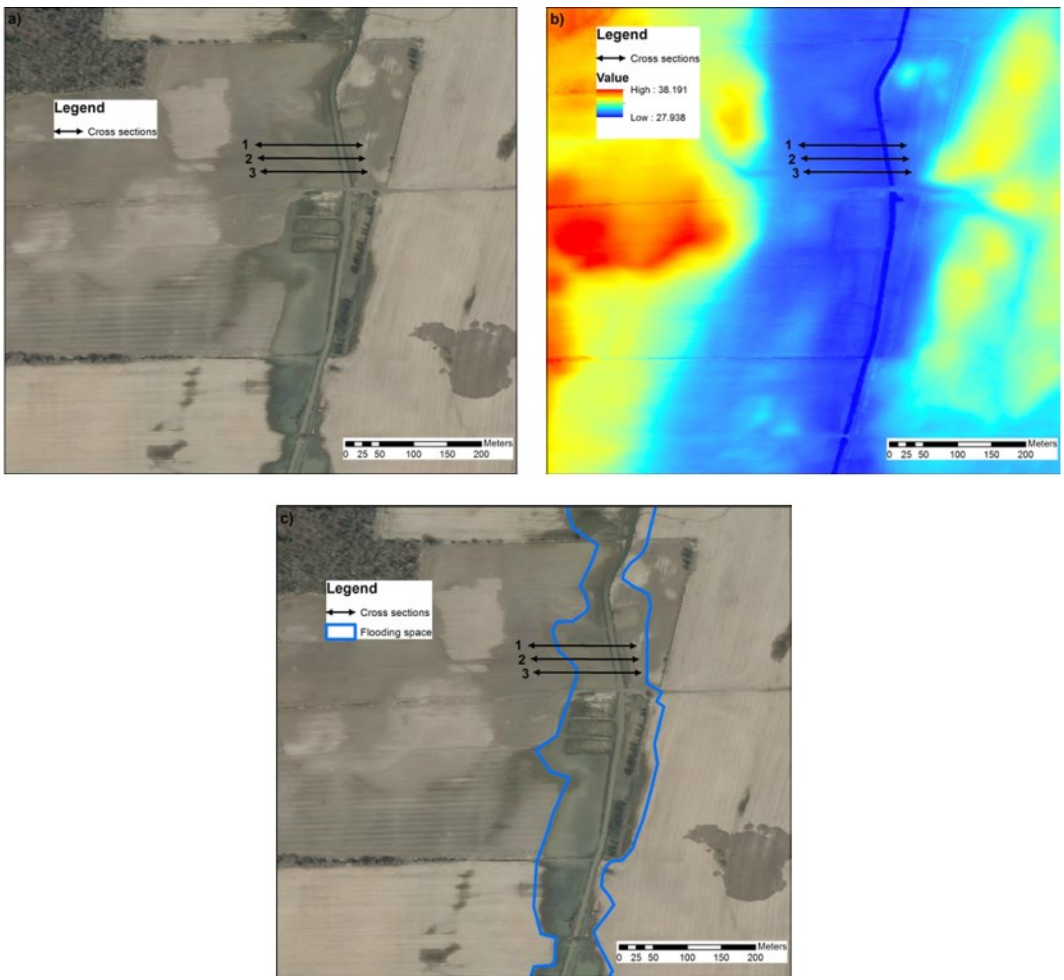


Figure 4.7: a) Spring 2014 aerial photograph showing the most prominent flooding zones; b) Elevation (DEM) revealing the extent of the valley bottom; c) flooding space for the stream delimited using a combination of LiDAR and aerial photographs.

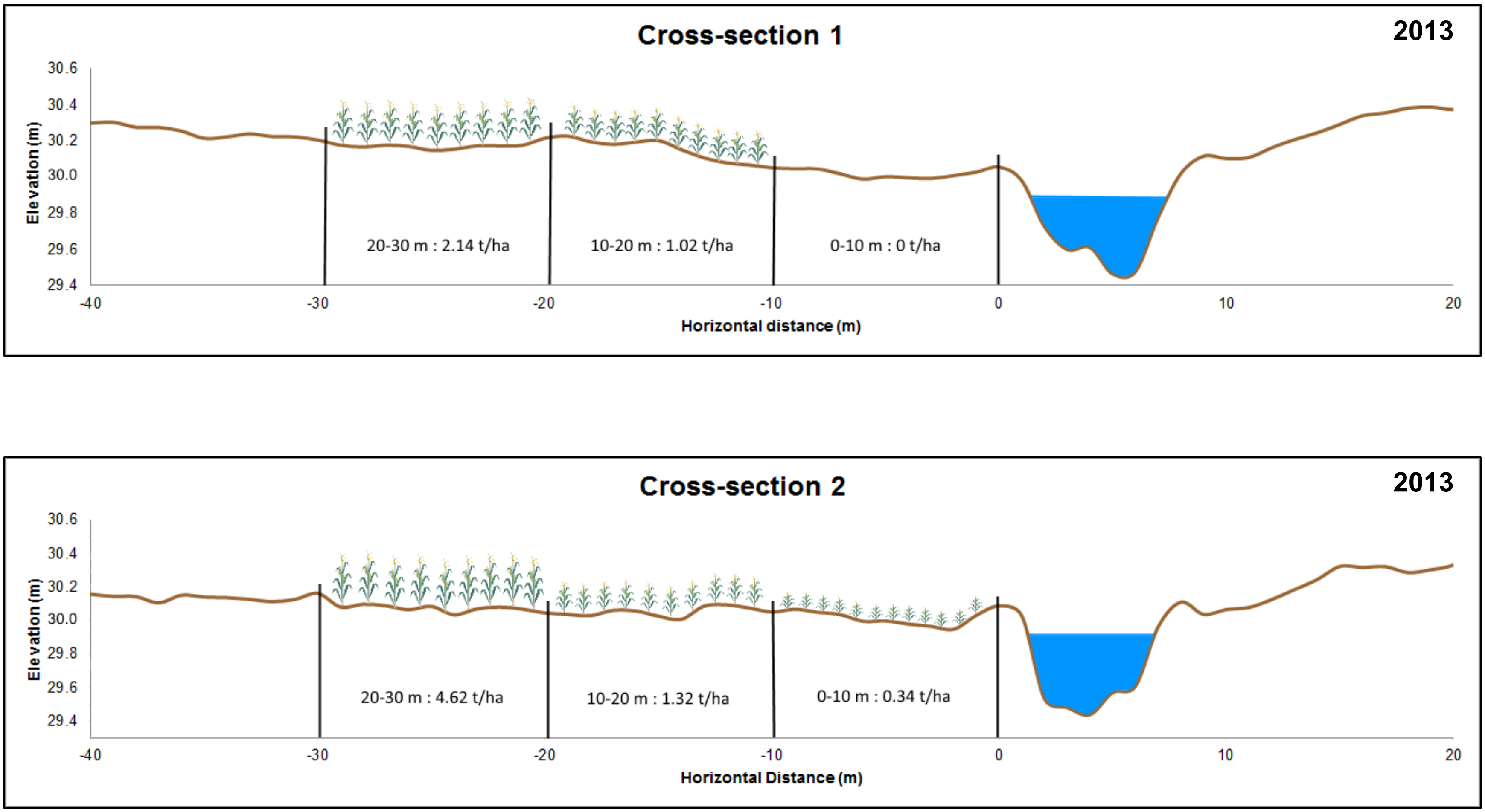


Figure 4.8: Cross-sections 1 and 2 of the Ruisseau Bisaillon and the measured crop yields for 2013.

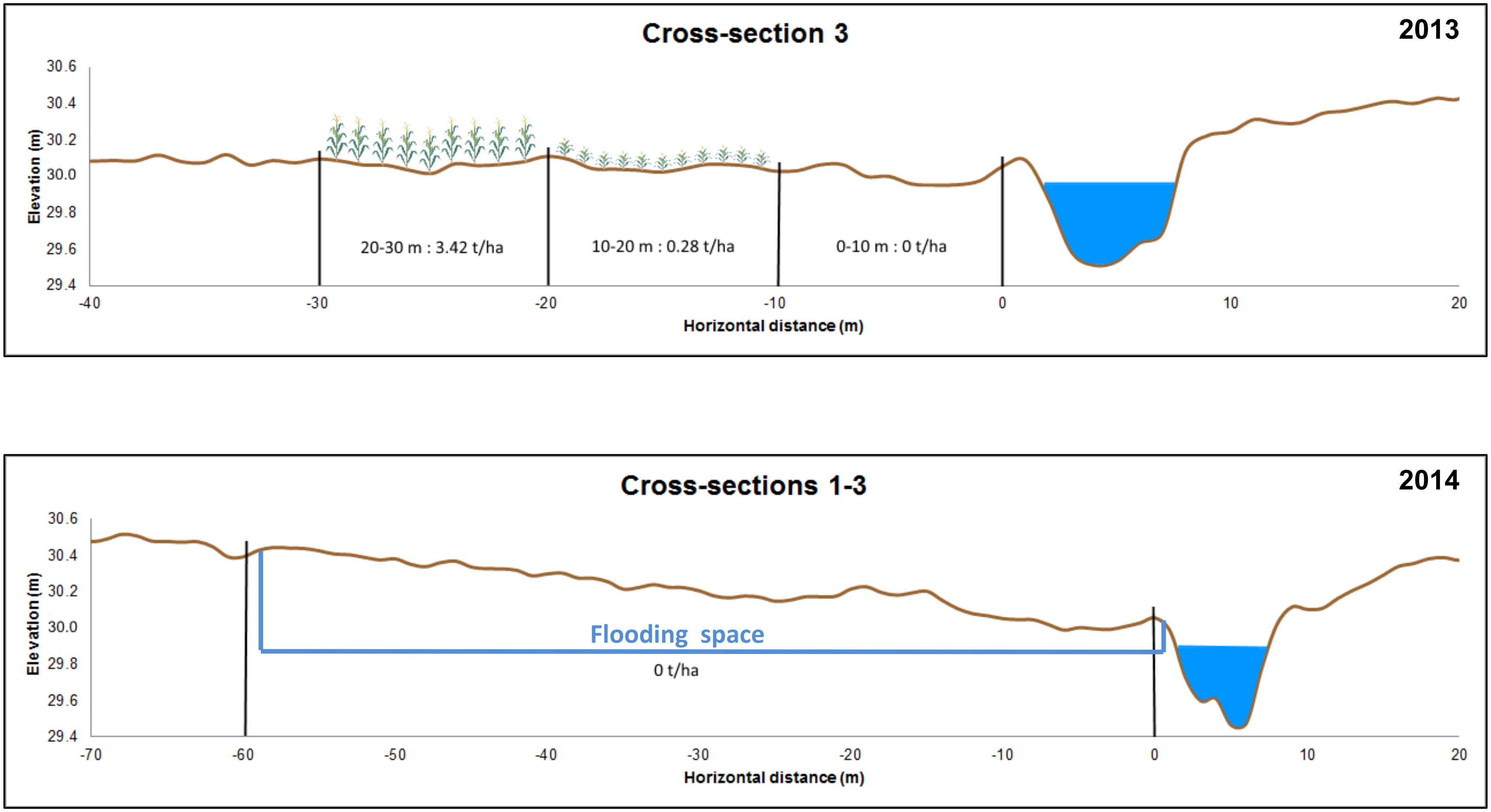


Figure 4.9: Cross-section 3 of the Ruisseau Bisaillon with the measured yields for 2013 (top) and cross-section showing the extent of the land that was not sowed in 2014 along with the flooding space.

