Revealing Hydrological Connectivity in Straightened Agricultural Lowland Streams: An Interdisciplinary Approach to Process-Based Restoration

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Abstract

Revealing Hydrological Connectivity in Straightened Agricultural Lowland Streams: An Interdisciplinary Approach to Process-Based Restoration

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Concordia University, 2025

This doctoral research in geography explores the restoration of hydrological processes in heavily modified agricultural streams of the St. Lawrence Lowlands, Québec. Over the past century, these streams have been straightened, incised, and backfilled, reducing their ecological integrity and connectivity. Chapter 2 (published article) examined residual hydrological connectivity in two straightened streams (Pot-au-Beurre and Martin) through high-resolution piezometric monitoring. Maximum correlations analysis between stream stage and groundwater levels revealed that, despite anthropogenic alterations, lateral and vertical exchanges persist, especially near abandoned meanders, indicating a potential for natural recovery where subsurface floodplain processes remain active. Chapter 3 developed on a steady-state hydrogeological model (MODFLOW) for a degraded 300 m reach of the Pot-au-Beurre. Results showed that residual floodplain features, such as fine and coarse alluvial deposits act as key nodes for groundwater–surface water exchanges. The study emphasizes the central role of geomorphological context in sustaining subsurface connectivity, even within simplified channel systems. Chapter 4 documented the co-design and implementation of the pilot project Un Méandre à la fois ("One Meander at a Time"), conducted with a local farming family. This semi-passive restoration initiative combined crop withdrawal from the historical floodplain, culvert replacement, and the delineation of a functional freedom space. Ecological and hydrological monitoring (vegetation, fauna, groundwater) assessed outcomes, while governance and social acceptability were analyzed to inform broader replication. Together, these components show that degraded agricultural stream restoration can build upon residual hydrological processes, provided that geomorphic conditions are respected and local stakeholders are engaged through flexible and adaptive strategies.

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Chapter 1. Main introduction

Agricultural headwater streams across the world have undergone extensive structural modifications such as channel straightening and disconnection from their floodplains to accommodate drainage and land consolidation (Kondolf, 2006; Wohl, 2017b; Mason et al., 2025). These interventions have profoundly altered hydrological and geomorphological processes, resulting in habitat simplification, loss of biodiversity, degraded water quality, and reduced flood- and drought- resilience (Florsheim et al., 2011; Flávio et al., 2017; Zhou & Endreny, 2020; Bieroza et al., 2024). Restoring these degraded fluvial systems presents a unique challenge: how to reestablish ecosystem services and connectivity in working landscapes, where agricultural production, land tenure, and regulatory constraints shape the feasibility and acceptability of restoration actions (Wohl et al., 2015a; Dumont et al., 2025). This thesis explores the restoration of small agricultural straightened streams through a process-based lens, focusing on hydrological connectivity as a key driver of both ecological function and restoration potential.

The following literature review is structured into five sections. Section 1.1 examines the marginalization and degradation of agricultural lowland streams, positioning them as neglected systems in both science and practice. Section 1.2 introduces hydrological connectivity as a conceptual foundation for restoration, emphasizing its multidimensional and multidisciplinary nature. Section 1.3 explores the rise of process-based restoration paradigm and contrasts them with traditional form-based approaches. Section 1.4 analyzes the specific challenges and constraints associated with restoring straightened streams in intensively cultivated environments. Finally, Section 1.5 outlines the research objectives of this thesis and describes its structure across three empirical chapters.

1.1 Agricultural lowland headwaters streams

Headwater streams, which correspond to first and second-order channels in the Strahler classification, constitute the majority of stream length in fluvial networks (Lowe & Likens, 2005; Freeman et al., 2007; Wohl, 2017b). While they are often associated with mountainous terrain, meandering headwaters also occur in lowland regions. Small headwater streams in lowland agricultural areas have long been neglected by scientists and restoration programs, even though

they play a crucial role in the functioning of watersheds (Lewandowski et al., 2009; Doyle et al., 2015; Bieroza et al., 2024). In temperate agricultural landscapes of North America and Europe, such streams account for nearly 50% of total channel length (Bieroza et al., 2024) where they play an essential role in intercepting, storing, and gradually releasing water, sediment, nutrients, and organic matter (Fisher & Likens, 1973; Heimann & Roell, 2000; Meyer, 2007; Ferreira et al., 2023). They also show unique characteristics compare to their downstream counterparts (shading, water temperature and chemistry, higher connectivity to riparian and hillslope zone), which creates suitable conditions for higher biodiversity (Richardson, 2019; Gates & Smiley, 2024). Despite their hydrological and ecological significance, these systems are among the most heavily altered and least protected components of river networks (Hill et al., 2014; Wohl, 2017b), and their degradation has cascading effects on downstream water quality, flood regulation, and biodiversity (Florsheim et al., 2011; Flávio et al., 2017; Palmer & Ruhi, 2019; Bieroza et al., 2024).

Most of the alterations of lowland headwater streams is associated with intensive farming over the past century (Brookes, 1987; Pierce et al., 2012; Wohl, 2018). The cumulative impacts of land clearing, artificial drainage systems, ditching, channel straightening, and infrastructure development (culverts, artificial sills, bank stabilization) have fundamentally disrupted natural hydrological and hydrogeomorphic dynamics (Pierce et al., 2012; Zhou & Endreny, 2020). These interventions, often intended to increase arable land, improve drainage efficiency or counter bank erosion, have resulted in a major reduction in the level of hydrological connectivity between the stream, its floodplain and its adjacent hillslopes (Lorenz et al., 2009; Mason et al., 2025) . Such structural interventions are often repeated through routine maintenance activities (e.g., dredging or vegetation clearing), reinforcing degradation over time and preventing spontaneous recovery (Rousseau & Biron, 2009). These interventions frequently prioritize short-term drainage efficiency at the expense of long-term ecological function.

The cases of straightened headwater streams in agricultural lowland areas are particularly problematic. Channel straightening, or channelization, consists in digging a deeper and straighter channel through a meandering stream with the objective of enhancing the drainage of adjacent lands and increase cropable land surface. This practice has been greatly applied in agricultural areas on lands considered unsuitable for agriculture (Frothingham et al., 2002; Rousseau & Biron, 2009; Mann, 2024). The drastic morphological alterations of lowland headwaters' channel and

floodplain resulted in the disconnection of the main runoff with many meander bends and thus to the artificial creation of abandoned meanders (Schilling et al., 2004; LaSage et al., 2008). Combined with further mechanical backfilling of the abandoned meanders, straightening practices have resulted in a major reduction in the level of hydrological connectivity between the streams, their floodplain and their adjacent hillslopes (Evans et al., 2007; Mason et al., 2025). Several studies have documented the negative impacts of straightening practices on hydrological networks, including increased flood peaks (Wyzga, 1996; King et al., 2009), reduced baseflow levels (K. Schilling et al., 2004; LaSage et al., 2008), destruction of aquatic habitats in relation to the uniformization of the channel cross-sections (D'Ambrosio et al., 2014; Zhou & Endreny, 2020), decrease in riparian biodiversity (Hupp, 1992; Franklin et al., 2009; Wiberg-Larsen et al., 2025) decrease on water quality (Lóczy et al., 2009; Käiro et al., 2017) and disturbances of the sedimentary dynamic (Simon, 1989; Graf et al., 2016).

Projections for climate change add further pressure on agricultural headwaters. Increased frequency and intensity of floods and droughts, along with reduced groundwater recharge, are likely to accelerate the loss of headwater systems (Capon et al., 2013; Aliyari et al., 2021). Meanwhile, continued agricultural intensification reinforces existing degradation. In the Saint-Lawrence Lowlands, one of the most densely farmed regions of Eastern Canada, small headwater streams are often confined between crop fields, drainage ditches, and rural infrastructure, with little room left for lateral mobility or expression of other natural processes (i.e. flooding) (Rousseau & Biron, 2009; Paradis & Biron, 2017). The degraded condition of small headwater streams in agricultural settings is rarely addressed directly, as interventions tend to be focused downstream, treating symptoms rather than sources (Bieroza et al., 2024).

Despite mounting evidence of their importance, lowland agricultural headwaters remain chronically underrepresented in both the scientific literature and legal frameworks (Lassaletta et al., 2010; Creed et al., 2017; Bieroza et al., 2024). They remain severely underrepresented in ecological monitoring, restoration planning, and legal frameworks such as the Clean Water Act (Lane et al., 2023) or the EU Water Framework Directive (Baattrup-Pedersen et al., 2018; Wynants et al., 2025). In many jurisdictions, they are excluded from protection or restoration funding due to their small size, intermittent flow, or perceived artificiality (Lassaletta et al., 2010; Wohl, 2017b). Monitoring programs often neglect them, and technical restoration guidelines typically

target larger rivers (Bieroza et al., 2024). In the province of Quebec (Canada), for example, riparian protection for agricultural streams is limited to 3 meters on each side of the bankfull level of the channel, whereas it is 10 to 15 meters for non-agricultural streams (Biron et al., 2014). As a result, key degraded sites with strong restoration potential are not targeted by governmental programs (Biron et al., 2018).

There has been a recent shift from researchers and institutions to emphasize the potential of small headwater streams in agricultural settings not only to mitigate pollution and regulate hydrology, but to restore broader catchment-scale function when managed appropriately (Colvin et al., 2019; Hill et al., 2014; Ferreira et al., 2023). Addressing the challenges specific to these overlooked hydrosystems requires conceptual frameworks that account for their past alterations, integrate surface and subsurface processes, and identify strategic locations for intervention. Hydrological connectivity is one of these integrative lenses, a point to which this thesis will return throughout.

1.2. Hydrological connectivity: a conceptual foundation for stream restoration

1.2.1 Definition, processes and roles of hydrological connectivity

Hydrological connectivity refers to the transfer of water, solutes, sediments, and energy across the landscape, linking various components of a catchment through hydrological fluxes (Pringle, 2003; Freeman et al., 2007; Bracken et al., 2013). It is not a static attribute, but rather a spatially and temporally variable property of river systems that governs the movement of mass and energy across boundaries, between uplands and channels, channels and floodplains, surface waters and aquifers (Wohl, 2017a). As such, it provides a powerful conceptual lens for diagnosing degradation in fluvial systems and for guiding restoration strategies that seek to re-establish functional linkages rather than merely restore form (Lexartza-Artza & Wainwright, 2009; Dwivedi et al., 2025).

Hydrological connectivity is intrinsically multidimensional, encompassing longitudinal, lateral, vertical, and temporal pathways (Ward, 1989; Amoros & Bornette, 2002; Poole, 2010). These dimensions interact to sustain dynamic processes of the river system, from the reach to the catchment scale. These different pathways can vary considerably over time, whether seasonally, inter-annually, or episodically in response to rainfall events. Even temporary hydrological connections can play disproportionately large roles in ecological processes (Mitsch & Gosselink, 1993; Zimmer & McGlynn, 2017; Scamardo & Wohl, 2024). Longitudinal connectivity refers to the downstream transfer of water, sediments, and organisms along the channel network.

Interruption, such as culverts, can fragment this longitudinal connectivity, impeding flow characteristics, sediment transport and aquatic organism migration.

Lateral connectivity describes the periodic bidirectional exchange between a river and its adjacent riparian area (Díaz-Redondo et al., 2018). This dimension supports overbank flows, floodplain inundation, and nutrient deposition, and is essential for the renewal of riparian habitats (Ward et al., 1999; Gumiero et al., 2013), the dissipation of flood energy (Džubáková et al., 2015; Shukla et al., 2024) and the transformation of nutrients and pollutants (Vidon et al., 2010; Kaase & Kupfer, 2016). In agricultural settings, through enlargement of channel, backfilling of low-lying riparian areas and implementation of levees on banks, emphasis has been put on unidirectional fluxes of water, from the riparian area to the channel, to maximize land drainage (Mason et al., 2025). As a result, the natural capacity of the riparian zone, including the floodplain, to temporarily store, supply and transform water, sediments and solutes from the channel is often disrupted, leading to a reduction in riparian habitats, deterioration in water quality and disequilibrium in the geomorphological process (channel incision, increased bank erosion, etc.).

Unlike longitudinal and lateral connectivity, vertical (or subsurface) connectivity, which represents exchanges between surface water with subsurface zones (Cranswick & Cook, 2015), has been comparatively overlooked in restoration science, despite its central role in regulating water quality, temperature, and nutrient retention (Boulton, 2007; Hester & Gooseff, 2010; Lehr et al., 2015; Mayer et al., 2022). Three major forms of subsurface exchange can be distinguished.

First, hyporheic exchange represents shallow and short-term flows that pass through the sediment just beneath and alongside the streambed and bank before re-entering the channel (Bencala et al., 2011; Boano et al., 2014) (Figure 1.1). These flows support biogeochemical cycling, mediate thermal regimes, and provide refuge habitat for benthic organisms (Malard et al., 2002; Harvey et al., 2019).

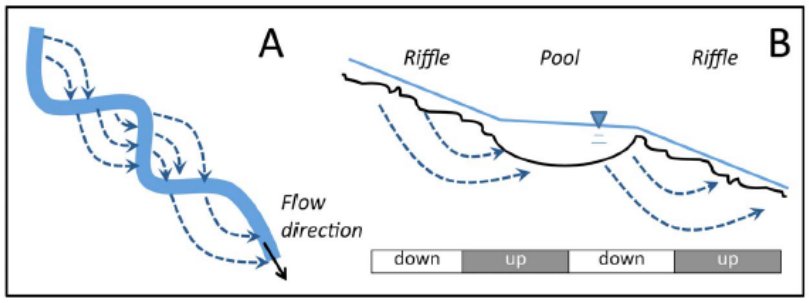


Figure 1.1. Conceptual representation of hyporheic exchanges at the scale of a stream's reach (A) and bedforms (B). (From Bencala et al., 2011)

Second, bank storage refers to lateral infiltration of water into alluvial banks during high-flow events which are gradually released back to the channel during recession periods, thereby supporting baseflows (Pinder & Sauer, 1971; Burt et al., 2002; Krause et al., 2007) (Figure 1.2). Bank storage can also occur through the infiltration of surface water from overbank flows on the floodplain or from hillslope runoff (Cranswick et al., 2015).