Since the first year's data collection was stopped a great distance before normal crop yields could be observed and the second year did not have any crops to collect near the stream, no statistical analysis can be conducted for this site. The situation in 2013 is a severe case of stubbornness from a farmer, as he lost a significant amount of money sowing maize so close to a frequently flooding stream (Figures 4.8 and 4.9). It seems the lesson was learned the following year as the crop-less area roughly corresponds to the delineated flooding space. When looking at the hydrograph for the nearby Richelieu (Figure 4.6), which probably creates a backwater effect on this stream, one can understand better what has happened: There was no significant meltwater flood in 2013, which encouraged the farmer to sow the entire field. A late flood in June then ruined the crops. In contrast, the spring flood in 2014 was severe, which discouraged the farmer to even attempt sowing. The southern neighbour has given up this risky cultivation near the stream a long time ago since a wide 50 m vegetated buffer strip is present along the stream (Figure 4.10). From our analysis of crop productivity, it is clear that leaving a more extensive riparian zone free of crops is the best solution for the farmer exploiting the study field zone, or at the very least, choosing more rugged and less costly crops such as pasture should be considered in the flooding space.

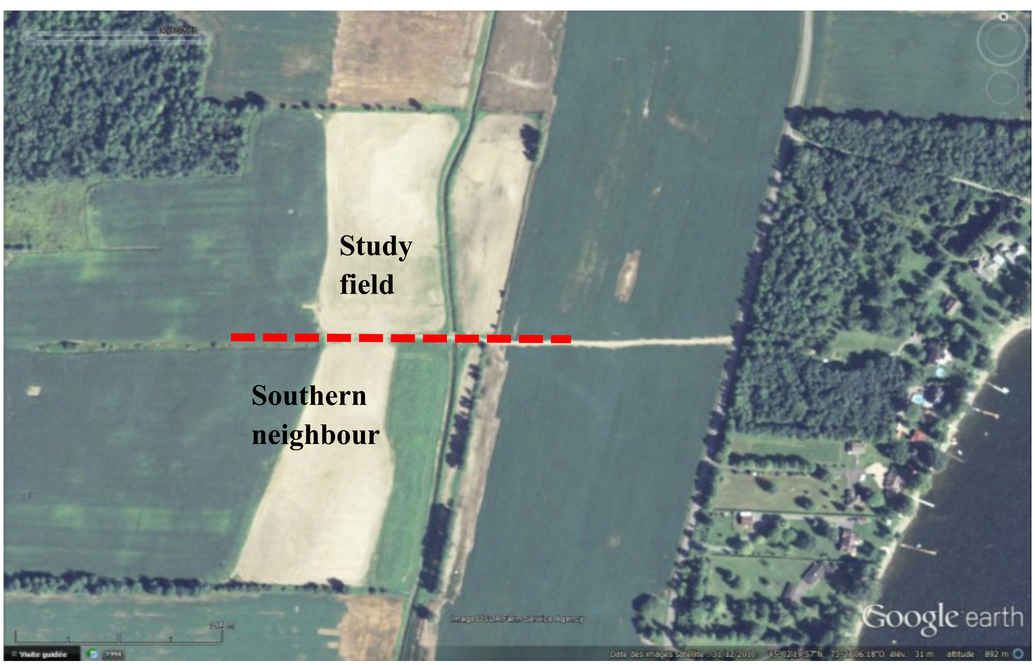


Figure 4.10: Contrasting optimism – the farmer south of the study field concedes up to 50 meters of riparian land to the stream as very frequent flooding generates poor yields most of the time (Google Earth, 2011).

4.2.3 Des Fèves River

Aerial photographs taken during the spring 2014 show extensive channelized portions of the Des Fèves River with adjacent darker patches outlining the traces of former meanders (Figure 4.11a), illustrating the higher hydrologic connectivity in those areas. The field chosen to establish the crop yield analysis covers one of those former meanders. Figure 4.11 also highlights the data used to delineate a flooding zone which is also featured on the following Figures (4.12-4.14).

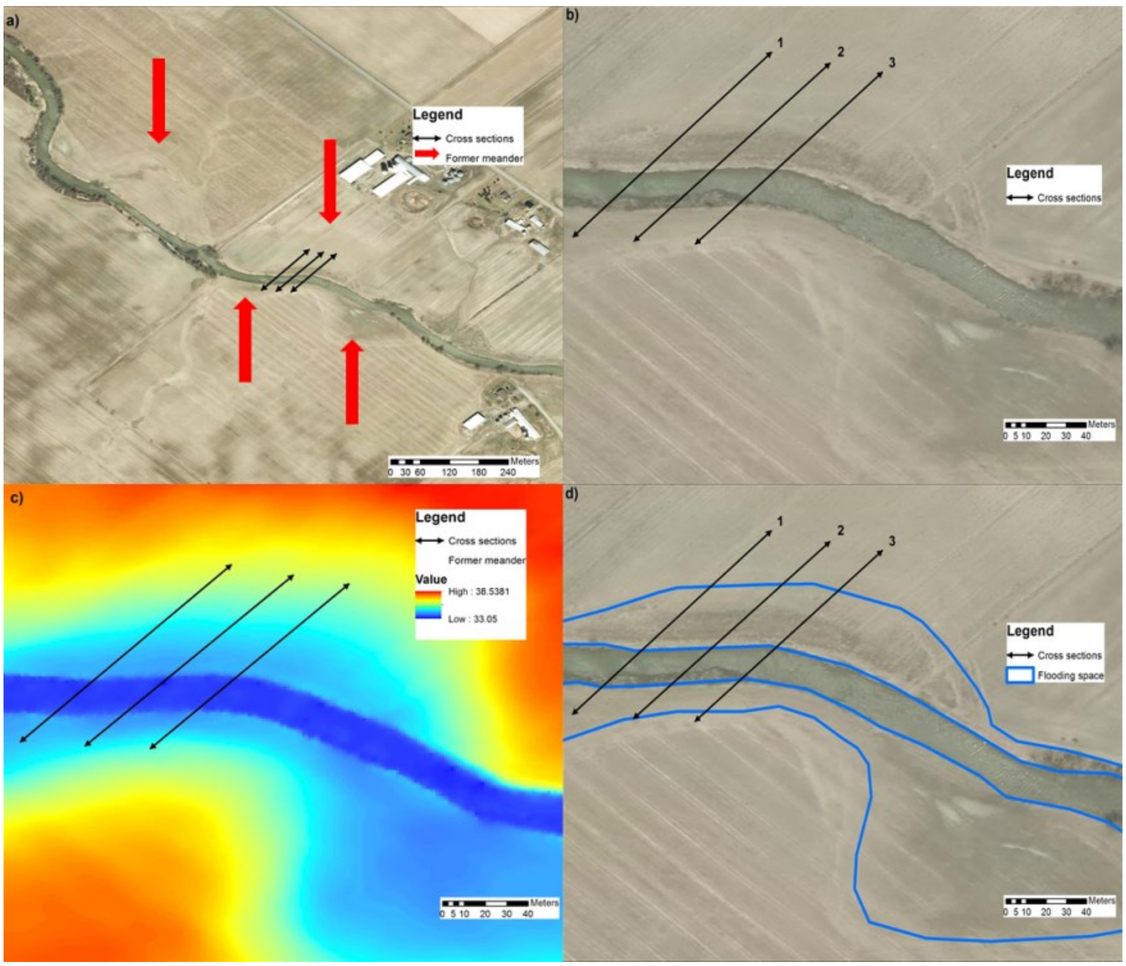
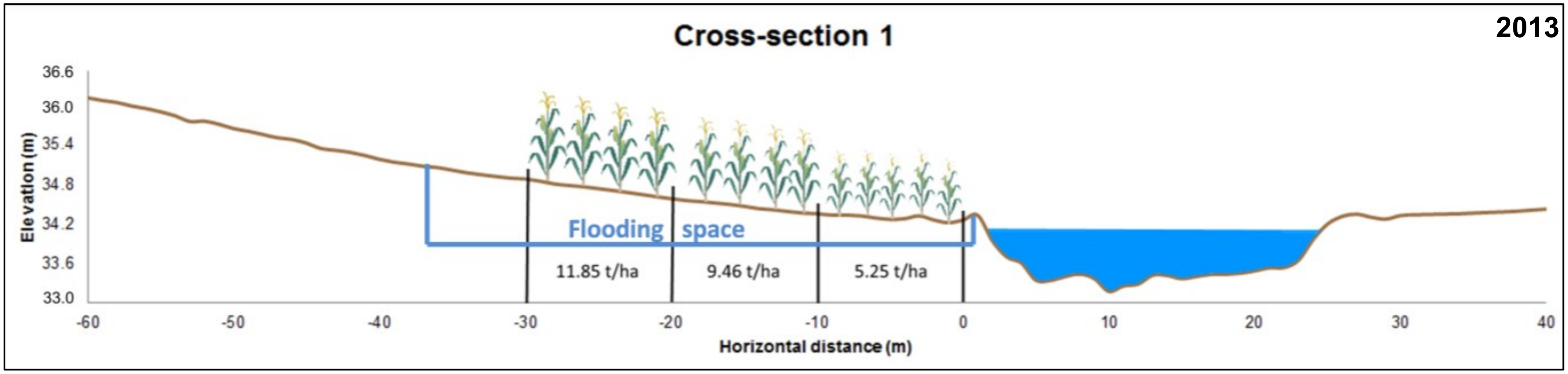


Figure 4.11: a) Former meanders appearing as darker zones in the spring due to a higher moisture content b) Closer view of the three crop productivity cross-sections in a former meander scar ; c) LiDAR DEM highlighting the extent of the lower elevation former meander zones; d) Flooding space defined using a combination of aerial photography and LiDAR analysis.



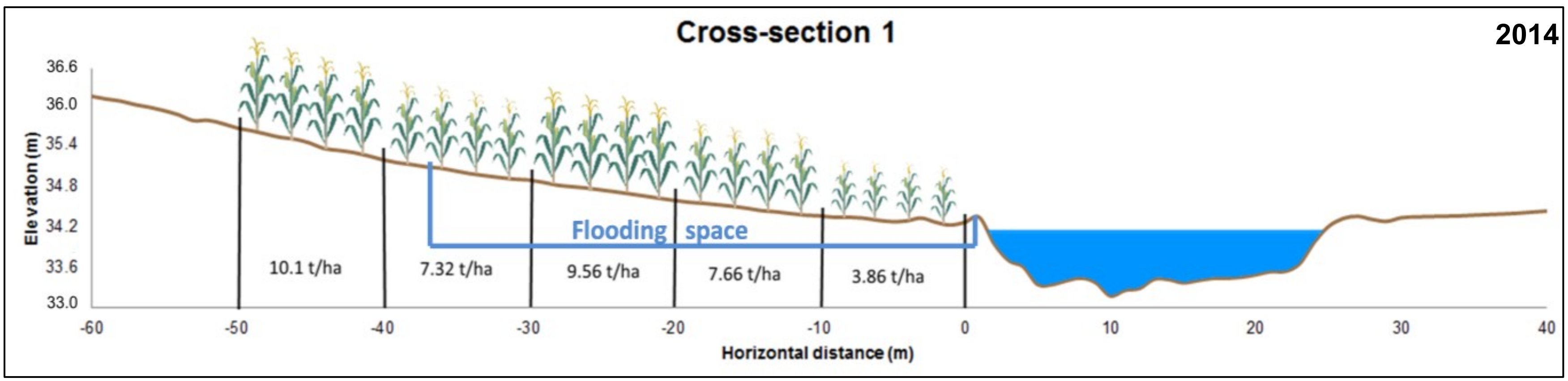


Figure 4.12: Cross-section 1 of the Des Fèves river valley and the measured yields for 2013 and 2014.

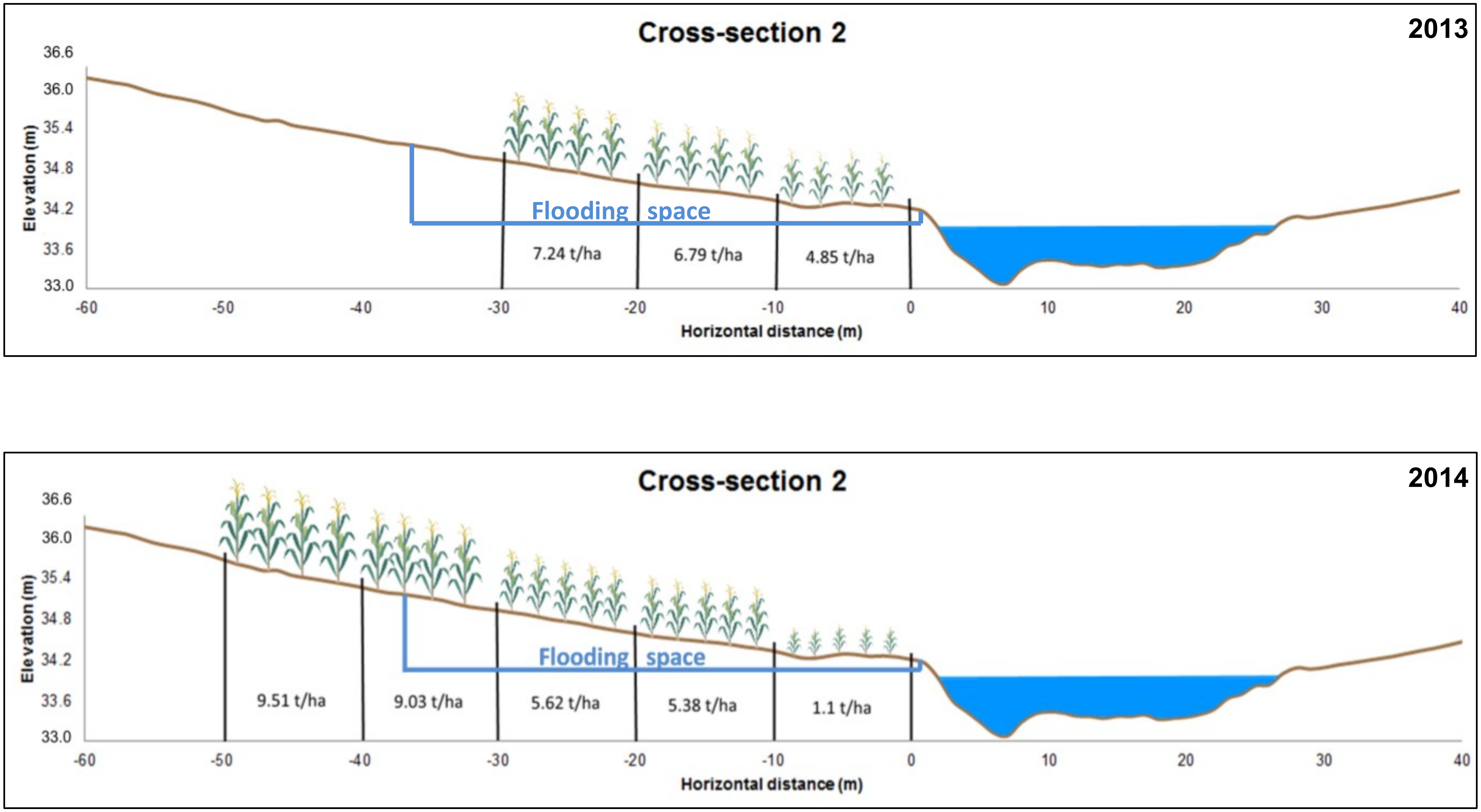


Figure 4.13: Cross-section 2 of the Des Fèves river valley and the measured yields for 2013 and 2014.

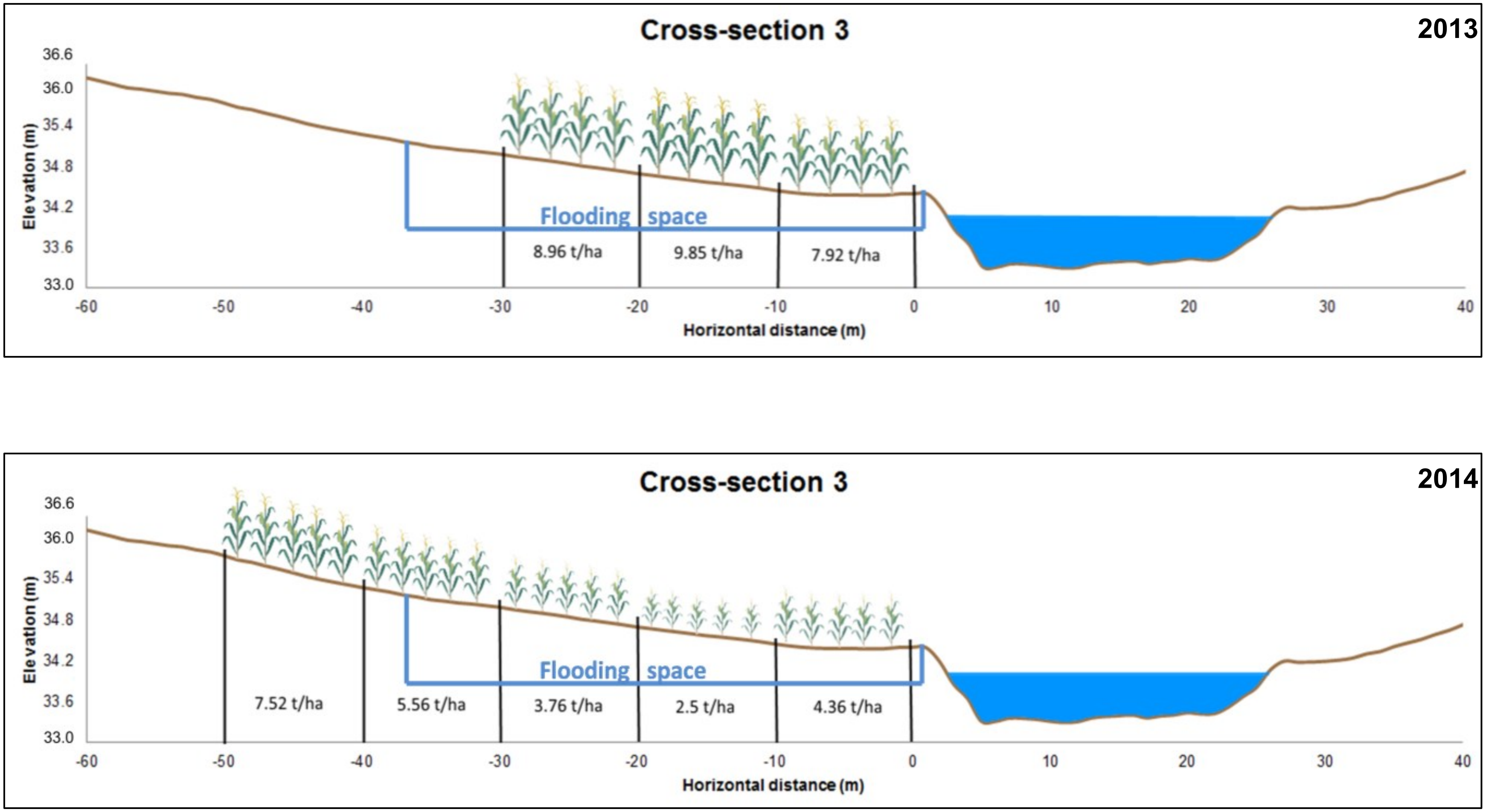


Figure 4.14: Cross-section 3 of the Des Fèves river valley and the measured yields for 2013 and 2014.

Since the 2013 data collection did not go beyond the flooding space, the focus here is on the 2014 data. Not only is the average yield at the 40-50 m interval 67% higher than those between 0-40 m, but the discrepancy between cross-sections also seems to narrow considerably (Figure 4.15). Also, cross-sections 1 and 2 at that last interval are the only ones to feature maize yields above the regional reference yields for insurance in that region – 9.27 t/ha (FADQ, 2014b). The above-par yields and lower variability across the field when outside the flooding zone provide strong arguments for the incorporation of hydrogeomorphological considerations for improved stream and crop management.

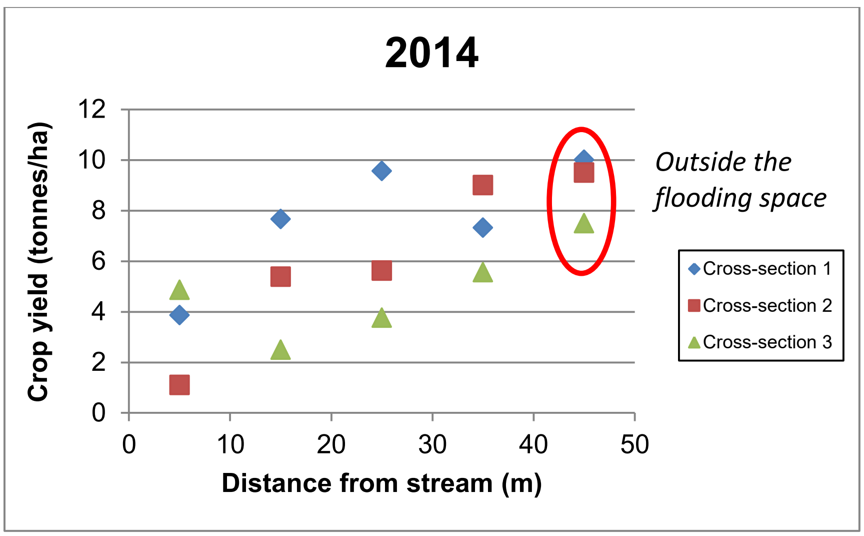


Figure 4.15: 2014 crop yields for the Des Fèves river site.