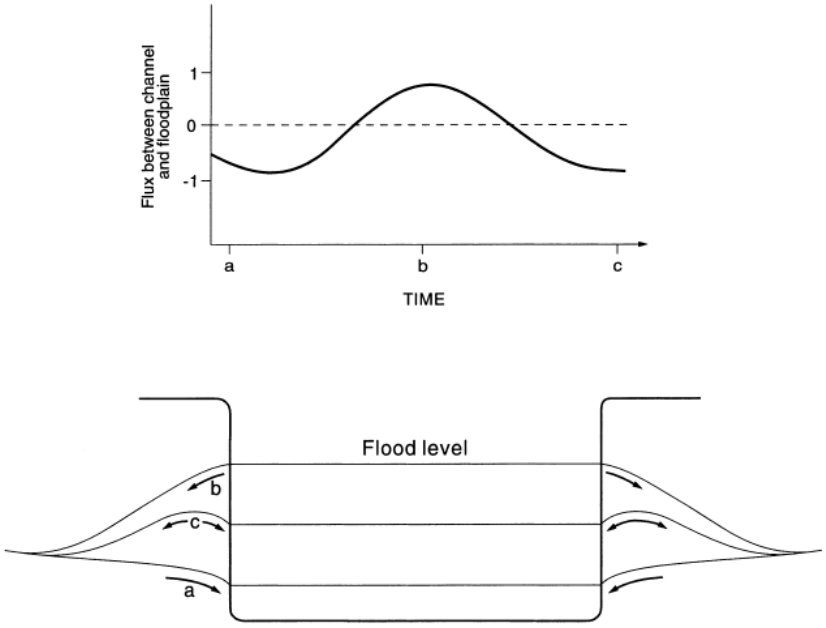


Figure 1.2. The bank storage process. Subsurface fluxes toward the riparian zone or toward the stream concur with fluctuations of the stream's stage level. (From Burt et al. 2002)

Third, river-aquifer exchanges are subsurface hydrological exchanges between the stream and the surrounding aquifers (Cranswick & Cook, 2015) (Figure 1.3). An aquifer is a general term that designates a permeable layer or region in the saturated zone of the ground (where soil pores are saturated with water) (Fitts, 2012). Shallow local aquifers can form in the unconsolidated alluvial

sediments of the floodplain. Deep aquifer–stream interactions occur over longer timescales and greater depths, playing a critical role in maintaining dry-season base flows and buffering climatic variability through the input of cool water (Winter et al., 1998; Sophocleous, 2002; Brunke et al., 2003; Pöschke, 2016). In agricultural lowlands, these subsurface exchanges are frequently disrupted by sediment compaction (Teufl et al., 2013; Shaheb et al., 2021; Dong et al., 2022), artificial drainage (Baker et al., 2012; Paradis & Biron, 2017), and altered flow regimes (Flávio et al., 2017; Schumann et al., 2021). The resulting loss of subsurface fluxes reduces the system's resilience and impairs its capacity to deliver key ecological services, such as flow and sediment-transport regulation (flood and base level) (Florsheim et al., 2011; Pierce et al., 2012; Lenhart et al., 2018; Bieroza et al., 2024).

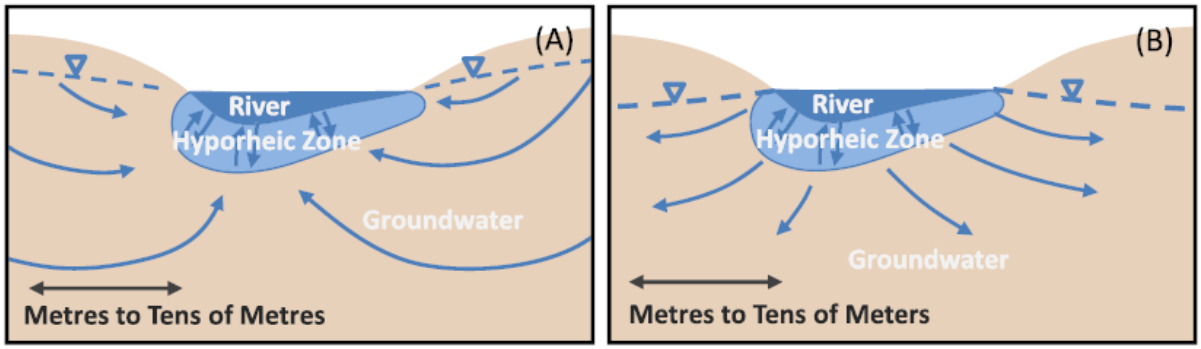


Figure 1.3. Conceptual models or river-aquifer exchanges at the reach scale: as the hydraulic gradient is toward the river (A) and the hydraulic gradient is away from the river (B). (Modified from Cranswick et al., 2015)

1.2.2 Controls on hydrological connectivity in lowland streams

Hydrological connectivity in lowland meandering streams is shaped by a complex interplay of surface and subsurface processes. On the surface, connectivity is governed primarily by overbank flows, whose paths are strongly controlled by the morphology of the floodplain and the relative elevation of levees and depressions (Stewart et al., 1999; Karim et al., 2012; Shukla et al., 2024). Phillips (2013) describes six types of relationships defining surface flow connectivity between lowland meandering stream and floodplain depressional features (Figure 1.4):

1. Through-flow connection: Water enters a depression (e.g., chute channel or recent cutoff) below bankfull level, flows through it, and re-enters the main channel downstream.

2. Flood channel: The depression remains dry under normal conditions but conveys surface water during overbank floods, with some of the water returning to the channel.

3. Fill-and-spill: The depression fills with overbank flow and spills laterally toward other floodplain areas, often via ephemeral channels.

4. Fill-and-drain: The depression fills during high flows and drains back into the main channel as floodwaters recede.

5. Tributary-occupied: A tributary or runoff input maintains water in the depression, which then drains to the main channel.

6.Disconnected: The depression has no surface water connection to the channel, except during very large floods that encroach upon it.

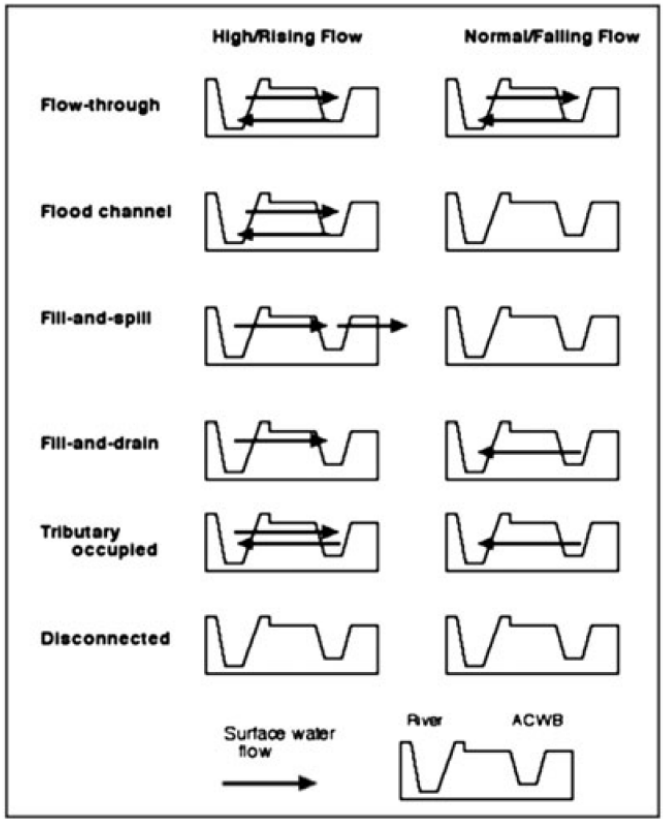


Figure 1.4. Schematic diagram of the six types of relationships defining surface flow connectivity between meandering stream and abandoned channel water bodies (ACWB). High flow refers to high sub-bankfull discharges (From Phillips, 2013).

These categories highlight how topography and flood dynamics govern the variability of lateral surface-water connectivity and storage in floodplain features, with implications for habitat functions and floodplain restoration planning. Beyond the channel-floodplain interface, surficial hydrological connectivity is also influenced by inputs from hillslope runoff and local precipitation,

with flow paths modulated by soil infiltration capacity, compaction, and land use (Croke et al., 1999; 2005). It results in highly variable, spatially heterogeneous surface-water flow regimes where there is not always a direct linear relationship between distance from the main channel and overflow connectivity (Hudson et al., 2012; Park & Latrubesse, 2017).

Subsurface connectivity is primarily controlled by fluctuations in the level of the stream and surrounding aquifers, which determine the local and regional hydraulic gradient, which generates forces driving water exchange (Cranswick et al., 2015). The hydraulic gradient is defined by the relative change of water heads in a specific direction, for example along a transect perpendicular to the stream (Krause et al., 2012; Boano et al., 2014) (Figure 1.5).

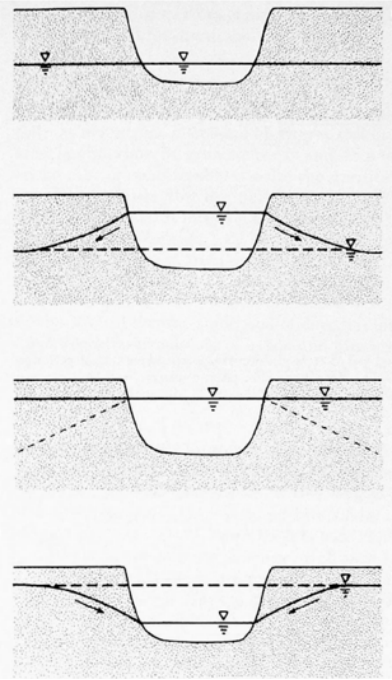


Figure 1.5. Conceptual time series showing the evolution of the hydraulic gradient between a river and its floodplain before, during and after a flood. The hydraulic gradient is defined by the difference in elevation between the stream level and the water table surface in the floodplain (expressed with the inverse triangle). (From Kondolf, 1987).

The magnitude and direction of subsurface flow are further modulated by the hydraulic properties of the floodplain sediments (Krause et al., 2012; Welch et al., 2014), the heterogeneity of stratigraphic layers (Duval & Hill, 2006), and the geometry of the channel and floodplain (Ali et al., 2011). Subsurface morphology of the alluvial sediments can even override surficial topography as a primary control on flow paths (Mills, 2015). Numerous studies have highlighted that, in natural lowland environments, abandoned meanders, due to their concave subsurface geometry and their

composition of coarse, permeable sediment, act as preferential zones for bank storage and groundwater exchanges (Sophocleous, 2002; Cabezas et al., 2008; Lehr et al., 2015; Larocque et al., 2016; Lemon, 2020; Ledesma et al., 2024). Even at low flow conditions, these features may maintain subsurface connectivity with the channel and with adjacent riparian aquifers. In this context, Larocque et al. (2016) proposed that the hydrogeomorphological processes responsible for meander formation, such as lateral erosion and sediment sorting, play a decisive role in shaping the subsurface connectivity between streams, riparian wetlands, and local aquifers. At the regional scale, broader geomorphological features, climate-driven recharge, and aquifer properties interact to govern long-range aquifer–stream exchanges (Toth, 1963; Flipo et al., 2014).

Together, these surface and subsurface controls define the spatial and temporal dynamics of hydrological connectivity in lowland systems. Their superposition generates a rich mosaic of water exchange pathways that are crucial for flood attenuation, nutrient processing, and habitat maintenance. Understanding these processes is essential not only for assessing hydrological functioning but also for designing restoration strategies that aim to recover ecological functions via enhanced connectivity.

1.2.3 Impact of channel straightening on hydrological connectivity

The straightening of lowland streams has profoundly disrupted both surface and subsurface hydrological connectivity between rivers and their adjacent floodplains (Clilverd et al., 2013; Zhou & Endreny, 2020). On the surface, such alterations reduce overbank flooding and limit the spatial extent and frequency of floodplain inundation (Schilling et al., 2004; King et al., 2009). Natural floodplains, once dynamic zones of water, sediment, and nutrient exchange, are now bypassed as flood peaks are confined within incised or leveed channels or backfilled floodplain (Zaborowski et al., 2024). This leads to increased peak flows, shortened flood wave travel times, and flashier hydrographs, shifting flood risks downstream (Lóczy et al., 2009). At the same time, the decrease of lateral sediment and nutrient transport toward the riparian zone can promote in downstream reaches rapid in-channel aggradation, often requiring repeated maintenance of channels (Moran, 2023; Gates & Smiley, 2024).

Few studies have examined subsurface hydrological processes between lowland straightened streams and their riparian zone. Channel incision can lower the local water table, drying out formerly saturated riparian soils and converting wet meadows into drier environments (Wyzga,

1996; Duval & Hill, 2006; Lóczy et al., 2009; Constantz et al., 2016; Pierce, 2020) . These morphological changes alter hydraulic gradients and constrain hyporheic and groundwater–surface water exchanges to a narrow zone near the incised channel (Ledesma et al., 2024; Schilling et al., 2004). While confined lowland channels may retain some hydraulic connection to shallow aquifers, their capacity to interact dynamically with broader floodplain sediments is severely diminished. As a result, biogeochemical functions, such as nitrate reduction, can be intensified at the river–floodplain interface but become spatially limited compared to their natural counterparts (Krause et al., 2007).

1.2.4 Methods for assessing hydrological connectivity

Hydrological connectivity is studied by combining several methods, each highlighting different dimensions of water movement in space and time (Ali et al., 2011). Connectivity is fundamentally multidimensional and therefore it draws on knowledge from several disciplines: hydrology, hydrogeomorphology, hydrogeology and, increasingly, biology and biogeochemistry (Biehler et al., 2023; Alp et al., 2024; Dwivedi et al., 2025). Hydrologists tend to focus on surface flow dynamics and hydrographic responses, while hydrogeologists study groundwater level gradients and exchanges between stream and aquifers. Hydrogeomorphologists, on the other hand, examine sediment transfers and interactions with floodplains. Biologists assess habitat distribution and connectivity in relation to physical processes, while biogeochemists study nutrient fluxes to detect areas of biochemical connectivity.