4.3 Conclusion

Economic factors related to agricultural stream management are probably the more important factors contributing to maintaining status quo (i.e. the methods currently employed appearing as the cheapest). As the first part of this chapter was expected to reveal, construction costs for the two-stage channel and over-wide ditch designs are usually higher than the traditional dredging approach, albeit to a varying degree (factors like drainage area and soil type are major contributors to this variability). However, what most short-cycled political systems fail to induce among many decision makers is a longer-term vision for varied alternative approaches in a wide array of domains, including environmental management. This can be exemplified by alternatives such as the two-stage channel requiring far less interventions in the long run, thus substantially paying off the initial cost, and bringing in ecological benefits that deciders are not yet including in their analysis. Two-stage channel and over-widened channel implementation is initially more expensive than the traditional ditch dredging operations, but a fourth, less popular approach of letting the stream adjust by itself to a stable profile is the cheapest of all alternatives. In this case, only land acquisition and stabilising outlets where bank erosion occurred need to be considered. As the second part of this chapter illustrates, crop yields are often much lower in these critical riparian areas, making them more easily acquired as they are less appealing to producers. Furthermore, two-stage channels have often been found to increase drainage efficiency for higher recurrence events (Powell et al., 2007a), further increasing the potential of acceptability of floodplain-centered alternatives since fields with severe flood problems would increase their yield. The next chapter is focusing on evaluating the surface drainage efficiency of the two-stage channel profile for the 3 study sites. This has important implications in terms of crop productivity and acceptability for farmers.

Drainage efficiency was at the origin of all the projects on river straightening and increased drainage density in agricultural watersheds in Quebec. Therefore, assessing the impact of an alternative channel cross-sectional shape on surface drainage is essential. Should results concur with the findings of researchers in the Midwest (Powell et al., 2007a) of a significantly improved drainage for high magnitude events, this would improve social acceptability. This is especially true of areas where crop yields are affected by flooding (Chapter 4), where better water evacuation can play a critical role in the ability to boost crop yields.

5.1 Model calibration

The first step in the modelling approach was calibration for both low and medium flow (see an example for Ruisseau Barrière on Figure 5.1). The value of Manning's n was chosen based on being closest to both field observations of water surface for a given discharge.

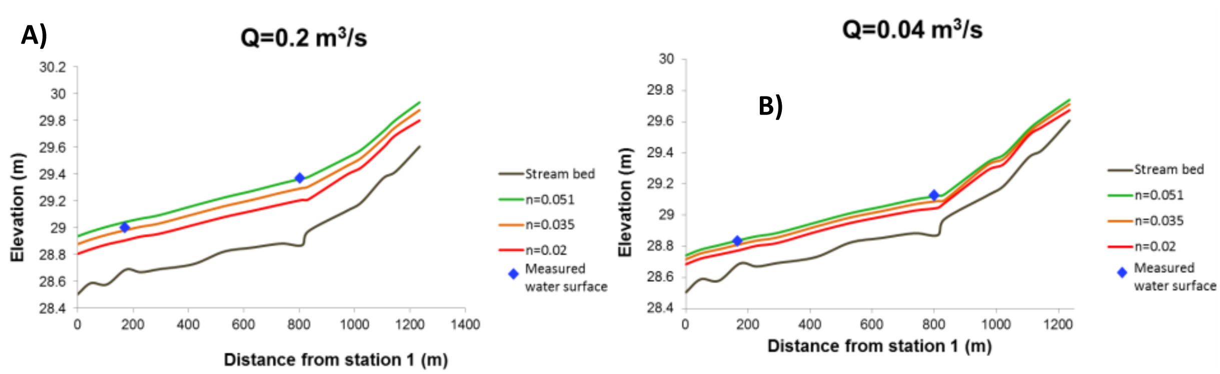


Figure 5.1: Water surface profiles generated by HEC-RAS modelling according to various Manning's n values for A) medium flow (07-29-2014) and B) low flow (07-02-2014) – Ruisseau Barrière (Bankfull discharge = 1.01 m^3/s).

In contrast with more complex fluvial environments (i.e. where floodplains are highly connected to the stream), channelized streams tend to present rather uniform condition of roughness. It is thus not surprising to observe the same Manning's n values for the medium and low flows. This uniformity reinforced confidence in attributing the same value to both high and very high flow flows, although considerable uncertainty remains. Constant roughness coefficients at varying stages was also found for the two other sites (Table 5.1 assembles all the relevant information for every site).

Table 5.1: Calibrated Manning's roughness coefficients (n) for the 3 sites with 4 levels of flow

Site	**Drainage area (km^2)**	**Low flow**		**Medium flow**		**High flow**		**Very high flow**	
		Q (m^3/s)	**n**	**Q (m^3/s)**	**n**	**Q (m^3/s)**	**n**	**Q (m^3/s)**	**n**
Cours d'eau Barrière	6.97	0.04	0.051	0.2	0.051	2.3	0.051	6.5	0.051
Upstream Des Fèves River Branch 53	2.41	0.015	0.045	0.11	0.045	0.9	0.045	2.8	0.045
Rivière L'Acadie Branch C	2.53	0.02	0.034	0.14	0.034	1.0	0.034	3.2	0.034

Branch C of the l'Acadie River has a considerably lower Manning's n than the 2 other sites. A possible explanation for this is the lack of vegetation on one bank perhaps partly related to shading from the nearby forest, combined with "burned" vegetation on the other side due to heavy pesticide application (Figure 5.2).

Figure 5.2: Dead vegetation due to pesticide application on the Branch C of the L’Acadie River.

5.2 HEC-RAS analysis

With the appropriate Manning's n, longitudinal water surface profiles can be generated (Figure 5.3). As expected we see that the higher the flow is, the smoother the water surface profile becomes as the effect of bed slope changes is reduced.

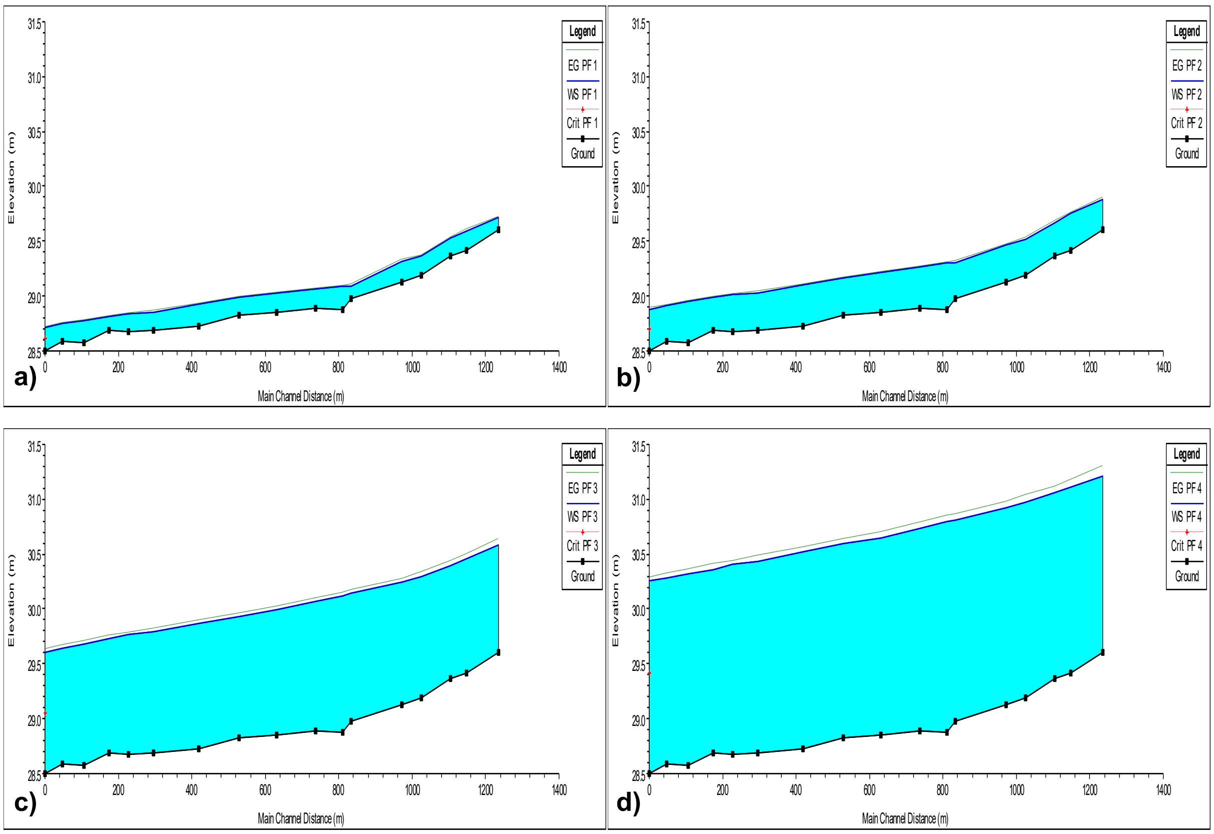


Figure 5.3: Water surface profiles generated by HEC-RAS for a) low; b) medium; c) high and: d) very high discharges for the Cours d'eau Barrière.

Figure 5.4 shows direct outputs of HEC-RAS modelling for different types of cross-sectional shape, while figure 5.5 presents the complete set of generated water surfaces in the form of histograms for 3 and 5 times the inset channel width as the floodplain width.