The choice of analysis method depends on the type of connectivity in question (lateral, vertical, or longitudinal) as well as the morphological context (e.g., floodplains, slopes, abandoned channels) and the spatial and temporal scales needed to capture significant variations in hydro-sedimentary processes. Fieldwork typically provides high-resolution data at the local-to-reach scale (Covino, 2017), while remote sensing and digital modeling can reveal broader patterns and long-term trends at the watershed scale (Ali & Roy, 2009; Bracken et al., 2013).

Many hydrological connectivity assessments are primarily based on field measurements. For surficial processes, instruments such as pressure transducers, flow meters, and time-lapse photography are commonly used to monitor the timing, duration, and extent of overbank flows (Krause et al., 2012; Shukla et al., 2024). For subsurface processes, piezometers and nested wells allow the measurement of vertical and lateral hydraulic gradients, which support the identification

of water table dynamics and groundwater exchange patterns (Burt et al., 2002; Lewandowski et al., 2009; Vidon, 2012; Buffin-Bélanger et al., 2016). High-frequency monitoring of surface and groundwater level using data loggers has also become increasingly relevant for capturing transient hydrological responses, especially in highly dynamic settings such as floodplains and abandoned meander features (Lehr et al., 2015; Dwivedi et al., 2025). It is however relevant to highlight that piezometer measurements indicate the transmission of pressure signals through an aquifer, but they don't allow to quantify directly the fluxes of water without additional information on the sediments' hydraulic conductivity (Krause et al., 2012).

Biochemical and isotopic tracers provide further insight into flow paths, residence times, and mixing processes within and between surface and subsurface environment (Cook, 2013). Natural tracers such as electrical conductivity, temperature, and major ions are commonly used to differentiate between surface water and groundwater contributions and to detect zones of groundwater exfiltration or bank infiltration (Kalbus et al., 2006; Kiewiet et al., 2020). Among these, radon has gained popularity as a conservative tracer of groundwater exfiltration, owing to its enrichment in groundwater relative to surface water and its short-lived duration (Kurth et al., 2015; Oh et al., 2021). Artificial tracers, such as dyes or bromide, can also be used to estimate hyporheic exchange rates, flow velocities, and water residence times (Bencala et al., 2011; Harvey & Gooseff, 2015). Tracers are particularly valuable in dynamic environments like floodplains, where multiple flow paths may coexist and vary seasonally. However, interpreting tracer results often requires integration with piezometric data, sediment characteristics, or numerical models to fully resolve the underlying processes.

Numerical models can also be used to study hydrological connectivity in different river system configurations and climate scenarios. Hydraulic simulation models, such as HEC-RAS or LISFLOOD-FP, can simulate flow stage and velocities, allowing for the assessment of longitudinal and lateral connectivity during flood events (Neal et al., 2012; Choné et al., 2021). At the watershed scale, distributed hydrological models such as SWAT or MIKE-SHE can combine surface runoff, infiltration, and soil moisture dynamics to assess connectivity between land and the stream network (Clilverd et al., 2016; Jutebring Sterte et al., 2018; Schulz et al., 2024) .To study subsurface hydrological processes, hydrogeological models such as MODFLOW, HydroGeoSphere, and FEFLOW can simulate hyporheic flow, storage in banks, and river-aquifer

exchanges under steady-state or transient conditions (Brunner et al., 2010; Diem et al., 2014; Ferraz, 2022). These subsurface models are particularly useful for quantifying the spatial and temporal variability of flow directions and magnitudes, and they can also help assess the role of geological and geomorphological heterogeneity. However, in general, models require a lot of input data and calibration efforts, and their predictive capacity remains dependent on the quality of field observations for validation and on the conceptual understanding of groundwater flow in the studied environments (Sophocleous, 2002; Aliyari et al., 2021; Ntona et al., 2022) .

Finally, remote sensing (with aerial, satellite and drone images) and GIS-based analyses can complement field-based and modelling methods by providing spatially explicit information on riparian landscape connectivity (ex. elevation, vegetation cover, floodplain morphology) (Ali & Roy, 2009; Park & Latrubesse, 2017). LiDAR and high-resolution DEMs are especially useful for delineating potential flow paths or disconnected zones, particularly in low-relief landscapes (Hauer et al., 2014).

Because of its focus on dynamic interactions, the concept of hydrological connectivity offers a theoretical and operational foundation for process-based restoration (Beechie et al., 2010; Wohl et al., 2015a; Palmer & Ruhi, 2019), an approach that prioritizes the reactivation of geomorphic and hydrological processes rather than the reconstruction of fixed channel forms. By identifying zones where hydrological exchanges are sustained or can be re-established (e.g., through meander reconnection, floodplain modification, or drainage reconfiguration), connectivity becomes both a diagnostic and a design tool for restoration planners. This shift from stabilizing forms to restoring functions will be explored further in the next section.

1.3 – From form to process: evolving approaches to stream restoration

1.3.1 A necessary transition

The process-based restoration approach marks a deliberate shift away from methods centered on reconstructing river forms, such as those promoted by the Natural Channel Design (NCD) framework (Rosgen, 2013). While this approach was initially developed as a drastic change compared to traditional river engineering, it did not fully deliver the paradigm shift it promised (Johnson et al., 2020). NCD relies on hydraulic geometry calculations to prescribe a theoretically stable channel and floodplain configuration, assumed to be in dynamic equilibrium with the

stream's flow regime. In doing so, it marked a difference from strictly utilitarian, hard-engineering practices by aiming to restore stability through form rather than infrastructure (Lave, 2009; Rosgen, 2013).

At the heart of the problem of form-based restoration is the requirement that new river configurations have to be stabilized to prevent them from being altered during extreme floods (Lave, 2009; Doyle et al., 2015; Dawson & Ashmore, 2025). However, it is now known that the resilience of river systems depends on their ability to constantly evolve towards a non-permanent equilibrium configuration that is adapted to contemporary environmental conditions, which is inhibited by stabilization interventions. In addition, stabilization works represent significant resource and financial costs (Nakamura et al., 2020) that are not compatible with the cost-benefit requirements of many governmental programs. Furthermore, restoration approaches based on forms can lead to bias in the choice of river configurations by decision-makers and authorities (Doyle et al., 2015). Among other things, it has been documented that meandering river styles have sometimes been favored as restored river configurations because they represent an idealized river style, even though this stream style may not be suited to the host areas (Kondolf, 2006).

While NCD has been widely adopted (Lave, 2009; Stowe et al., 2023), many restored systems have failed to demonstrate sustained improvements in habitat quality, hydro-sedimentary regulation, or water quality (Johnson et al., 2020; Stowe et al., 2023). Although some individual projects have shown ecological gains (Reese & Gillette, 2024; Parant et al., 2025), meta-analyses and long-term evaluations often report inconsistent or transient results, particularly in human-impacted settings (Wohl et al., 2015a; Padovan et al., 2022; Stowe et al., 2023). Recognizing these shortcomings, many studies have called for a shift in focus: away from morphology-driven design, and toward approaches that prioritize the dynamic processes that shape rivers and their floodplains (Wohl et al., 2015a; Rundell, 2023; Dawson & Ashmore, 2025).

1.3.2 Process-based restoration

Process-based restoration is an approach to river restoration that aims to restore the normal rates and magnitudes of the physical, chemical, and biological processes that support river ecosystems, including their floodplains (Beechie et al., 2010). The goal is to allow river ecosystems to evolve and function sustainably in response to future disturbances and changing environmental factors,

including natural river dynamics (such as bank erosion, channel migration, and flooding) as criteria for success (Beechie et al., 2010; Ciotti et al., 2021; Wohl et al., 2024) .

The basis for process-based river restoration is that the flow regime of a river is the driving force behind geomorphological processes (erosion, sediment transport, accumulation) and therefore the structure or forms of the river system (Poff et al., 1997; Malavoi & Adam, 2007; M. Palmer & Ruhi, 2019). The intensity, frequency, duration, consistency, and rates of change in the hydrological regime of a given stream determine a whole series of adaptations in the abiotic and biotic processes that make stream providers of ecosystem services (Beechie et al., 2010; Wohl et al., 2024).

We now know that this flow regime can be broken down into multiple dimensions of hydrological flows that vary over time and interact at multiple spatial scales, from the stream channel to the river reach to the watershed (i.e., hydrological connectivity). A detailed understanding of the state of hydrological connectivity is therefore a fundamental step in establishing a process-based restoration approach (Wohl et al., 2015). This detailed understanding must be adapted to the scale of the planned restoration intervention, but it will always be necessary to understand the global variables at the watershed scale that can influence the flow regime.

In a process-based restoration approach, diagnostic efforts should focus on identifying constraints and obstacles to the expression of the stream's natural hydrological regime (Friberg, 2016) . These constraints can be point sources (bridges/culverts, riprap, levees, dikes, dams, diversions) or diffuse (soil compaction, vegetation loss, pumping/extraction). They may also vary over time. For example, an undersized culvert can impede flow during floods (creating backwater upstream and pressurized flow downstream), while having little impact outside flood periods. Heavy agricultural land use in a watershed will have a more limited effect on the flow regime during the summer period given the dense vegetation cover, but it will significantly alter the runoff and flow regime in spring and fall when the soil is left bare. Furthermore, in anthropized environments (urban, residential, and agricultural), particular attention should be paid to documenting constraints that are invisible from the surface, such as the effect of drainage and stormwater management networks (Evans et al., 2007; Schilling et al., 2012).

1.3.3. A significant contribution from hydrogeomorphology

Hydrogeomorphology is the science of the forms and processes related to water flow on Earth. Over the past few decades, hydrogeomorphology has played a central role in diagnosing the condition of streams and developing process-based restoration approaches (Biron et al., 2018; Schwindt et al., 2019; García et al., 2021; Wohl et al., 2024). One of its major contributions is the formulation of concepts that allow a stream to be described and analyzed within its own spatio-temporal framework.

Before even considering any restoration intervention, it is essential to recognize that a stream has been responding to local or watershed disturbances for a long time. The founding concept of Lane's Balance (1955) (Figure 1.6) illustrates this dynamic well by highlighting the natural tendency of a stream to adjust its shape mainly in response to any natural or human-induced variations in the hydrological regime and/or sediment supply. In the short term, a stream thus tends to maintain a dynamic balance between the water flow and the sediment load available in the watershed.

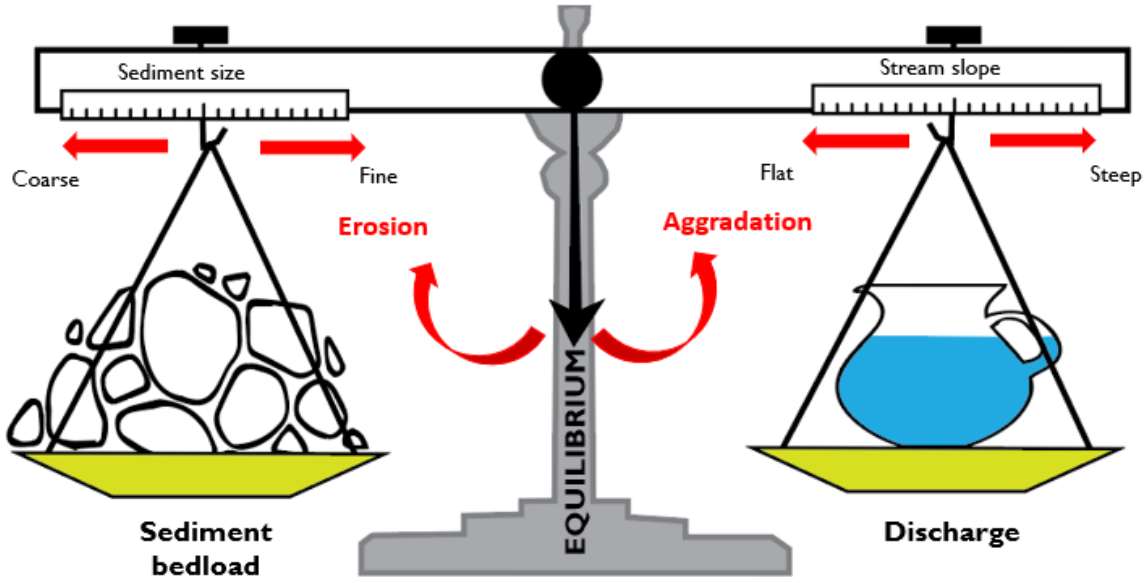


Figure 1.6. Lane's balance illustrates how variations in sediment load, grain size, slope, and discharge drive stream aggradation or erosion (incision) (Inspired from Lane (1955)).

When a restoration project is considered, it is necessary to first assess the stage of the stream's evolutionary morphological trajectory (Cluer & Thorne, 2014; Tullos et al., 2021; Wohl et al.,

2024). This analysis makes it possible to anticipate the natural direction of its evolution and adjust the intervention accordingly to accompany, slow down, or accelerate the processes underway. To support these analyses, several studies have put forward the concept of hydrogeomorphological trajectory (Simon, 1989; Brierley et al., 2008; Brierley & Fryirs, 2016; Buffin-Bélanger et al., 2024). This concept is based on the idea that, in the absence of new stressors, a stream follows a more or less cyclical sequence of morphological transformations aimed at returning to a relative state of equilibrium. For example, an incising stream in an agricultural watershed may be the result of repeated straightening in upstream reaches, which increases locally flow velocity. In its rebalancing trajectory, the channel will tend to widen and then gradually create a new active floodplain that is better adapted to the new hydrological conditions. This dynamic continues until the next major disturbance. The Stream Evolution Model proposed by Cluer and Thorne (2014) clearly illustrates this morphological cycle in the context of degradation. It also provides a better understanding of how certain repeated anthropogenic actions can lock rivers into a state of chronic imbalance. This model is now widely used to guide process-based restoration strategies (Brierley & Fryirs, 2016; Powers et al., 2019; Scott, 2024).