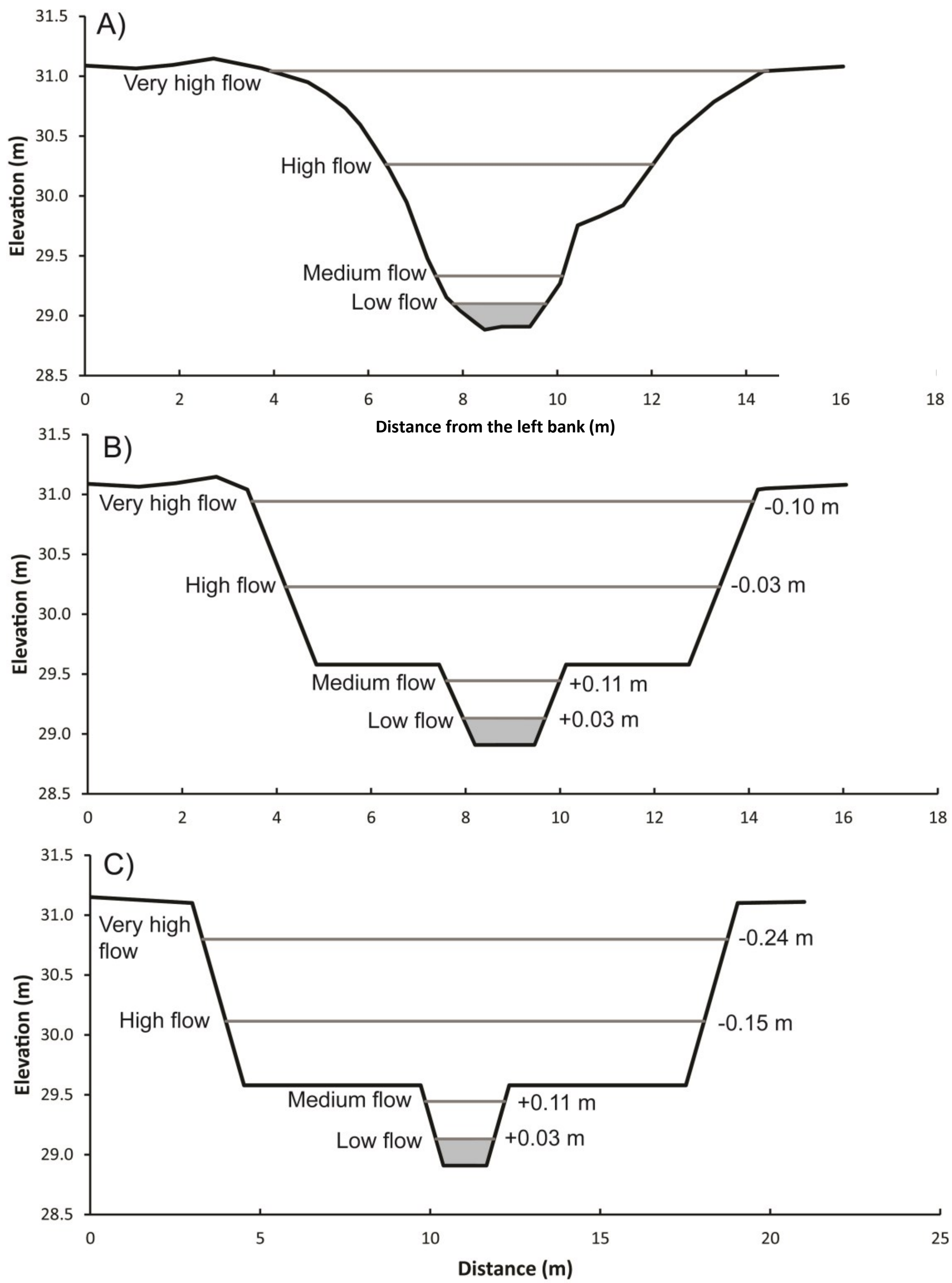


Figure 5.4: HEC-RAS output for a) the actual channel, b) a fictitious two-stage profile with 3 times the inset channel width and c) a fictitious two-stage profile with 5 times the inset channel width as the floodplain width. Values on the right correspond to the difference in flow stage compared to the actual channel.

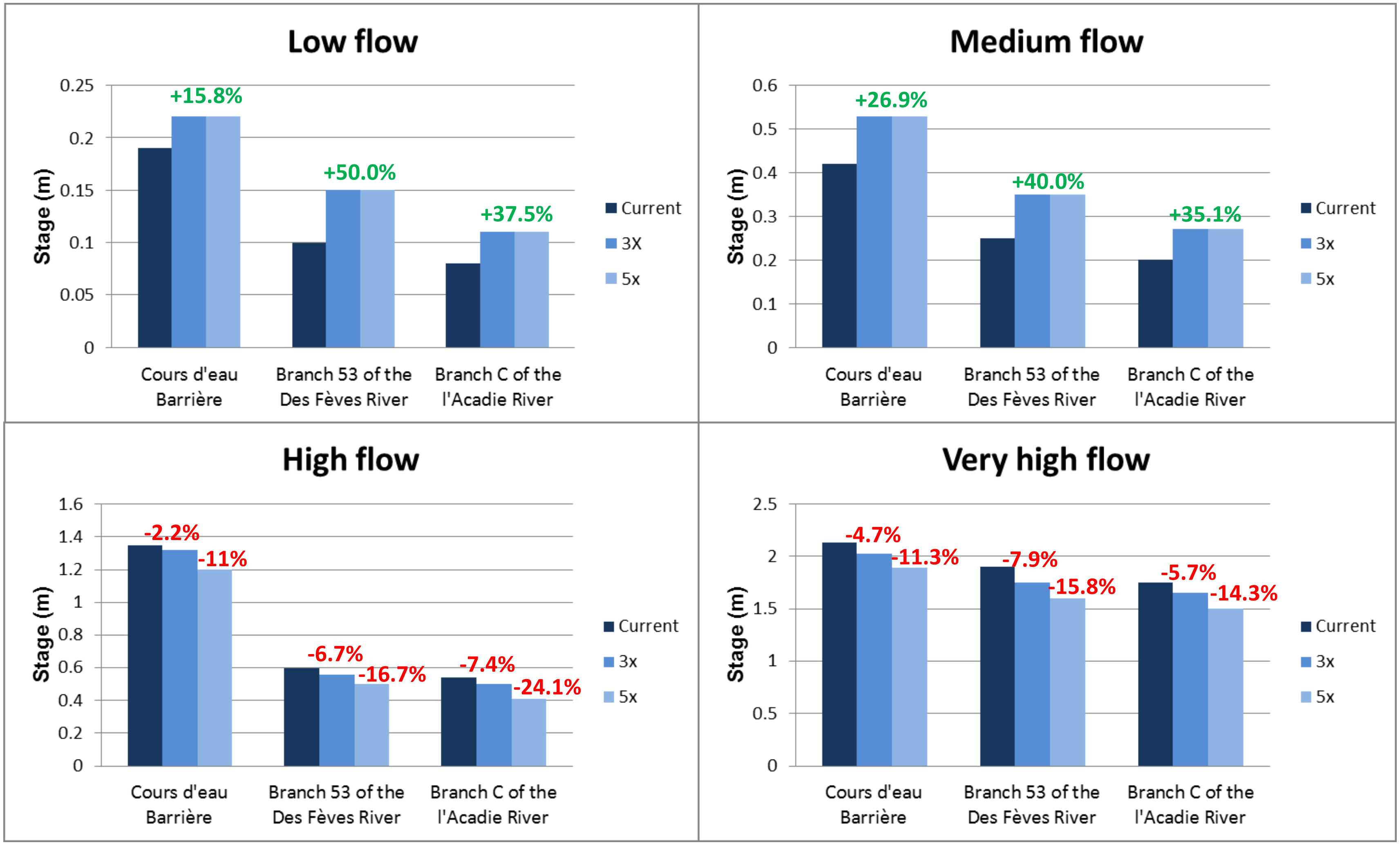


Figure 5.5: Stage variation for low, medium, high and very high flows for the 3 sites with the current profile and the 2 tested fictitious 2 stage profiles – colored numbers indicate the percentage of change in stage compared to the current design.

Table 5.3 presents the effect of a two-stage profile on the drainage capacity, i.e. on the maximum discharge when the channel is entirely full of water. The design based on 5 times the channel width can clearly handle more catastrophic flow events (up to 54% more drainage capacity). Thus, leaving this increased amount of space has great potential for limiting the impact of flooding for farmers.

Table 5.3: Effect of the two-stage profiles on the maximum in-stream discharge

Site	Maximum in-stream discharge – Current (m^3/s)	Maximum in-stream discharge– 3X (m^3/s)	Maximum in-stream discharge– 5X (m^3/s)
Cours d’eau Barrière	6.5	7.2 (+11%)	8.9 (+37%)
Upstream Des Fèves River Branch 53	2.4	(2.7 (+13%)	3.7 (+54%)
Rivière L’Acadie Branch C	2.8	3.2 (+14%)	4.3 (+54%)

Since less maintenance is one of the expected benefits of a natural two-stage profile, is should be expected that the roughness coefficient will increase over decades as vegetation takes a firmer grip of the banks and benches. The impact of increasing roughness coefficient was tested with a sensitivity analysis for the Cours d’eau Barrière’s by using the very high discharge until maximum in-stream channel stage was met (Table 5.4).

Table 5.4: Sensitivity analysis of water stage for the very high flow discharge (6.5 m^3/s) when increasing Manning's n for the Cours d'eau Barrière

Manning's n value	3X Stage (m)	5X Stage (m)
0.051 (current)	2.03	1.89
0.055	2.12 (+4.4%)	1.98 (+4.7%)
0.060	2.21 (+8.8%) - maximum in-stream flow stage	2.06 (+9.0%)
0.065	Field flooding	2.14 (+13.2%)
0.070	Field flooding	2.21 (+16.9%) - maximum in-stream flow stage

With increasing roughness, maximum in-stream flow stage is rapidly reached in the case of a two-stage channel with a floodplain width of 3 times the inset channel width, but less so in the case of the wider channel (5X). It is obviously very hard within this project to quantify precisely the timeframe of non-maintenance required to increase the roughness of the stream to the critical levels noted above. Furthermore, the impact of reduced velocities due to the increase in vegetation on sediment deposition would need to be assessed through long-term monitoring. Luckily, some Midwestern two-stage ditches have been constructed over a decade ago (e.g. projects in Crommer ditch Michigan and a tributary to Bull creek Ohio are respectively 12 and 14 years old- Powell et al., 2007b), so the monitoring programs carried in these pilot projects could be used to better understand the long-term evolution of these channels in Quebec.

5.3 Conclusion

Hydrodynamic modelling clearly reveals that two-stage profiles do not undermine the drainage capacity of channelized streams. On the contrary, drainage is often improved for very high flow events, concurring with other studies conducted in the Midwest (e.g. Powell et al., 2007a, Jayakaran et al., 2010). At the other end of the flow spectrum, low water flows tend to have a higher stage when benches are incorporated as they narrow the width of the bottom of the ditch. This results in a more suitable habitat for several water fauna species during extended dry periods. Therefore, a natural two-stage profile is likely more resilient as it can help attenuate the effects of the increase in extreme weather events, both dry and wet, which are expected to affect several regions of the world including Quebec (Ouranos, 2014). Another major benefit of improving hydraulics is the potential gain in crop yield for flood prone fields. As flooding is inevitable, two-stage channels represent a compromise whereby providing a little more lateral space to the stream can transfer floodplain dynamics within the ditch, improving water quality in the stream (e.g. nitrate reduction) and crop yields.

The main downside to the hydraulics of the two-stage channel is caused by one of its major benefits: reduced maintenance. This can translate in a long-term increase in roughness as vegetation expands, negating or even worsening drainage compared to the initial trapezoidal ditch model. Since no implemented two-stage channel in the Midwest is older than 15 years, it is hard to estimate the timeframe for this to happen. However, several naturally formed two-stage ditches have prevailed for several decades without significant maintenance and still feature predominantly grassed banks and benches. An investigation of the vegetation succession in those systems would certainly be interesting as we can only speculate about how grasses prevailed to this day. In terms of solutions in the eventuality of a significant increase in roughness, we can think of harvesting the vegetation to produce energy. Heating systems using wood pellets produced from *salix spp.* are widespread in Europe and an emerging market in North America.

On a final note, lower flow stage resulting from two-stage channels could also mean fewer days under water for subsurface drainage outlets – and thus less pressure problems – therefore improving social acceptability. Subsurface drainage is known to play a crucial role in the implementation success of a natural fluvial functioning in ditches. The following chapter explores this role in detail as well as potential alternatives to accommodate deep drains and the presence of benches within an agricultural stream.

Results from chapter 5 on surface drainage efficiency lead to believe alternative management methods could indeed be implemented in Quebec. However, there remains one major obstacle for the implementation of hydrogeomorphological alternatives in agricultural stream management in Quebec: Deep subsurface drainage outlets. As Figure 3.2 illustrates in theory and Figure 6.1 in practice, deep drains clogging with sediment are a major issue for stream naturalization as they often contribute to the triggering of dredging operations. As stated in chapter 1, this problem was never encountered for the numerous two-stage channel projects in the Midwest (Dr. Jessica d'Ambrosio, personal communication, July 19, 2014). The first part of this chapter explores the hypothesis of an endemic problem due to the unique cadastral heritage found in Québec. Obviously, little can be done to change the shape of the fields and their subsurface drainage systems. Considering this fact, the second part of the chapter evaluates ways to accommodate natural fluvial functioning while maintaining adequate tile drainage efficiency.