Another major contribution of hydrogeomorphology to the advancement of process-based restoration approaches is the conceptualization of a living space for streams, within which their natural dynamics (i.e., flooding, erosion, sediment deposition) are expressed and which constitutes the source of many ecosystem services (Piégay et al., 2005; Kondolf et al., 2006; Fuller et al., 2019). This idea has taken several forms: free-moving rivers (Becker et al., 2022), good functioning space (Piégay et al., 2005; Terrier et al., 2016), river corridor (Harvey & Gooseff, 2015) and freedom space for river (Biron et al., 2014). Initially introduced as innovative conceptual frameworks to better understand how rivers function, these tools are now used to diagnose river degradation by identifying the spatial “needs” of streams to maintain or restore their ecological and geomorphological functions.

The concept of freedom space for rivers (Biron et al., 2014) proposes a mapping method that combines two dimensions: the space required for lateral channel migration (mobility space) and the space required for flood expansion (floodplain space). By combining mobility and flood spaces, including riparian wetlands, a minimal and functional freedom space are determined. Such a framework presents streams as a dynamic zone with high spatial and temporal variability.

Although the boundaries of the functional freedom space often coincide with those of the floodplain, the concept places greater emphasis on processes (flooding, erosion, deposition) than on the shape of the landscape alone.

In practice, the delimitation of the freedom space, based on the analysis of historical images and digital terrain models, is a relatively simple method to support more complex diagnoses of hydrological connectivity. It allows for the pragmatic identification of an area of high hydrological and sediment exchange between the channel and its riparian environment. While the full extent of the hydrological connectivity of a stream is only limited by its watershed boundary, the freedom space represents a concrete and operational expression of a high connectivity area, which is useful for land-use planning and restoration.

1.3.4 Implementation of process-based restoration

Once a clear diagnosis of stream hydrological connectivity, watershed constraints, and the likely evolutionary trajectory under those constraints is established, restoration objectives and actions can be defined. A key challenge lies in determining how these objectives should be framed. There is currently no consensus on whether goals should prioritize the ecosystem services that the stream can realistically provide, given its morphology and connectivity, or whether they should primarily reflect human demands for ecological services (Ehrenfeld, 2000; Wohl et al., 2015a; Worley et al., 2023). This ambiguity often leads to a mismatch between the set objectives and the physical or ecological potential of the stream. For example, in Québec, restoration has long been oriented toward creating aquatic habitats for recreational and commercial fishing (Biron et al., 2018; Gariépy-Girouard et al., 2025). Assessments thus focused on the presence or absence of target species or habitats, and interventions frequently consisted of installing structures to create such habitats, regardless of whether they aligned with stream dynamics (Zika & Peter, 2002; Ryder & Miller, 2005).

What emerges from recent work is that unrealistic objectives, meaning disconnected from the underlying dynamics of the stream should be avoided (Beechie et al., 2008; Harman et al., 2012; Langhammer et al., 2023). Instead, effective planning requires combining site-scale and catchment-scale objectives, ensuring that restoration actions address the primary drivers of hydroecological degradation (Sinclair et al., 2023).

Finally, it is essential to recognize the hierarchical and functional interdependence among stream components (hydraulics, hydrogeomorphology, geochemistry, biology). The Stream Function Pyramid (Harman et al., 2012) (Figure 1.7) illustrates that physical functions such as hydrology, hydraulics, and geomorphology form the foundation that supports higher-order physicochemical and biological processes. In this perspective, restoring higher-level functions is only feasible if the underlying physical processes are first stabilized or re-established.

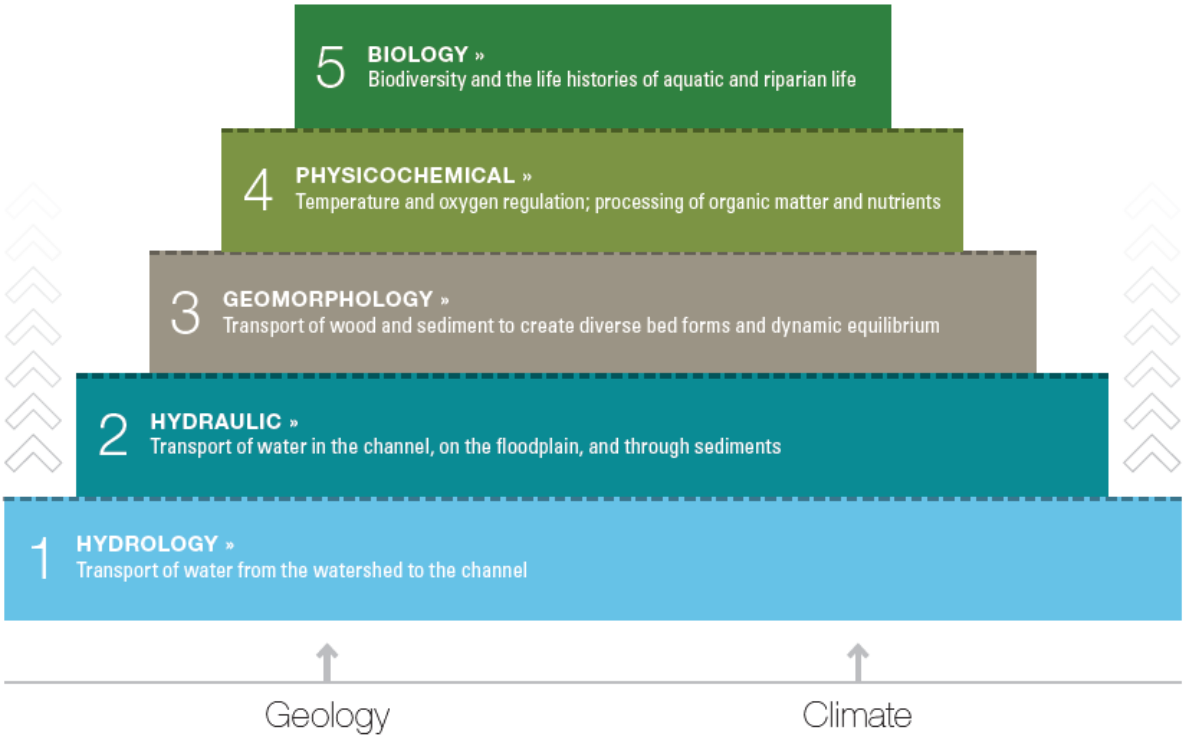


Figure 1.7. The Pyramid of Stream Functions is a hierarchical conceptual framework that organizes stream functions into five interdependent levels. It aims to illustrate how fundamental physical functions support chemical and biological functions. This framework is a valuable tool for defining project objectives, developing assessment methods, and creating standardized operating procedures for restoration programs (from Harman et al., 2012)

Finally, the choice of restoration measures must also be appropriate to the available resources and to the receiving environment, i.e. the local community where the restoration project is taking place. Numerous authors have mention that social acceptance, stakeholder engagement, and alignment with local land-use realities are essential to the long-term viability of restoration projects (Palmer et al., 2005; Tullos et al., 2021; Alp et al., 2024) Ignoring local values, knowledge, or constraints, including from indigenous peoples, can lead to resistance, inappropriate interventions, or abandonment of restored areas (Duchêne & Morel Journel, 2000; Reyes-García et al., 2019;

Löfqvist et al., 2023). Restoration planning must therefore incorporate community consultation and co-design processes, especially in agricultural regions where land tenure, productivity concerns, and historical relationships to water strongly influence the range of acceptable interventions (Liu et al., 2018; Dumont et al., 2025).

A range of restoration measures supporting the restoration objectives for river processes has been gradually developed over time, using both active and passive approaches. Active approaches involve mechanized modification of the river landscape: excavation of the floodplain and re-establishment of connections with former meanders or river branches (Bernal & Mitsch, 2013; Erwin et al., 2016; Nichols & Viers, 2017; McMahon et al., 2021; Pierce & Schilling, 2023), two-level channels (Powell, 2006; Roley et al., 2012; Paradis & Biron, 2017; Huttunen et al., 2024) and the creation of lateral or central benches in the active channel (Hester et al., 2016). In recent years, active restoration techniques using bioengineering or deadwood structures have emerged to modify water flow and erosion and sedimentation patterns (Bosworth et al., 2025). These low-tech approaches (Wheaton et al., 2019) advocate the use of natural materials to reduce intervention costs, but also to mimic the natural stream dynamics. Dead wood and beaver dams actively contribute to hydrogeomorphological dynamics by complexifying the configuration of the flow channel(s) and creating temporary water retention areas (Gurnell, 2014; Brazier et al., 2021).

Another avenue of active, process-based restoration that has recently gained traction is the *Stage 0* approach. Originally conceptualized by Cluer and Thorne (2014), this method emerged from a critic of traditional channel evolution models that historically framed stream adjustment as a linear progression toward a single-channel, meandering form. In contrast, *Stage 0* seeks to re-establish the depositional environments and multi- channel networks, such as anabranching or anastomosing systems, that historically characterized many low-gradient alluvial valleys before human interventions (Cluer & Thorne, 2014; Powers et al., 2019). The *Stage 0* approach consists in actively infilling the active channel using native materials such as gravel, soil, and wood, and reshaping the entire valley floor to reach a target surface. This approach promotes the self-formation of fluvial floodplain and wetlands by maximizing lateral and vertical hydrological connectivity by restoring valley-floor processes, including the formative role of floods and large wood (Flitcroft et al., 2022).

Passive restoration is an approach that aims primarily to allow ecosystems to recover naturally by eliminating or reducing human-induced pressures in order to allow regeneration and ecological succession processes to take place (Chazdon et al., 2024; Aleeje et al., 2025). In stream restoration, this generally involves abandoning certain practices carried out in the stream (or in its riparian zone, e.g., crops, grazing) (Kristensen et al., 2013; Mueller Price et al., 2016) or removing or modifying artificial infrastructure that limits the evolution of streams, such as thresholds, riprap, and cross-structures, such as agricultural culverts (Groll, 2017; Mikuś et al., 2019; Chazdon et al., 2024). These passive actions are generally much cheaper than active interventions, which makes them more popular with certain government agencies, particularly in Europe with the Water Framework Directive (Groll, 2017).

It is recommended to adopt restoration approaches that combine both passive measures, such as abandoning agricultural practices in a floodplain, and active measures, such as adding deadwood structures to restore lateral hydrological connectivity. As Chazdon (2024) points out, no dichotomous distinction should be made between passive and active restoration approaches. Rather, they should be seen as a continuum of actions that differ in the time required to observe changes and the intensity of human intervention required (Jones et al., 2018; Chazdon et al., 2024).

Finally, a monitoring protocol is essential in a process-based restoration approach in order to be able to adapt interventions to the pace of process recovery (Ryder & Miller, 2005; Mattern et al., 2020; Ciotti et al., 2021). Ideally, these monitoring measures should combine several indicators, some more specific (species-based) and others more related to the overall state of the ecosystem, to allow for a more holistic assessment of the restoration project (Ryder & Miller, 2005; Pander & Geist, 2013; Frainer et al., 2018). Several restoration projects use aquatic organisms, such as macroinvertebrates or fishes to assess the success of restoration projects (Gallardo et al., 2012; Rubin et al., 2017; Sinclair et al., 2023). Alternatively, studies often use habitat complexity or morphological variability as fish indicators (Stoffers et al., 2022; Roni et al., 2025). Several projects compare their monitoring with reference streams, following BACI protocols (Smiley Jr et al., 2009; Rubin et al., 2017; Driscoll et al., 2025). Nevertheless, monitoring of stream restoration projects is still rare (Buchanan et al., 2012; Mattern et al., 2020; Resop et al., 2024) or projects use experimental designs that are not appropriate for detecting changes in the ecosystem, particularly

for heavily modified streams, such as small agricultural streams in lowlands (Friberg, 2016; Wren et al., 2022).

1.4 Restoration in small straightened headwater streams in agricultural areas

1.4.1 Ecological potential

Even if they are often overlooked in restoration practices, small headwater streams in agricultural lowlands play a central role in hydrological and ecological functions. Rather than emphasizing their marginalization, it is important to recognize their underestimated potential to regulate flows and improve water quality through strategic reconnections with riparian wetlands and floodplains (Gumiero et al., 2013; Nakamura et al., 2020). Groundwater discharge, which can account for 35–60% of nutrient inputs in lowland catchments, represents a key pathway linking agricultural practices to stream water quality (Van Stempvoort et al., 2021, 2022). Because these flows often carry legacy nutrients accumulated over decades, reconnecting subsurface–surface exchanges and strengthening riparian and wetland buffers is essential to mitigate nutrient delivery and foster more resilient agricultural landscapes.

Paradoxically, small headwater streams are often recommended as targets for formal restoration projects, particularly as part of compensatory measures, because of their lower costs per unit length compared with large river systems (Doyle et al., 2015). However, despite this operational targeting, process-based restoration projects remain rare in channelized headwater streams in agricultural lowlands, thus limiting the real ecological scope of these interventions (Huttunen et al., 2024).

1.4.2 Diversified approaches, but uneven ecological results

Several types of interventions have been tested in small straightened agricultural streams in lowlands, often in response to specific issues (e.g., water quality) or funding opportunities (e.g., compensation programs) (Wren et al., 2022). The most common measures remain the establishment of herbaceous riparian strips (Smiley et al., 2011; Terrier et al., 2016). Other approaches have also been tested, such as two-level channels (Paradis & Biron, 2017; Hallberg et al., 2024), levee removal (Franklin et al., 2009), re-meandering (Lorenz et al., 2009; Kristensen et al., 2013; Pedersen et al., 2014) drainage management (Pierce et al., 2012), floodplain

excavation (Evans et al., 2007; Booth & Loheide, 2010; McMahon et al., 2021) or channel raising (Kristensen et al., 2012) to promote better lateral connectivity with the floodplain. Others studies also documented the addition of dead wood (Zika & Peter, 2002; Gates & Smiley, 2024) and the addition of coarse substrates to stimulate hyporheic exchange (Kasahara & Hill, 2007; Vial, 2023), or the creation of floodplains (Hester et al., 2016) and grazing management in riparian areas (Pedersen et al., 2006; Mueller Price et al., 2016; Morra et al., 2023).