Figure 6.1: The red arrow points to a drainage outlet half-filled with bench sediment (inset channel can be seen in the middle of the ditch) in the Gibeault-Delisle stream in the municipality of Saint-Michel (QC).

6.1. Analysing subsurface drainage in Québec

Table 6.1 highlights the percentage of drains below the theoretical bench elevation of two of the three study sites (calculated using the regional curves of channel geometry for Montérégie – Figure 3.1). The third site (L'Acadie River branch C) had only one drain, and is thus not included in this analysis.

Table 6.1: Number of subsurface drainage outlets which present a conflict with the presence of benches for two of the three study sites

Name	Number of drains	Number of problematic drains	Average depth of problematic drains below projected bench elevation (cm)
Des Fèves River branch 53	27	5 (18.5%)	18.8
Ruisseau Barrière (Lacolle)	21	7 (33.3%)	20.2

Interestingly, the vast majority of the deeper drains were located in the upstream portion of the study reach. This corresponds in both cases to the shallowest part of the channel (e.g. the Ruisseau Barrière is 3.2 meters deep near its mouth and 2.1 meters deep in the upstream part of the reach). However, ditch depth alone does not entirely explain why those drains are deeper than others: They also generally correspond to the farthest reaching subsurface drainage systems (Figure 6.2). This observation is in agreement with the hypothesis that the *seigneurie* cadastral layout, unique to Quebec, may be responsible in part for the problem of deep drain outlets.. However, section 6.1.1 will nevertheless investigate the possibility of bad tile drainage design in the province based on field observations in areas where outlets of different depths, draining similarly shaped fields with similar topography were found in close proximity.

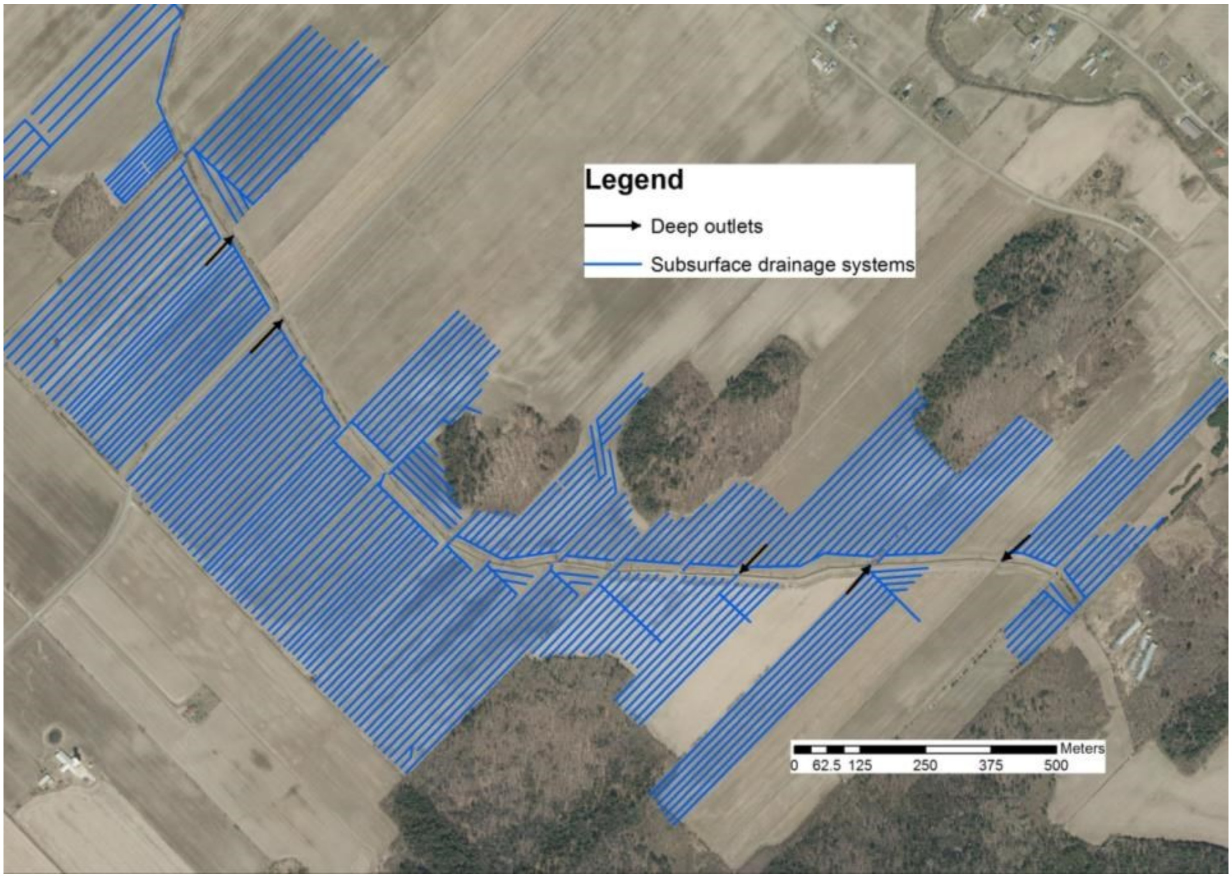


Figure 6.2: Deep outlets and their associated subsurface drainage systems (which are among the longest), Branch 53 of the Des Fèves River.

Table 6.2 compares four cases where drain depth was obtained from long profile plans (defined by engineering firms for dredging operations).

Table 6.2: Subsurface drainage plans and characteristics (red is below projected bench height)

Stream	**Max length of drained field (m)**	**Field slope (0 m = top of the field)**	**Bank height (m)**	**Tile drainage system slope**	**Drain depth (m)**
Branch 10 of Rivière Turgeon (45°16’45.3’’N; 73°45’16.5’’W)	335	0.06%	1.98	0.10%	1.25 **(0.73 m above bed)**
Branch 10 of Rivière Turgeon (45°17’29.2’’N; 73°44’48.5’’W)	831	0-180 m: 0.43% 180-831 m: 0.02%	1.83	First 180 m: 0.71%, then 0.10%	1.68 **(0.15 m above bed)**
Ruisseau Morin (45°13’39.8’’N; 73°44’48.6’’W)	1452	0.35%	2.28	0.25%	1.42 **(0.86 m above bed)**
Ruisseau La Saline (45°15'33.0’’N; 73°33’42.6’’W)	553	0-384 m: 0.12% 384-553 m: 1.40%	2.56	First 384 m: 0.17%, then 1.8%	1.22 **(1.34 m above bed)**
Branch 1 of Ruisseau Bergeron (45°20'53.0’’N; 73°27’21.4’’W)	737	0-562 m: 0.01% 562-737 m: 0.46%	1.76	First 562 m: 0.17%, then 0.40%	1.56 **(0.20 m above bed)**
Cours d’eau Brunet (45°10'47.4’’N; 73°14’21.9’’W)	463	0.06%	1.88	0.12%	1.73 **(0.21 m above bed)**
Ruisseau Brosseau (45°10'47.4’’N; 73°14’21.9’’W)	1098	0.025%	2.32	0.12%	1.95 **(0.37 m above bed)**

This assessment provides no indication of major anomalies between the designed tile drainage system and the actual outlet depth. Shorter systems generally provided ample vertical space for the outlet, but not necessarily the highest. Factors like field slope and bank height appear much more influential than field length alone. For example, the Ruisseau Morin field is very long (1452 m), covered by a single subsurface drainage system. You would expect a very deep drain, but a constant moderate slope and a high bank rather allow for a suitable height above the bed. In contrast, the field draining in the Cours d'eau Brunet is much shorter (463 m), but its flat topography and relatively short bank produce an outlet only 21 cm above the stream bed.

6.2. Comparing Quebec and Ohio

6.2.1 Field shape

The *seigneurie* cadastral layout results in agricultural fields that are long and narrow. A statistical comparison between field dimensions in Quebec and Ohio is presented in Table 6.3.

Table 6.3: Two-sample t-test for agricultural field length, width and length/width ratio between Ohio and Québec (critical t-value = 2.1448, confidence interval= 95%)

Dimension	**Ohio mean**	**Québec mean**	**Max Ohio**	**Max Québec**	**Min Ohio**	**Min Québec**	**p-value**	**t-statistic**
Length (m)	805	728	1308	1301	345	160	0.476	0.7233
Width (m)	407	150	788	370	127	60	0.000203	4.4752
L/W Ratio	2.55	6.95	6.16	20.30	1.00	1.26	0.007823	-3.0232

Interestingly, Table 6.3 reveals that field length is not significantly different between the two regions. Many rectangular fields were encountered when sampling Ohio, quite different from the near-square shape which is often assumed characteristic of the Midwestern United States. Those rectangular fields were, however, much wider than those in Québec. This dimension was thus the sole driver for the significant difference in length to width ratio, which is markedly smaller in Ohio. Assuming an equally flat landscape and a single large tile drainage system, we should expect deeper drains in Ohio (and probably the entire Midwest) as well. Several factors may explain why deep drains are not considered a problem by most scientists working in the Midwestern area:

-Long fields in Ohio contain multiple subsurface drainage systems whereas Québec fields more frequently have a single subsurface drainage system (Figure 6.3);
- Drainage systems are aligned with the smallest dimension (width) in Ohio, whereas in Quebec they follow the field length;
-Ditches were dug deeper in the Midwest;
-Sites selected for two-stage channel pilot projects (where deep drains was never an issue according to Ohio State University researchers) were selected because they already featured some benches (Powell et al., 2007b), meaning that they were left undisturbed for some time and that therefore no clogged drains prompted a dredging operation;

While none of the aforementioned hypotheses could be thoroughly verified in this thesis, the last one is examined in the following section where similarities and differences in subsurface drainage design between Ohio and Québec are discussed.

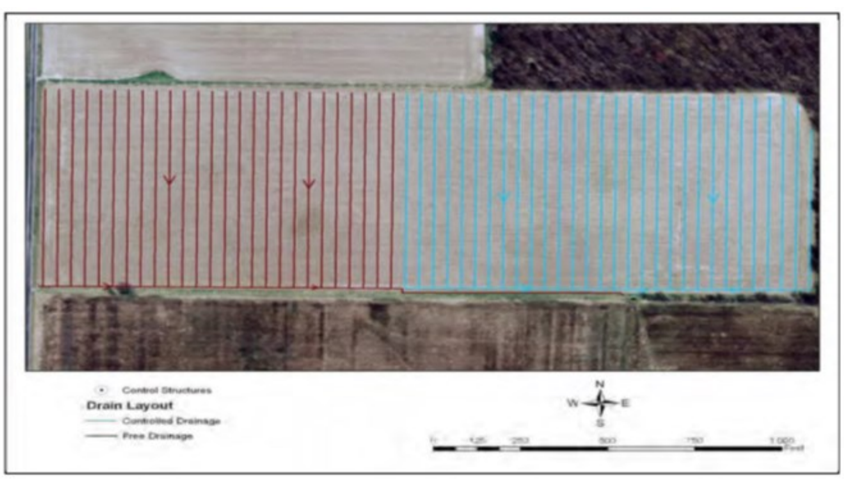
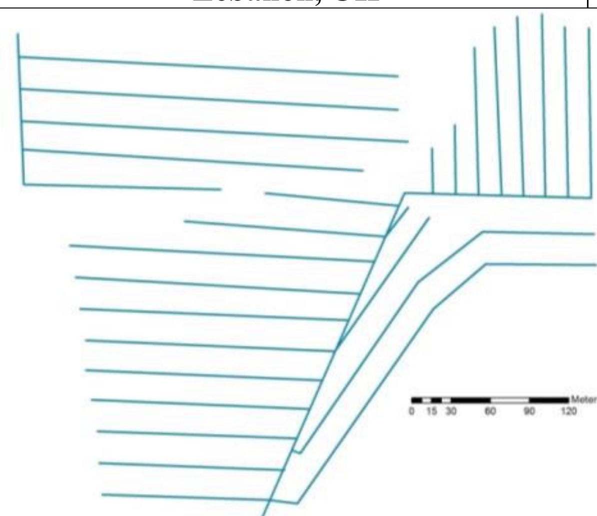
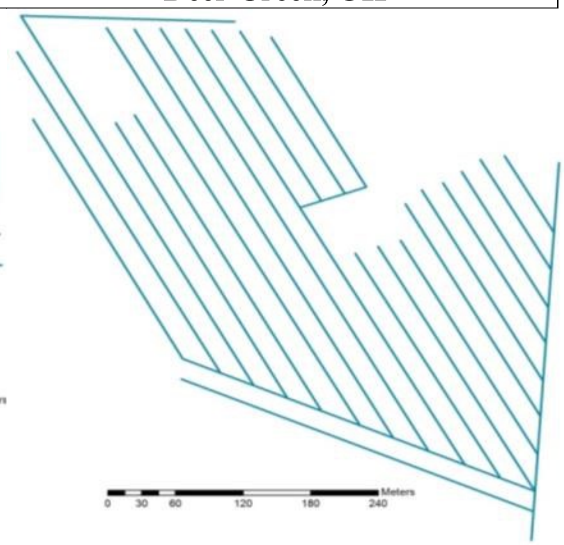


Figure 6.3: Located near Defiance Ohio, this rectangular field has 2 independent tile drainage systems, ideal for analyzing the effect of controlled drainage on water quality (ADMC, 2011).

6.2.2 Tile drainage design in Ohio

Since topographical and surficial deposits contexts are highly similar between Quebec and Ohio, and since most of the agricultural practices in Quebec are highly influenced by Midwestern expertise, it would appear surprising to find major differences in drainage practices. Table 6.4 presents tile drainage system layouts and physical characteristics of two Ohioan sites (plans provided by Larry Brown of Ohio State University).

Table 6.4: Two Ohio tile drainage plans and their corresponding physical properties

Lebanon, OH	**Deer Creek, OH**
	
Max length of field: 300 m	Max length of field: 450 m
Field slope: 0%	Field slope: 0.2%
Bank height: 1.6	Bank height: 1.9 m
Tile drainage slope: 0.0015	Tile drainage slope: 0.0035
Outlet depth: 1.1 m (0.5 m above bed)	Outlet depth: 1.05 m (0.85 m above bed)
Drainage area: 5.31 km^2 (0.49 m theoretical bench height)	Drainage area: 7.58 km^2 (0.54 m theoretical bench height)

These physical characteristics compare well with those in Quebec (Table 6.2). Again a flat terrain and low bank height seem to be the key variables influencing the outlet depth. The Lebanon site has a very small tile drainage system, but its outlet is still half a meter above the bed of the trapezoidal ditch. This height could be conflicting with natural fluvial features (the 5.31 km^2 drainage area corresponds to a bench height of 0.49 meters for this region). Also, instructions about maintaining lateral drain depth between 36 and

48 inches (91 and 1.22 m) were found on one of the plans. Similar recommendations are made in Quebec (Savoie, 2013), another indication that tile drainage practices do not seem to differ markedly between Ohio and Quebec.

6.3. Solutions to very deep subsurface drainage outlets

The problem of very deep drain outlets may not be due to flaws in their design, but is mostly found in Quebec despite the fact that other areas are also characterized by flat and very long fields (section 6.2.1). Consequently, effort needs to focus on providing innovative and sustainable solutions to accommodate natural fluvial adjustment while maintaining proper tile drainage efficiency, which is key for agricultural productivity. Reshaping fields or removing tile drainage systems are clearly unrealistic solutions from an economic perspective, and were not considered here. The following sub-sections explore more realistic alternatives centered on the outlet itself.

6.3.1 Raising the level of the outlets

The most straightforward solution to deep drains would be to raise the level of the outlets. However, several issues arise when examining this option. First, if only the outlets were to be modified (i.e. by reducing their slopes), the gain of vertical clearance from the stream would be nearly negligible since a) slopes are very shallow and b) outlet pipes are very short (~8 m on average). In addition, there would be a loss in drainage efficiency created over the entire tile drainage system with a shallower slope at the end.

The other way of raising the level of the outlets would be to modify the entire subsurface drainage network. As noted in section 6.1, no anomalies were detected for the tested fields (which doesn't preclude problems occurring in untested fields, but which indicates this is not a widespread problem). Therefore, there is very little room for modifications since minimal drainage depths must be respected to maintain drainage efficiency (e.g. drains too close to the surface which can be crushed by heavy machinery). Even assuming that an entire subsurface drainage system can be raised enough to have its outlet above bench elevation, there would be considerable costs involved (approximately $1600/ha, estimated by subtracting materials cost from total tile drainage installation cost). With typical field areas around 10 hectares, this is clearly not a realistic solution from an economic point of view, and would also result in severe soil disturbance and potential crop deficiencies. The following section proposes a more efficient way of raising the level of the outlets using pumping systems.

6.3.2 Pumped outlets

Pumping systems allow raising the outlet above the bank of a stream (Figure 6.4). They also give more control over the rate of water removal as opposed to no control at all from conventional gravity systems. Though not widespread, electrical pumps can often be seen alongside Southern Québec roads where they can easily connect to electrical lines. However, they are never seen on stream reaches far away from roads since the cost of bringing electrical power would be very high ($74/m – Hydro-Québec, 2015) and there was until now no incentive to change the drainage system since gravity outlets appear to work well (in combination with dredging). The need for stream naturalization accommodation that is exposed in this thesis brings however a new argument in favor of such systems. Though seemingly high, the cost of $74/m is competitive when compared with the other alternatives evaluated in chapter 4 (assuming the installation of pumps doesn't raise that figure considerably). Other possibilities also exist where there is no need for the construction of an electrical line. Gasoline (petrol) fueled pumps do exist although there is little information available in the literature on these pumps. This option obviously has the downside of producing greenhouse gases, and the cost of fuel must be factored in. For the former problem, it should be noted that during a year, the most critical drainage period extends only over a few weeks (spring thaw and the occasional big storm during summer and early fall), meaning that more often than not pumps would not be emitting any pollutants. For the latter issue, subsidizing might be necessary (this could also apply to the electrical option). Also, with a gasoline fueled pump infrastructure already in place, a shift towards solar energy would be much smoother. This ever growing technology already has the potential to fuel small pumps (Figure 6.5), and it may in the near future be able to support water brought by big subsurface drainage systems. More generally, pumped outlets could improve acceptability of the saturated buffer technique for deep drains. Even though with this approach most of the drainage water is diverted along a vegetated buffer strip (Figure 1.10) farmers, which are conservative by nature, would still want the stream to be dredged to clear the outlet. Having a pump would entirely solve this problem. Lastly, pumped outlets could very well be combined with the re-saturated buffer technique, since pumps could facilitate the distribution of water parallel to the stream over long distances. The following sections explore alternatives where modifications to the outlet are minimal.

Figure 6.4: This electrical pump is located close to a road, where electrical lines are already present.

Figure 6.5: Solar panels provide enough power to run small pumps, and may eventually be able to provide power to efficiently drain large tile systems. Image taken from: http://belkomsolutions.com/?page_id=909

6.3.3. Extending the outlet to the inset channel

An alternative to deal with deep drain outlets is to extend the outlet in the inset channel, also known as the first stage (Figure 6.6). This approach is low cost as it only requires a slight change in the outlet's length. Two situations may occur: reaches where the projected inset channel is wider than the current trapezoidal profile and reaches where it is narrower. The main difference between the two is that a narrower inset channel will result in the outlet being submerged more frequently (water stage rises faster in the first stage while the opposite is true in the second stage, where high magnitude events are contained more efficiently). A reduction in tile drainage efficiency would occur, making this option less acceptable. Shared by the two situations is the loss of the denitrification opportunity induced by the presence of a floodplain. Indeed, having the drain pass through the bench is almost identical to a vegetated buffer strip bypassed by subsurface drainage. The following section illustrates an option which combines the idea of minimal intervention on the outlet while eliminating the issues of impaired drainage efficiency and greatly improving the denitrification potential of the stream.

Figure 6.6: Sketch of a tile drainage outlet passing through a bench, emptying into the inset channel of a two-stage profiled ditch (Swedish Agricultural Commission, 2012).

6.3.4 Horseshoe wetland

This horseshoe wetland alternative, also known as pocket wetland, has the potential to shift dredging from a linear process to a punctual one, i.e. sediments only need to be removed from small pockets instead of from entire reaches, which are often over a kilometer in length. This is a benefit which, when combined with the denitrification potential, may greatly improve water quality. In order to explain this concept to stakeholders and farmers in Quebec, an artist was hired to represent the horseshoe wetland concept (Figure 6.7). Consulted farmers were in fact quite enthusiastic about pocket wetland idea, particularly because it would give them control over the management of their subsurface drainage outlets. However, many of them raised concerns over the power of the stream during high magnitude events and the resulting bank erosion potential. Another risk is that massive sediment deposition would occur in these miniature wetlands because of the abrupt widening of the channel, resulting in drain clogging. Finally, issues were raised concerning the modification of the shape of the field which will make heavy machinery circulation more annoying for farmers. The degree of disturbance varies according to the location of the outlet: in most situations it is at the corner of a field (Figure 6.8), which is already hard to reach for machinery, while drains in the middle of the field are rarer and mostly present for very wide fields. This would nevertheless imply increased difficulty to reach these areas. Further work is needed before considering any widespread implementation of the horseshoe wetland approach. This work should focus on 2D morphodynamic modelling (to assess the impact of the recirculation zone within the wetland and overall sediment dynamics) and a first experimental site to collect data which could be used to calibrate and validate a model. Below are first small steps which were taken to evaluate in more detail the implementation potential for this idea through the scopes of cost and hydraulics.