Despite this diversity of techniques and measures, the ecological results of restoration projects, mostly active ones, for small agricultural streams in lowlands are often mixed (Kristensen et al., 2011), particularly as regards water quality (Pearce & Yates, 2015; Vidon et al., 2019; McMahon et al., 2021; Hallberg et al., 2024). Positive effects on biological communities are also variable: riparian strips have been document to have little impact on fish and amphibians (Smiley et al., 2011) and several restoration projects failed to improve macroinvertebrate or fish biodiversity, particularly when watershed stressors are not addressed (Lorenz & Feld, 2013; Friberg, 2016; Baattrup-Pedersen et al., 2022; Brettschneider et al., 2023).

However, some projects show promising results. The in-stream addition of dead wood has been documented to promote the creation of complex habitats for fish (Zika & Peter, 2002; Gates & Smiley, 2024), while re-meandering can improve lateral connectivity (Lorenz et al., 2009) as well as the physical diversity of aquatic habitats and several wildlife groups (Smiley Jr. & Dibble, 2005). Other interventions, such as riparian grazing management, also contribute to carbon storage, nutrient retention, and the regeneration of diverse plant communities in riparian areas (Pedersen et al., 2006; Mueller Price et al., 2016; Morra et al., 2023).

The lack of success in some restoration projects has been explained by specific factors such as an insufficient understanding and considerations of soil moisture regime of the floodplains (Booth & Loheide, 2010), a weak range of stream power unable to naturally re-initiate stream meandering (Kristensen et al., 2013), an insufficient flow velocity variability to replicate natural aquatic habitat conditions (Pedersen et al., 2014) or limited riparian carbon-rich material essential for denitrification processes (McMahon et al., 2021). The management of historically nutrient-enriched sediments, which frequently accumulate in channels and riparian margins in agricultural

land, also represents a significant challenge (Wohl et al., 2015a), often limiting the achievement of water quality objectives at the reach scale (McMahon et al., 2021).

1.4.3 Social and economic constraints on process-based restoration

Despite their ecological potential, process-based restoration projects for degraded small agricultural streams frequently encounter social resistance. This is largely because the processes being restored (erosion, flooding, sediment deposition, return of riparian vegetation) are still often perceived as risks or nuisances, even though they are essential for the regeneration of natural environments and the provision of ecosystem services, as highlighted by some studies conducted in Quebec (Ruiz et al., 2021; 2023; Campeau et al., 2023).

Some agricultural producers believe that the costs of implementation exceed the benefits, even though some studies have shown the positive economic impacts of restoration measures, such as buffer riparian strips (Daigneault et al., 2017) and removal of small dams, weirs or levees (Alp et al., 2024). For example, evidence from national-scale programs, such as in New Zealand, indicates that riparian restoration in agricultural lands can generate substantial net economic benefits, with benefit–cost ratios ranging from 1.4 to over 20, largely due to reductions in nitrogen leaching and improvements in water quality (Daigneault et al., 2017). Beyond direct farm-level gains such as reduced erosion, improved livestock health, and lower maintenance costs (Lenhart et al., 2018), restoration interventions can also provide catchment-scale economic benefits including flood risk mitigation, carbon sequestration, enhanced recreational opportunities, and increased property values (Nakamura et al., 2014; Alp et al., 2024). However, these benefits are often diffuse or indirect, with no immediate or tangible return for the landowners concerned. This raises issues of equity and redistribution of efforts and gains at the watershed level (Zaga-Mendez et al., 2020), and highlights the need for incentive structures or payment for ecosystem services programs that better align with individual and collective interests (Iftekhar et al., 2017).

The loss of cultivable land, whether real or perceived, is another major source of reluctance (Evans et al., 2007; Lenhart et al., 2018). This constraint reinforces the importance of appropriate financial and land support mechanisms (Terrier et al., 2016), particularly to secure long-term engagement.

Finally, as highlighted by Ryan et al. (2003), social acceptability increases when restoration is presented not as an abstract ecological approach, but as a concrete strategy for improving the

resilience of agricultural land. This more pragmatic communication strategy, rooted in the daily concerns of producers, not only encourages their initial commitment, but also strengthens their long-term adherence. It also offers a response to a structural challenge often encountered in agricultural settings: governance that tends to position farmers as passive beneficiaries rather than active partners. In their study of programs in Quebec, Zaga-Mendez et al. (2020) found that the rigidity of the rules surrounding certain public programs hinders producers' autonomy and limits their power to act. These programs, while important, treat farmers as passive beneficiaries of a centralized subsidy network over which they have little control, compromising their active participation in the design and implementation of agro-environmental practices, which include stream restoration initiatives. Valuing the expertise of agricultural producers and their capacity to act by involving them from the earliest stages of planning is therefore a fundamental lever for ensuring the legitimacy and sustainability of restoration projects in agricultural areas.

1.4.4 Institutional and governance challenges

Institutions can also slow down the implementation of process-based restoration, mainly because of the uncertainties that come with these approaches: variable response times, unclear spatial effects, and dependence on the hydrological regime (Kristensen et al., 2011). These uncertainties contrast sharply with the accountability and short-term results requirements of public programs. This logic leaves little room for the nonlinear trajectories and gradual adjustments that characterize process-based restoration projects.

In heavily developed agricultural areas, these constraints are even more pronounced as institutions have to contend with productive land uses, a mosaic of landowners, and intense land pressure. Indeed, restoration in anthropized environments cannot be limited to an ecological or technical approach: it must be thought of as a process of negotiation between actors, knowledge, and values (Mould et al., 2018; García et al., 2021). As such, hydrogeomorphology is not only a framework for analyzing the physical constraints of a territory or the hydrological connectivity within a watershed, but can also play a mediating role between the biophysical, social, and political dimensions of restoration efforts (Flávio et al., 2017; Wohl et al., 2024).

Consequently, rethinking the restoration of small agricultural streams requires a transformation of practices, but also of the institutional frameworks that govern them. This transformation involves

recognizing uncertainty as an intrinsic component of river systems, giving local actors real opportunities for participation, and adapting planning tools to the reality of small watersheds.

It is at the intersection of these tensions, between ecological potential, institutional constraints, and agricultural imperatives, that this thesis is positioned, using a three-phase approach to explore the conditions for understanding, planning, and implementing process-based restoration in small straightened agricultural streams.

1.5. Research objectives and thesis structure

The overall objective of this thesis is to explore how hydrological connectivity can inform the restoration of small, straightened streams in agricultural lowlands, where ecological potential remains largely neglected due to prevailing institutional, economic, and operational constraints. Building on the conceptual approaches presented in the previous sections, the specific research objectives are articulated around three complementary chapters that investigate the dynamics, feasibility, and reproducibility of process-based restoration rooted in hydrological connectivity.

The first objective is to assess how vertical and lateral hydrological exchanges shape the functioning of straightened headwater streams and their adjacent floodplains at two sites in the Saint Lawrence lowlands. Chapter 2 addresses this by combining high-resolution piezometric monitoring and hydrogeomorphic mapping to document spatiotemporal variations in surface–subsurface interactions. This analysis identifies key areas of connectivity and highlights the role of both alluvial plain heterogeneity and human modifications in mediating groundwater–surface water fluxes.

The second objective is to deepen the understanding of subsurface hydrological functioning in a straightened stream–floodplain system through numerical modelling. Chapter 3 develops a conceptual steady-state hydrogeological model using MODFLOW to quantify fluxes between distinct geomorphological units and explore how groundwater flowpath respond to different floodplain configuration. Rather than simulating future restoration scenarios, the model is used to uncover residual hydrological processes that could support a low intervention, process-based restoration strategy, particularly in systems where historical channel straightening and floodplain infilling have altered the stream surface dynamics.

The third objective is to evaluate the ecological and social outcomes of implementing such a restoration strategy. Chapter 4 reports on the pilot implementation of a passive restoration project ("Un méandre à la fois") on the same stream reach as the one modelled in Chapter 3. This chapter analyses changes in vegetation, fauna, morphology, and perceived land value following the implementation of a freedom space (removal of crops from the former floodplain) and the replacement of an undersized culvert. It also identifies the governance, financial, and relational conditions that enabled the project to emerge and become socially acceptable.

Together, these three chapters propose a reach-scale, interdisciplinary perspective on how hydrological connectivity can guide process-based restoration planning and implementation in small agricultural catchments. This thesis aims to demonstrate how the analysis of residual hydrological connectivity in straightened and degraded agricultural streams can serve as an integrative framework for designing and guiding process-based restoration approaches that reconcile ecological issues, operational feasibility, and social acceptability. More broadly, this thesis proposes a framework where integrating new scientific knowledge with trust-based relationships can lead to innovative and durable ways of rethinking agricultural landscapes. It also advocates for shifting the perception of small degraded agricultural streams: rather than viewing them merely as drainage conduits or ecologically impoverished environments, they should be recognized as crucial components of hydrological systems, the very headwaters where rivers are born.

Chapter 2: High-resolution spatiotemporal analysis of hydrologic connectivity in the historical floodplain of straightened lowland agricultural streams

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ABSTRACT

In agricultural watersheds, human interventions such as channel straightening have disrupted the hydrologic connectivity between headwater streams and their riparian environment and have thus undermined the ecological services provided by these small streams. Knowledge of the hydrologic connectivity between these streams and their immediate environment (shallow riparian groundwater in the historical floodplain and on adjacent hillslopes) in human-impacted settings is critical for understanding and restoring these hydrological systems but remains largely incomplete. The objective of this research is to investigate the hydrogeomorphological conditions controlling hydrologic connectivity in the historical floodplain of straightened lowland streams. Detailed measurements on the spatiotemporal variability of groundwater-surface water interactions between straightened reaches, historical floodplain including abandoned meanders, and the adjacent hillslopes were obtained using a dense network of piezometers at two sites in the St. Lawrence Lowlands (Quebec, Canada). Results show that the complex mechanisms controlling hydrologic connectivity in naturally meandering lowland rivers also operate in highly disturbed straightened reaches, despite backfilling and agricultural practices. The pre-straightening hydrogeomorphological configuration of the floodplain partly explains the complex patterns of piezometric fluctuations observed at the sites. The apex of the abandoned meanders stands out as a focal area of hydrologic connectivity as water levels indicate pressure transfer that may reflect flows from the stream, the hillslopes, and the surrounding historical floodplain. These unique field observations suggest that abandoned meanders should be promoted as key elements of restoration strategies in lowland agricultural straightened headwater streams.

2.1 Introduction

Historically, much investment and effort have been placed into the rapid drainage of water during the flood season and during periods of heavy rainfall to increase field productivity in agricultural watersheds of temperate regions. This led to major morphological modifications, such as the straightening and deepening of meandering streams, over the 20th century in Europe and North

America, which have particularly affected small headwater streams in lowland agricultural settings (Brookes, 1987; Wohl, 2018). The wide-ranging consequences of these interventions on the fluvial system include earlier and higher flood peaks (Schumm et al., 1984; Hupp, 1992; Wyzga, 1996), longer and lower low-water levels (Schilling et al., 2004; LaSage et al., 2008), modification of the spatiotemporal patterns of sediment transport (Brookes, 1987; Simon, 1989; Rousseau & Biron, 2009; Graf et al., 2016), reduction of aquatic (Trautman & Gartman, 1974; D'Ambrosio et al., 2014; Käiro et al., 2017) and terrestrial biodiversity (Hupp, 1992; Franklin et al., 2009), and decreased vertical and lateral hydrologic connectivity (Wohl, 2018).

A growing number of approaches now promote the restoration of natural hydrogeomorphological processes rather than fluvial landforms (Kondolf et al., 2006; Beechie et al., 2010; Wohl et al., 2015a). Process-based restoration aims to increase the resilience of fluvial systems to changes in the hydrological and sediment-transport regime, e.g., extreme events, which is particularly important in the context of rapid climatic changes (Buffin-Bélanger et al., 2015). Increased hydrologic connectivity between degraded streams and their historic floodplain, including their abandoned meanders, is widely recognized as a means to improve the ecological condition and resilience of rivers (Beechie et al., 2010; Gumiero et al., 2013; Phillips, 2013; Wohl et al., 2015a). In this context, hydrologic connectivity refers to the level of connection between surface waters and the groundwater reservoir of a fluvial system through water exchange and pressure transfer. Increased hydrologic connectivity can be achieved by combining active restoration methods (e.g., remeandering, removal of levees, raising the river bed) or by promoting more passive approaches such as freedom space for rivers (e.g., delimiting a space where the river can flood and migrate freely) (Biron et al., 2014; Massé et al., 2020). Despite the many advances in conceptualizing hydrologic connectivity within fluvial systems and developing restoration approaches, straightened lowland headwater streams in agricultural settings still receive limited attention (X. Liu et al., 2014). Most restoration projects in small degraded lowland rivers do not include improvement of hydrologic connectivity in their design objectives (Boulton, 2007; Wohl et al., 2015a) despite the known ecological benefits of promoting hyporheic exchanges in small lowland rivers (Hester & Gooseff, 2010; Kasahara & Hill, 2006; Wohl et al., 2015a).

Important questions remain unanswered regarding the extent of hydrologic connectivity between straightened lowland headwater streams and their associated floodplain and hillslopes. This is

particularly true in rural regions where streams have been backfilled and are often located in cultivated areas. The straightening and deepening of small lowland streams lower the water table in the near-stream zone (Pierce & King, 2017) and reduce the spatial extent of bank transient storage in the riparian zone (Schilling et al., 2006; Schilling & Jacobson, 2014). Embankments along channelized lowland streams can also reduce surface-groundwater exchanges with the floodplain (Clilverd et al., 2013). Nonetheless, few studies have focused on patterns and controls on surface-subsurface hydrological or pressure exchanges within straightened lowland streams (Pierce & King, 2017) and on the potential role of their riparian zones for restoring ecological processes (Liu et al., 2014).