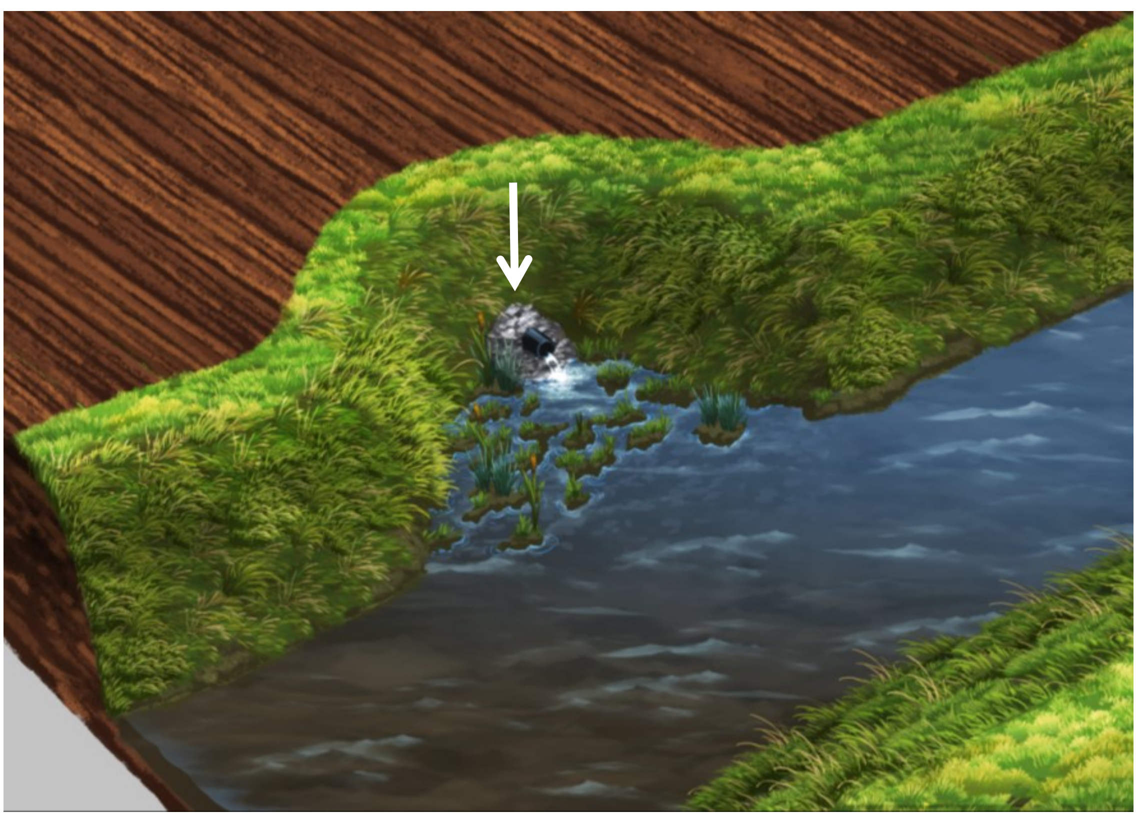


Figure 6.7: Horseshoe wetland applied to a deep subsurface drainage outlet (white arrow).

Figure 6.8: Field corners are already hard to reach and generally escape agricultural operations, making it easier to apply the horseshoe wetland for the drains that empty there and less so for outlets situated in between.

6.3.4.1 Implementation cost

Table 6.5 integrates the cost for implementing horseshoe wetlands for the 2 study sites where problematic drains were present.

Table 6.5: Estimated construction cost of horseshoe wetlands at identified deep drains for the 2 sites presenting problematic drains

Site	Costs surrounding construction ($)	Fertile spoil		Mineral spoil			Total cost ($)
		Vol (m^3)	Removal cost ($)	Vol (m^3)	Removal cost ($)	Transport cost ($)	
Des Fèves River branch 53	5000	21	800	59	2250	1030	9080 ($3.8 /m)
Ruisseau Barrière (Lacolle)	5800	30	1120	164	6120	2870	15910 ($4.0 /m)

In addition to the very low implementation cost when compared with other approaches (see Chapter 4), it is expected that drain clogging would be managed individually by farmers (who have access to the machinery), thus greatly reducing maintenance cost for society. The assumption of farmers accepting to manage and dredge the pocket wetlands by themselves when required is supported by the fact that farmers currently have to go through a rather long administrative process to reach the same result. Disconnecting drains in this fashion can work very well in synergy with the passive self-formed approach (see Table 4.5) and adds very little to the overall cost.

6.3.4.2 HEC-RAS Analysis

Hydraulic modelling reveals that the hydraulic influence of a 3 m by 3 m horseshoe wetland on a 6-m wide ditch would be overall small (Table 6.5). There would be a slight increase in stage with reduced velocity for both low flow (0.2 m^3/s) and high flow (4 m^3/s) tested events (Table 6.5).

Table 6.5: Flow characteristics before and after integration of a 3x3 m horseshoe wetland on a 6-m wide ditch

Test	**Low flow stage (m)**	**High flow stage (m)**	**Near bank low flow vel. (m/s)**	**Near bank high flow vel. (m/s)**	**Channel low flow vel. (m/s)**	**Channel high flow vel. (m/s)**
Standard ditch	0.29	1.59	0.1	0.3	0.3	1.1
With horseshoe wetland	0.30 (+1 cm)	1.63 (+ 4 cm)	0	0.1 (-66.7%)	0.2 (-33.3%)	0.3 (-72.7%)

Local channel widening causes a considerable reduction in velocity as the wetted perimeter increases sharply. It also explains the slight increase in stage (due to a change in the balance between kinetic and potential energy). Though lacking a bit of depth, this analysis shows that the main concern with this technique should be an accelerated sediment deposition at the wetland and thus a more frequent need to dredge, not erosion.

The rate of sediment accumulation was not estimated and could be an interesting analysis to conduct within a more refined 2D modeling exercise. This has important implications as the acceptability of implementing the horseshoe wetland largely depends on the maintenance frequency for farmers although as we will see in the following concluding chapter, they can play a large role by reducing sediment input in agricultural streams.

Channel dredging of lowland agricultural streams is ubiquitous, but it also contributes to several watershed management issues. For example, it is linked to both a failure to retain sediment in the fields and a lack of natural fluvial processes that would favor sediment storage within the channel. Management approaches that incorporate river dynamics concepts while maintaining proper drainage efficiency were explored in this thesis. The findings described in chapters 3 to 5 confirm the main benefits of incorporating hydrogeomorphological concepts that were identified in previous work in the Midwest: While the initial implementation cost for a two-stage or over-widened channel is higher than that of dredging, greatly reduced maintenance efforts and recurrence can translate into a lower cost in the long run (notwithstanding the ecological services which were not quantified in this project).

One of the novelties of this research, which was not assessed by most Midwestern researchers, is the analysis of the option of letting the stream reach a two-stage profile naturally over time. With such a natural-process approach, cost becomes nearly negligible as the earth removal and transportation work is carried out almost entirely by the stream instead of by heavy machinery.

This thesis also identified issues specific to Quebec's agricultural landscape, in particular the relatively widespread presence of deep subsurface drainage outlets which interfere with sediment accretion. Indeed, most dredging projects are initiated because of subsurface drainage impairment. Based on the limited information available in the scientific literature from outside the province and on primary data collected in the state of Ohio, it seems likely that this is a unique feature of Quebec's streams. Several options modifying the outlet and/or its surroundings were explored. Electrical pumps (when nearby power is available) and a small pocket wetland are the most promising solutions. Finding solutions to the problem of deep drain outlets is very important considering the widespread use of tile drainage in southern Quebec.

Another novelty of this study is the use of HEC-RAS modelling to confirm the potential of two-stage channel designs for curbing extreme flow conditions. When inset channel width is narrower that the trapezoidal ditch width, stage is higher for low-water periods, providing better habitat for aquatic fauna. Conversely, a reduced stage for high magnitude events can lead to improved crop productivity and acceptability of the required additional space for these channels.

The necessity for additional lateral space has often been mentioned in the scientific literature, but rarely has this critical riparian space been the subject of a crop productivity investigation. Site selection for chapter 4 was not random, and clearly the bias towards sites with flooding problems favored a correspondingly strong response. However, even if it would be farfetched to imply that all agricultural streams frequently flood adjacent fields, it remains a recurrent problem in low land areas (e.g. Richelieu River floodplain). A more thorough analysis should be conducted to better understand flooding dynamics in agricultural areas and their impact on riparian zone productivity. This would require a larger sample and a non-biased site selection process so that less problematic fields can be included as well and statistical tests can be run. This effort would greatly benefit river managers and help determine appropriate levels of financial compensation for the loss of cultivated land). Ways of financing all of these efforts also need to be discussed. MRCs and MAPAQ, who share the bill for dredging agricultural streams, could be interested in the new approaches proposed in this thesis that reduce human interventions in the long run. This would require as a first step to implement some experimental sites (two-stage channels, pocket wetlands, and/or a combination of both). Experimental sites also allow assessing social acceptability, one of the most crucial aspects for the widespread application of these techniques. A second step would involve 2D morphodynamic modelling as there are still considerable uncertainties related to sediment movement in some zones (e.g. pocket wetland). Considering that the two-stage channel design is a genuine success story in the Midwest, it would be in the interest of MRCs and MAPAQ to support such research initiatives and contribute to more sustainable management of agricultural streams. Lastly, while it is encouraging or even exciting to explore these innovative approaches, the importance of best management practices in the field should continue to be promoted in order to reduce the input of sediments to agricultural streams. Of utmost importance is to ensure that a vegetated buffer strip is always in place, as too often this is still not the case in Quebec (Figure 7.1A), although there are a few examples of good practice (e.g. Figure 7.1B). On the positive side, no-till approaches are growing in popularity in Quebec, leading to healthier, more cohesive soils and reduced sediment output to streams. Cover crops are also increasingly being discussed and many pilot projects using them are underway throughout the province. A combination of these practices with more traditional approaches like vegetated buffer strips along with the geomorphologically sound stream management options presented in this thesis would lead to major environmental benefits but also to more sustainable land for producers.

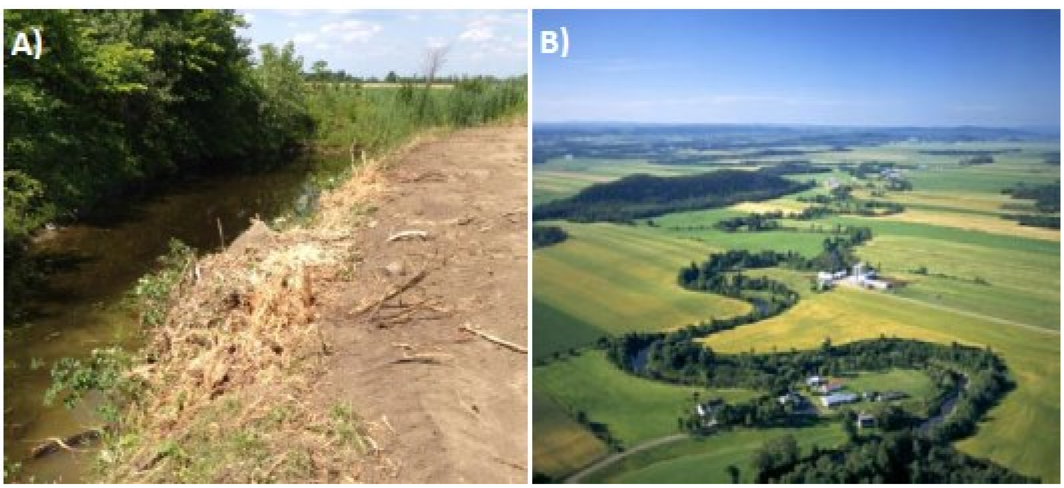


Figure 7.1: A) Problematic riparian buffer in Branch 2B of Saint-Pierre River and B) ideal forested riparian buffer on the Ouelle River.

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