The St. Lawrence Lowlands (Quebec, Canada) is a vast agricultural area that shelters at least 30 000 km of straightened streams (Rousseau & Biron, 2009). In this study, a unique data set of piezometric time series, at an unprecedented spatiotemporal resolution, combined with detailed topographic and stratigraphic survey data are used to analyze small-scale surface-groundwater interactions between straightened headwater streams in the St. Lawrence Lowlands, their historical floodplains, including abandoned meanders, and hillslopes. We hypothesized that despite severe perturbations, the historical floodplain and hillslopes remain partially hydrologically connected to the straightened channel through subsurface interactions, as observed in unperturbed lowland meandering rivers (Cranswick & Cook, 2015; Larocque et al., 2016). The objective of this study is thus to investigate the hydrogeomorphological parameters controlling the level of hydrological connectivity in straightened lowland headwater streams, with a focus on the subsurface component, as a step toward the identification of novel process-based restoration approaches for these degraded agricultural streams.

2.2 Methodology

2.2.1 Study sites

We selected two sites in the St. Lawrence Lowlands that are representative of straightened headwater streams in agricultural areas: Petit-Pot-au-Beurre (PB) and Martin (Ruisseau Martin, RM) streams. Both streams have nivo-pluvial hydrological regimes (high waters in early spring due to snow melt, an upsurge in autumn and low water in summer).

The Petit-Pot-au-Beurre stream is a small second-order stream having a drainage area of 12.8 km^2 (Figure 2.1). The watershed is mostly covered (approx. 90%) by crop fields (corn, soybean, and

fodder plants). Our study site (stream elevation approximately 15 m a.s.l.) encompasses one abandoned meander, the surrounding historical floodplain, and the adjacent hillslope (Figure 2.1). The amplitude of the former meanders in the 1-km studied reach varies between 10 and 52 m. Bankfull width and depth are approximately 3 m and 1.5 m, respectively. The average annual discharge at the on-site gauging station is 0.2 m^3/s with an annual peak discharge slightly greater than 3 m^3/s. The stream can dry out during the summer. The channel was straightened before 1990, and backfill material was placed upon the former channel and the floodplain, erasing most topographic features. A shallow half-circular depression is the only remnant of surface topography from the pre-straightening floodplain. No subsurface drainage is present within the studied abandoned meander area, but drainage tile is present at proximity on the opposite bank of the stream.

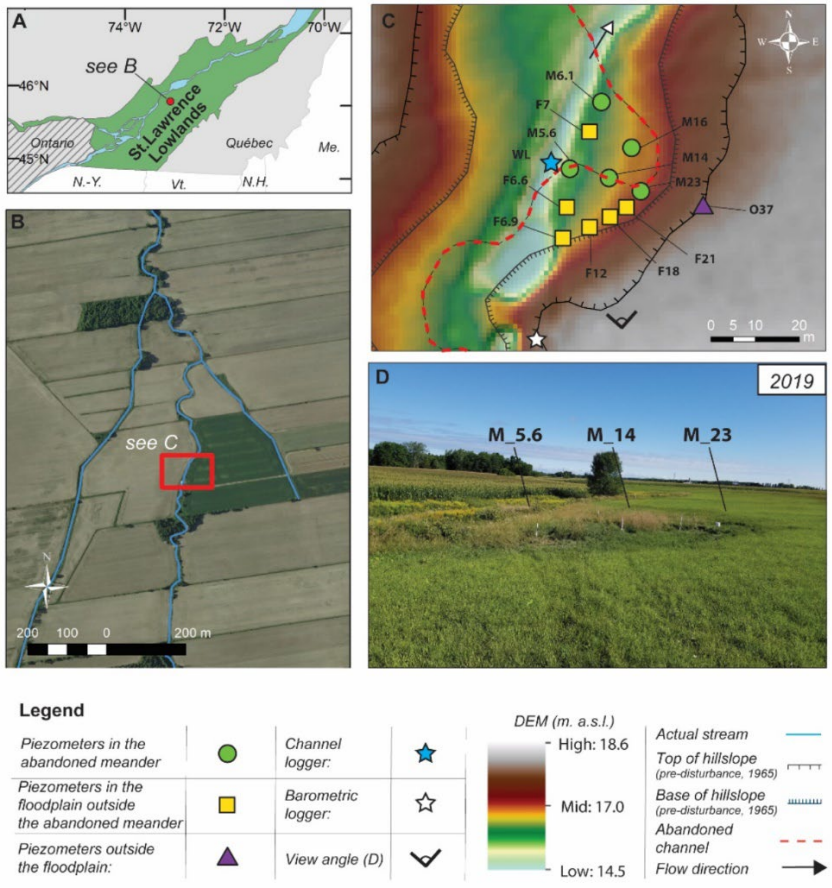


Figure 2.1: (A) Location of the Petit-Pot-au-Beurre (PB) site in the St. Lawrence Lowlands (Quebec, Canada), (B) in a vast agricultural zone with several straightened meander streams; (C) Piezometers installed within the abandoned meander, in the historical floodplain and on the adjacent hillslope, where numbers next to letters M, F and O indicate the distance (in m) between the piezometer and the stream; (D) The current crop at the site showing fodder plants.

The Ruisseau Martin (RM) is a midsize, second-order stream having a drainage area (26 km^2) that is 90% covered by agricultural fields of mainly maize and corn (Figure 2.2). The average historical meander amplitude and floodplain width average are 60 and 80 m, respectively. The modern channel bankfull width and depth are 5 m and 2 m, respectively. The average annual RM discharge is 1.5 m^3/s at the on-site gauging station. We monitored two sites along a 500 m reach of RM. The RM-UP site encompasses a 41-m wide abandoned meander having a floodplain on either side of the channel (note that all references to left and right in this paper are when looking downstream). The RM-DS covers a 22-m wide abandoned meander and the surrounding left floodplain (Figure 2.2). The channel was straightened between 1965 and 1966, but no backfilling was added to the floodplain. Thus, the straightened channel flows through an undisturbed floodplain that is bounded by a 3-m high hillslope on both sides. Small gullies have formed in the left-side hillslope, indicating potential surface runoff during precipitation events.

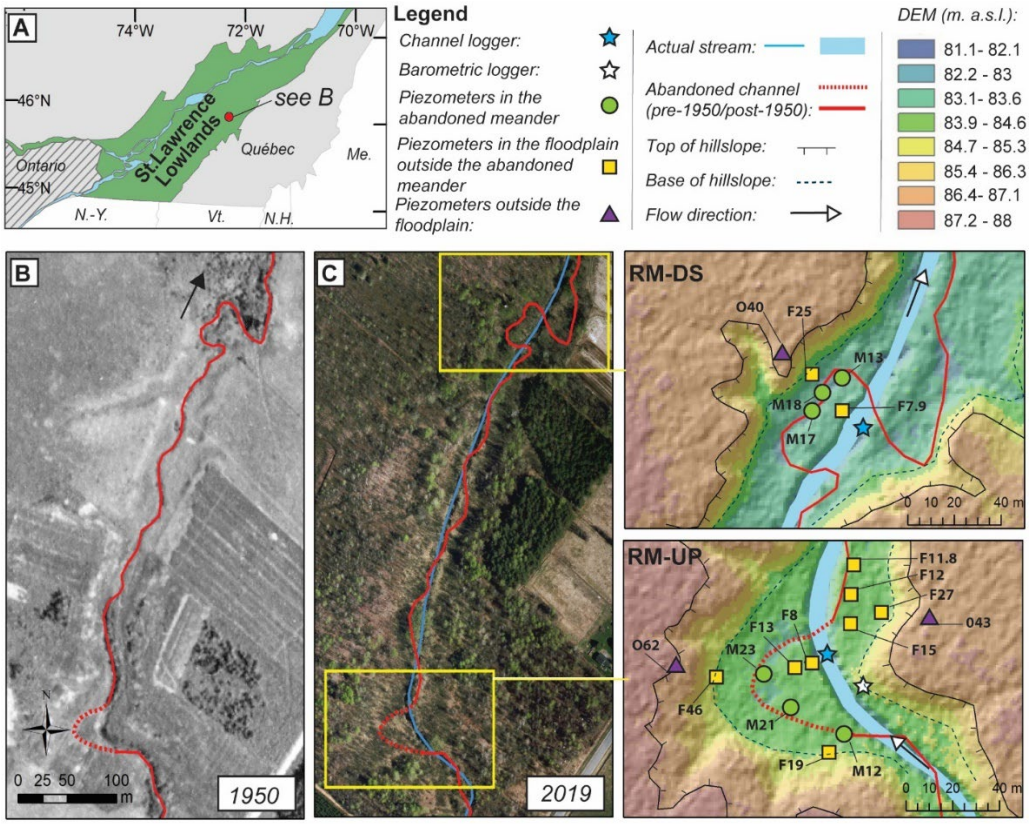


Figure 2.2. (A) Location of the Ruisseau Martin (RM) site in the St. Lawrence Lowlands (Quebec, Canada) in (B) an area that was mainly agricultural but (C) which has recently evolved toward agroforestry farming. Piezometers were installed within two abandoned meanders (RM-UP, RM-DS) and on the historical floodplain and the adjacent hillslopes, where numbers next to letters M, F and O indicate the distance (in m) between the piezometer and the stream.

The studied sites were cultivated until the 1980s. Since then, no cultivation has taken place, and natural (unassisted) colonization by vegetation has occurred. This site allows observation of a fully mature forest, including shrub and forested swamps and herbaceous marshes. It also allows observation of the evolution of a straightened channel and floodplain following completely passive vegetation restoration (40 years). No subsurface drainage is present within the study area.

2.2.2 Topographic and stratigraphic surveys

We performed high-resolution topographic and stratigraphic surveys at each of the three abandoned meanders (PB, RM-UP, RM-DS) to circumscribe the spatial extent of the alluvial material of the floodplain and to position field sensors to record surface and subsurface water fluctuations. Surface topography was measured with a Total Station (Leica TC805L) and georeferenced with a DGPS (differential GPS, model Spectra precision 80). The vertical precision of the DGPS varied between 2 and 4 cm. We assessed the stratigraphy from several boreholes on the floodplain and adjacent hillslope. The excavation of the boreholes was conducted using either an auger (83 mm diameter, 0.50 m length) and up to three 1 m extensions or using a manual gas-powered drill (Pionjar 120) that produced samples of 51 mm (2 in) in diameter and 1 m in length, up to a maximum of 3.35 m. We based our unit differentiation on in situ visual assessments of colour, texture, and organic material in sediment samples collected at regular depths from the boreholes. We also dug larger pedons (1 m width, 1.5–1.7 m depth) at several locations to assess bedding structures within the alluvial unit.

We used the collected sediment samples from the boreholes for grain-size analyses. Coarse fractions (0.08-2 mm) were assessed with a sieve column, whereas we used a sedimentary column and pycnometer to determine the fine fractions (Poppe et al., 2000). The hydraulic conductivity of the different units was estimated from the grain-size distribution using HydrogeosieveXL software (Devlin, 2015). We also performed slug tests in all piezometers, using 25 cm and 50 cm water column injections, and estimated hydraulic conductivity using the Hvorslev (1951) and Bouwer & Rice, (1976) methods.

2.2.3 Surface water measurements and piezometric surveys

The stream stage elevation in the studied reaches was measured continuously at 30 min intervals using pressure transducers inserted within pipes installed in the stream bank. Hydraulic heads in the artificially abandoned channel, in the historical floodplain, and on the hillslope were monitored

with pressure transducers installed in piezometers with data recorded at 30 min intervals. Piezometers were installed along lines running perpendicular and parallel to the current channel. Additional loggers were then installed in relation to floodplain configuration. The former channel and floodplain configuration was assessed using LiDAR data (light detection and ranging) and historical aerial photographs.

Piezometers were installed using a manually operated drill with 1.5″ PVC pipes having a 40-cm perforated section at the bottom. Maximum piezometer depth was determined by the depth of the alluvial unit, which was in turn determined through visual assessment of the stratigraphy. The annular space around the PVC pipes was filled with coarse sand and bentonite at the top. Different pressure transducers were used (*Onset Hoboware Titanium*, *Solinst Levelogger Gold Junior* and *Edge model 3001*). At each site, a *Solinst Barologger* was used for barometric compensation.

We excluded data from January and February (winter) to avoid ice cover effects on surface water heads. The longest time series spans from October 2017 to June 2020; the shortest spans from August 2018 to June 2020. We compiled hourly precipitation for these time series using data from the closest Environment and Climate Change Canada weather stations (each site is less than 20 km from a station). On-site hunting cameras allowed to confirm that rain events measured at the weather stations occurred at the study sites.

We used cross-correlation analyses to assess interactions between the piezometer time series and the channel stage at an event-based scale. Although cross-correlation analyses can be applied to a complete time series (Larocque et al., 2016), event-based applications are more applicable to smaller spatial and temporal scales (Buffin-Bélanger et al., 2016). These analyses were thus only performed during large hydrological events in the channel (i.e., events that triggered a minimum stream level rise of 0.25 m). We documented approximately 40 events at each site over 2.5 years. The end of a hydrological event was determined either from a new rise in water levels in the channel or from water levels in the channel reaching a pre-flood level. Care was taken to avoid complex hydrological events from cross-correlation analyzes, including multiple consecutive increases occurring over short periods. The lag time corresponding to the maximum cross-correlation coefficient (MCCC) between river levels and head data were estimated for all events and all piezometers. A MCCC value close to 1 with a lag time of zero indicates that both fluctuations (in the channel and in the piezometer) are almost synchronous and that their

hydrographs have similar shapes. Negative time lags indicate that the fluctuation in the piezometer precedes the fluctuation in the channel. This cross-correlation analysis of channel-floodplain peak stages assumes that large MCCC and short lag times indicate a greater potential for hydrological interactions. It should be noted here that this type of analysis is based on hydraulic pressure gradients, which only infer pressure exchanges, and not directly hydrological fluxes.

At the event-based scale, we documented for each event the ratio of the amplitude of water-level fluctuations in the piezometers compared with those in the channel (hereafter Average Amplitude ratio) and the ratio of the duration of the rising limb in the piezometers compared with that in the channel (hereafter Average duration ratio). We visually interpreted the full hydraulic head time series to characterize the hydraulic gradients between the straightened streams, their respective historical floodplain, and the adjacent hillslopes in terms of magnitude and orientation at a seasonal time scale. Event-based and seasonal piezometric patterns were classified either as "flood" or "low-flow" periods to facilitate interpretation. The studied streams display two flood periods (March to mid-May and mid-October to December) and one low-flow period (mid-May to mid-October).

2.3 Results

2.3.1 Stratigraphy

2.3.1.1 Petit-Pot-au-Beurre (PB)

At the PB site, the stratigraphic logs reveal backfilling, alluvial, and regional units (Figure 2.3). The backfilling unit is a deposit of poorly sorted clay with silt of a highly variable thickness (thin near the former hillslope and thicker above the historical floodplain). The alluvial unit, ranging between 0.70 and 2.00 m in thickness, can be subdivided into four subunits arranged in complex assemblage, each representing a depositional feature, namely overbank deposits, point bars, bedload material, and floodplain topsoil. The bottom surface morphology of the alluvial unit is concave, with its deepest part near the abandoned meander apex (Figure 2.3). The regional unit is a sandy silt deposit, described as a shallow marine deposit from the St. Lawrence Lowland (Ministère des Ressources naturelles et de la Faune du Québec, 2012) with a gley horizon at the bottom. The average hydraulic conductivity values for the regional and the alluvial units are 1.15×10^{-7} and 1.09×10^{-5} m/s, respectively.

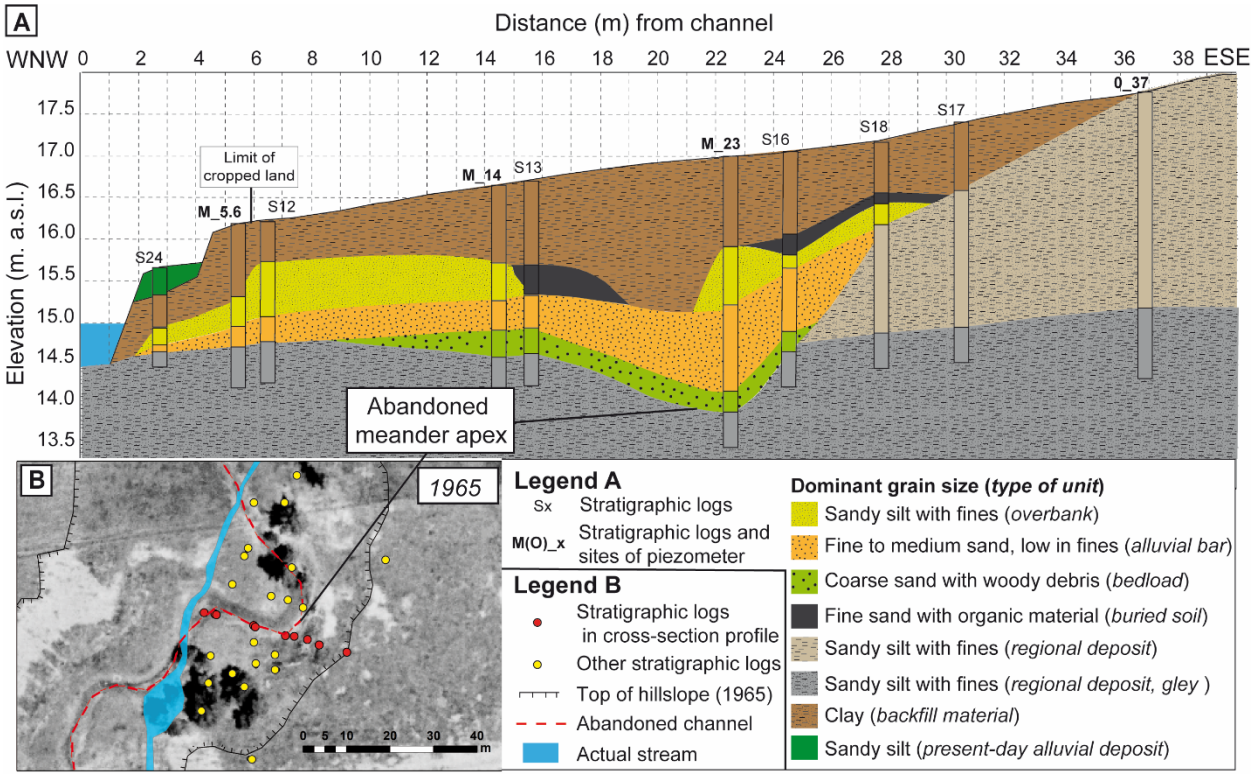


Figure 2.3 (A) Stratigraphic cross-section profile at PB site. Logs labelled with letter S (ex. S_24) were only used for the stratigraphic characterization. Logs labelled with letter M (ex. M_5.6) and O were also used for piezometer installation. Numbers represent the distance to the stream (in m). Note a vertical exaggeration of 3×. (B) Historical aerial photograph (1965) of the PB site prior to channel straightening, with the position of the actual channel. Red dots indicate the stratigraphic logs that were used to build the cross-section profile.

2.3.1.2 Ruisseau Martin (RM)

The RM floodplain shows an alluvial unit ranging from 0.70 to 1.95 m in thickness (Figure 2.4 (RM-UP), see Appendix A: Figure A for RM-DS). Despite much heterogeneity in the subunit assemblages, the logs from the floodplain generally show fine sand, grading into medium to coarse sand with woody deposits. Some morphological features show active erosional or depositional surfaces, which suggest recent surficial floods. The regional unit forming the left hillslope of the RM stream reveal alternating medium sand and clayey silt deposits of varying thickness, also described as shallow marine surficial deposit from the St. Lawrence Lowlands. The floodplain is embedded in the same regional unit. At the RM-UP site (Figure 2.4), a very hard clayey matrix is found beneath the regional unit in the right hillslope. The alluvial material of the right end portion of the left floodplain as well as the right floodplain is embedded in the same material, described as glacial till (Ministère des Ressources naturelles et de la Faune du Québec, 2012). The average hydraulic conductivity values for the medium sand and clayey silt regional units and for the alluvial units are 2.61×10^{-5}, 2.46×10^{-7} and 1.96×10^{-5} m/s, respectively.

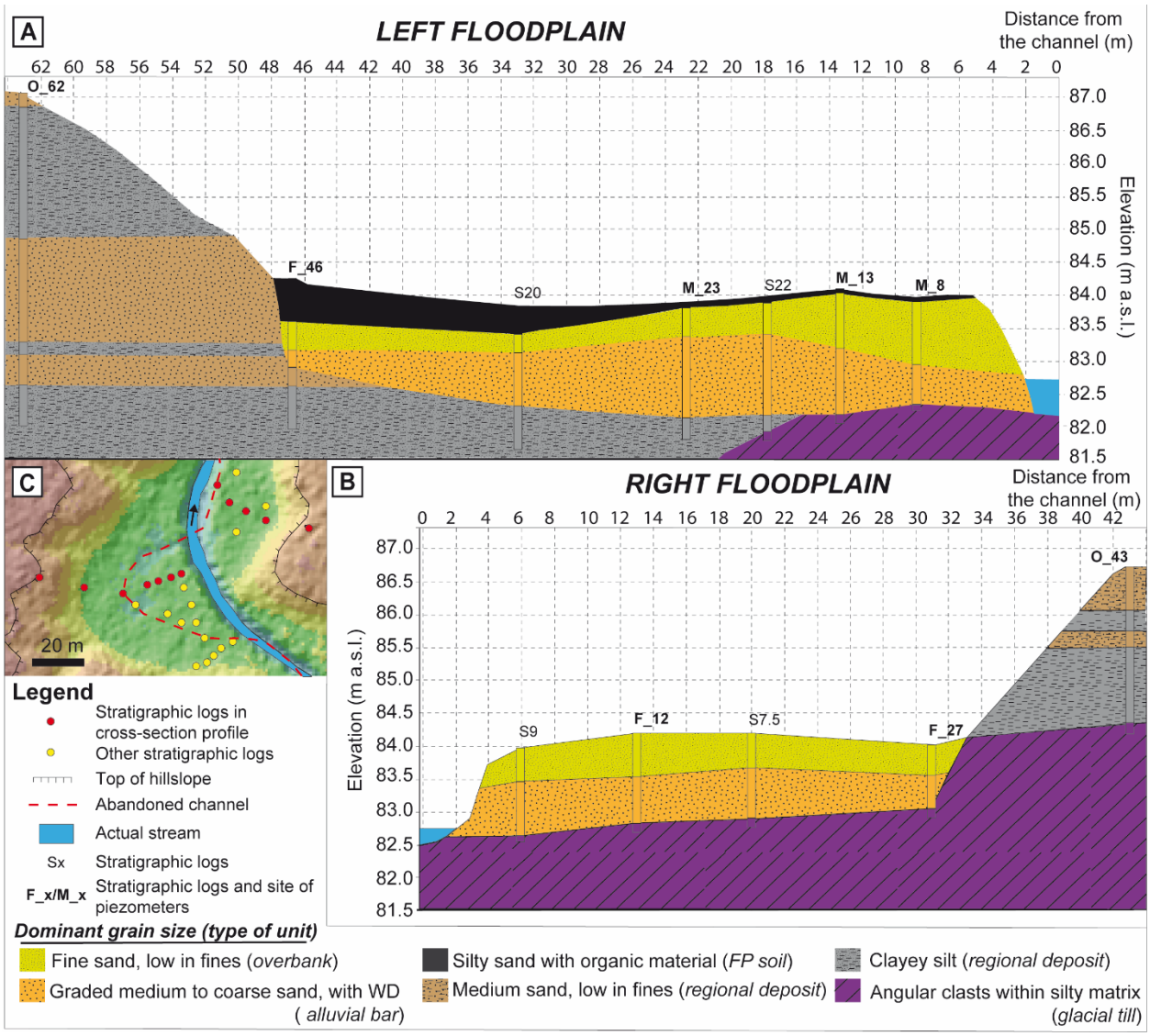


Figure 2.4 Stratigraphic cross-section profile at RM-UP site, representing the (A) left and (B) right floodplain (looking downstream). Borehole logs labelled with S (ex. S_22) were only used for the stratigraphic characterization. Borehole logs labelled with M (ex. M_8), F, and O were also used for the piezometer installation. Numbers represent the distance to the stream (in m). Note a vertical exaggeration of 4×. (C) Digital elevation model of the RM site, with the position of the former and actual channel. Red dots indicate the stratigraphic logs that were used to build the cross-section profiles.

2.3.2 Piezometric head

2.3.2.1 Flood periods

For hydrological events occurring during the flood periods, the range of average MCCC values for all the piezometers located in the historic floodplain at the PB and RM sites is between 0.78 and 0.98 (Figure 2.5, row 1). Not surprisingly, the average MCCC values generally decrease with distance from the stream. These values indicate that the shape of the hydrograph of piezometers located near the stream limit is more similar to the stream hydrograph than those of piezometers

near the lateral limit (near the hillslope). This is coherent with the higher average amplitude ratio values (close to 1) measured closer to the stream limit of the historical floodplain than closer to the lateral limit (Figure 2.5, row 3). The average time lags values vary between -4 and 6 hours, with the lowest (negative) values generally observed near the lateral limit of the floodplain at all sites (Figure 2.5, row 2). These relatively small time lags reveal quasi-synchronous fluctuations throughout the entire historic floodplain during hydrological events, with slightly prior response near the lateral limit compared to the fluctuations in the channel. Piezometers located outside the floodplain generally shows the lowest MCCC and amplitude ratio values and highly variable lag time and duration ratio values.

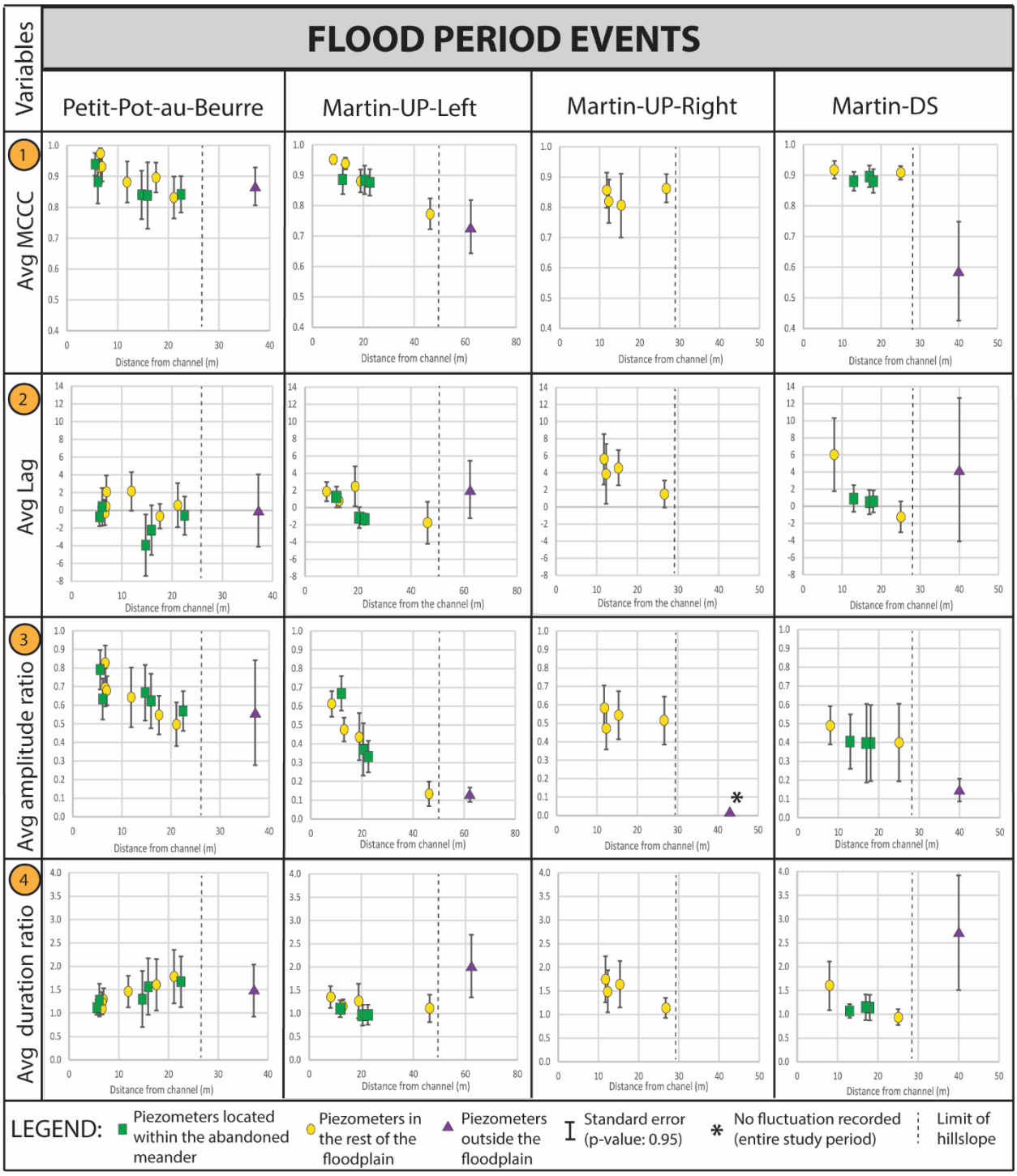


Figure 2.5. Cross-correlation analysis (MCCC (maximum cross-correlation coefficient), lag time, rows 1 and 2) and hydrograph characteristics (peak amplitude ratio, peak duration ratio, rows 3 and 4) for piezometers at the (A) PB, (B) RM-UP left, (C) RM-UP right, and (D) RM-DS for the flood periods (early March to mid-May, mid-October to late December). The vertical dashed line represents the lateral limit of the historical floodplain.

Results from the PB and RM-UP sites suggest that during a hydrological event, the piezometers located in the abandoned meander (green squares in Figure 2.5) generally react before (shorter

time lags) those situated at a similar distance to the channel but outside the abandoned meander (Figure 2.5, rows 2), although due to the large time lag variability, these differences are not statistically significant. Moreover, at the RM-Up site, the left floodplain (where the abandoned meander is located) shows higher average MCCC and lower average time lags than the opposite (right) floodplain (Figure 2.5, rows 1 and 2).

Observations of seasonal water level patterns suggest that the hydraulic gradient in the PB and RM floodplains remains predominantly oriented toward the channel during the entire flood periods when water levels in the channel remain below bank level (Figure 2.6 (A), see Appendix A, Figure B, C). On some occasions at PB, at the onset of a hydrological event, a slightly inverted hydraulic gradient develops between the groundwater level in the piezometers close to the channel and those located near the hillslope (Figure 2.7). Overbank flood events only occur on few occasions (in early spring at PB, in spring and fall at RM). At PB, overbank floods are limited to narrow strips near the stream, as illustrated by maximum values exceeding surface elevation in Figure 2.6 (B). At RM, overbank flood events systematically cover the entire historic floodplain (Appendix A: Figure B and C). During the entire flood period at the PB and RM sites, water levels in the hillslope remain constant and exceed the heads in the nearest floodplain piezometer by at least 0.5 m (Figure 2.6 (A), Appendix A: Figure B and C). The only exception is the RM-UP right hillslope where no water was ever detected in the piezometer.

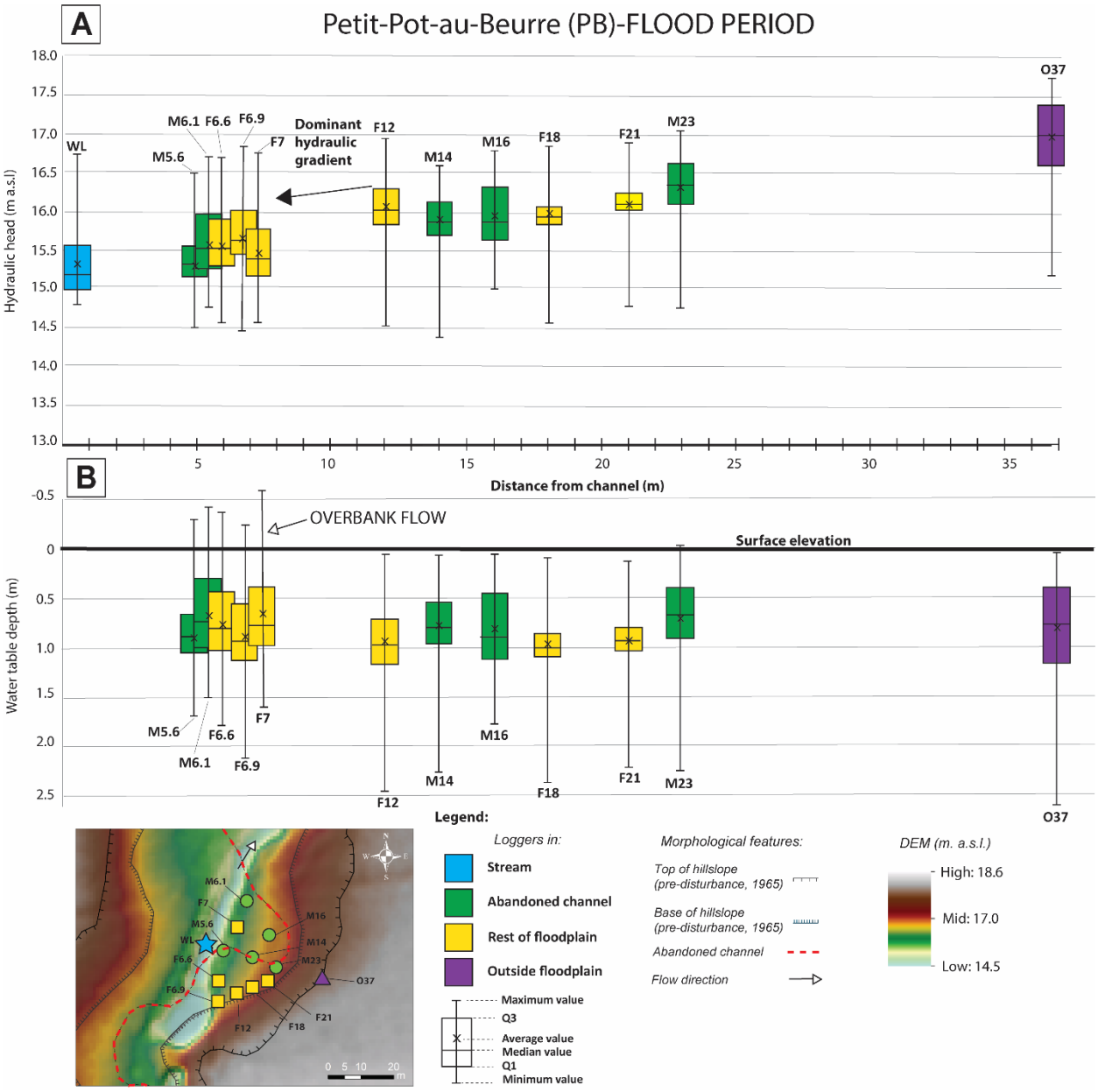


Figure 2.6: Box plot graphs showing A) hydraulic heads and B) water table depths in PB piezometers for the flood period (mid-March to mid-May and early October to late December). Negative water table depths indicate water level above the surface.

Observations of piezometric patterns at the seasonal scale also suggest that the water table near the abandoned meander apex remains generally nearer the floodplain surface than elsewhere at similar distance from the channel (Figure 2.6 (B)). At RM-UP left and RM-DS (Appendix A: Figure B and C), the water table depth around the apex of the abandoned meanders remains near zero throughout the flood period. At PB, this pattern is particularly clear in the early spring period for piezometers located near the lateral limit of the floodplain and inside the abandoned meander

(M_16 and M_23, green lines in Figure 2.7) which maintain higher head elevation than piezometers located just outside (F_18 and F_21, yellow lines in Figure 2.7). It is also notable that during the late spring flood period (mid-April to mid-May) at PB, the amplitude of fluctuations observed near the abandoned meander apex (M_16 and M_23) during hydrological events are much higher than those observed in the piezometers (F_18 and F_21) outside the abandoned meander (Figure 2.7). These patterns coincide with the initiation of a head decrease in the hillslope, leading to the low flow period.

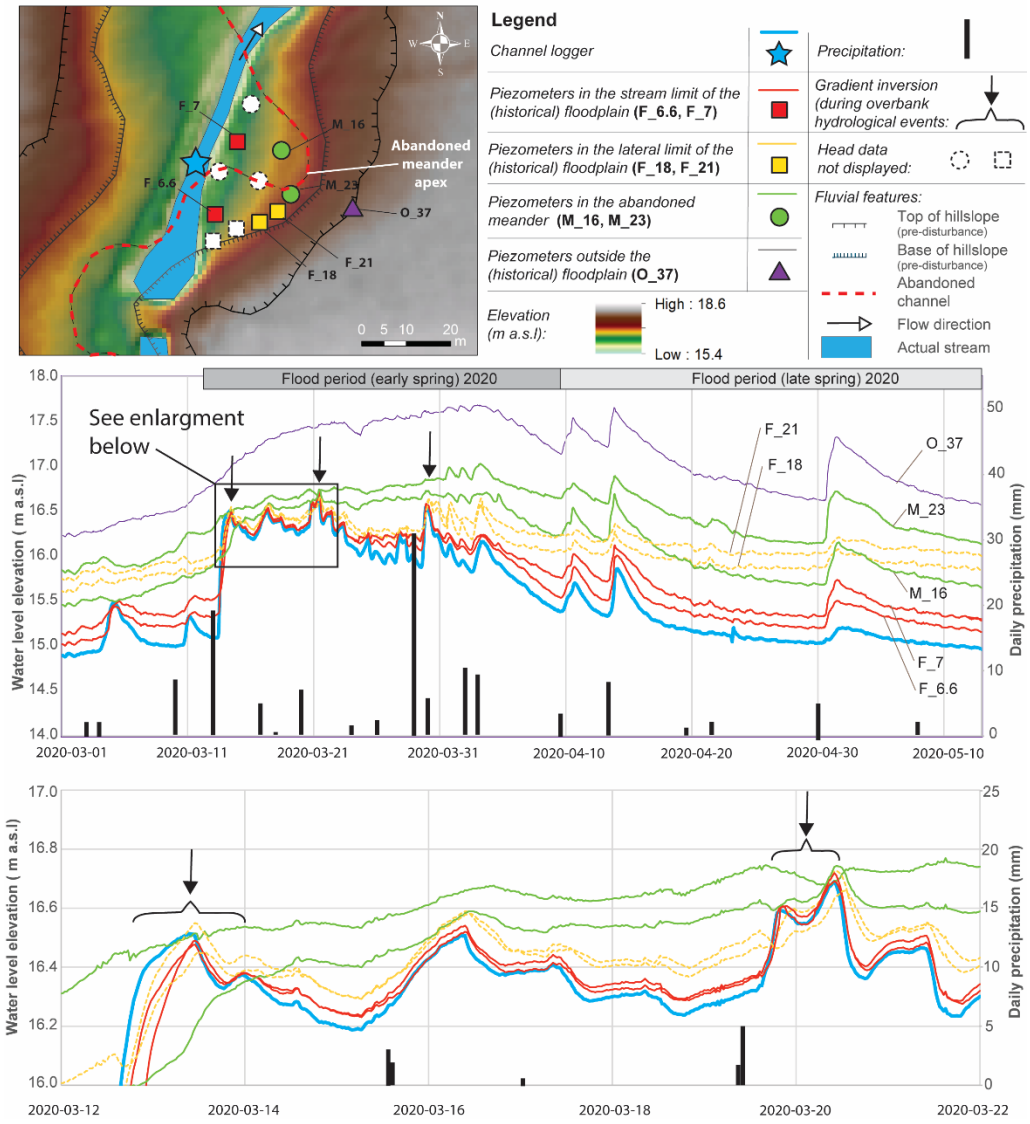


Figure 2.7. Hydrograph for the flood period between March 1 and May 15, 2020, at the PB site. Notice the distinct head elevation for the early flood period and the larger amplitude of fluctuations during events in the late flood period for the piezometers located in the abandoned meander apex (green lines) compared with those located at a similar distance but outside the former meander (yellow lines). The top and base of the hillslope are presented as they were before channel straightening and backfilling of the floodplain.

2.3.2.2 Low-flow period

For hydrological events occurring during the low-flow period, lower values of MCCC are generally observed in the historic floodplain than during the flood periods (Figure 2.5 and 2.8, row 1). The most obvious difference between the flood period and the low flow period is observed in the piezometers located near the actual channel at the RM-UP site with the highest average MCCC values measured closer to the hillslope, unlike the PB site (Figure 2.8, row 1). The same difference between sites applies to the amplitude of head fluctuations with the amplitude ratio at PB generally much lower near the lateral limit of the floodplain during the low-flow period (Figure 2.8, row 3), indicating fluctuations with relatively small amplitude compared to those close to the channel. Unlike PB, the average peak amplitude ratio at RM is higher close to the lateral limit of the floodplain than close to the stream (Figure 2.8, row 3).

At the RM sites, piezometers located in the abandoned meander exhibit the highest amplitude among all piezometers (green squares in Figure 2.8, row 3). Results at RM also suggest that the relative duration of hydrological events is shorter in piezometers located in the abandoned meander (Figure 2.8, row 4). Among all the sites, the average time lags oscillate between −8.5 and 10.8 h (Figure 2.8, row 2), with less contrast for piezometers located within the abandoned meander than piezometers located outside the abandoned meander compared with the flood period.

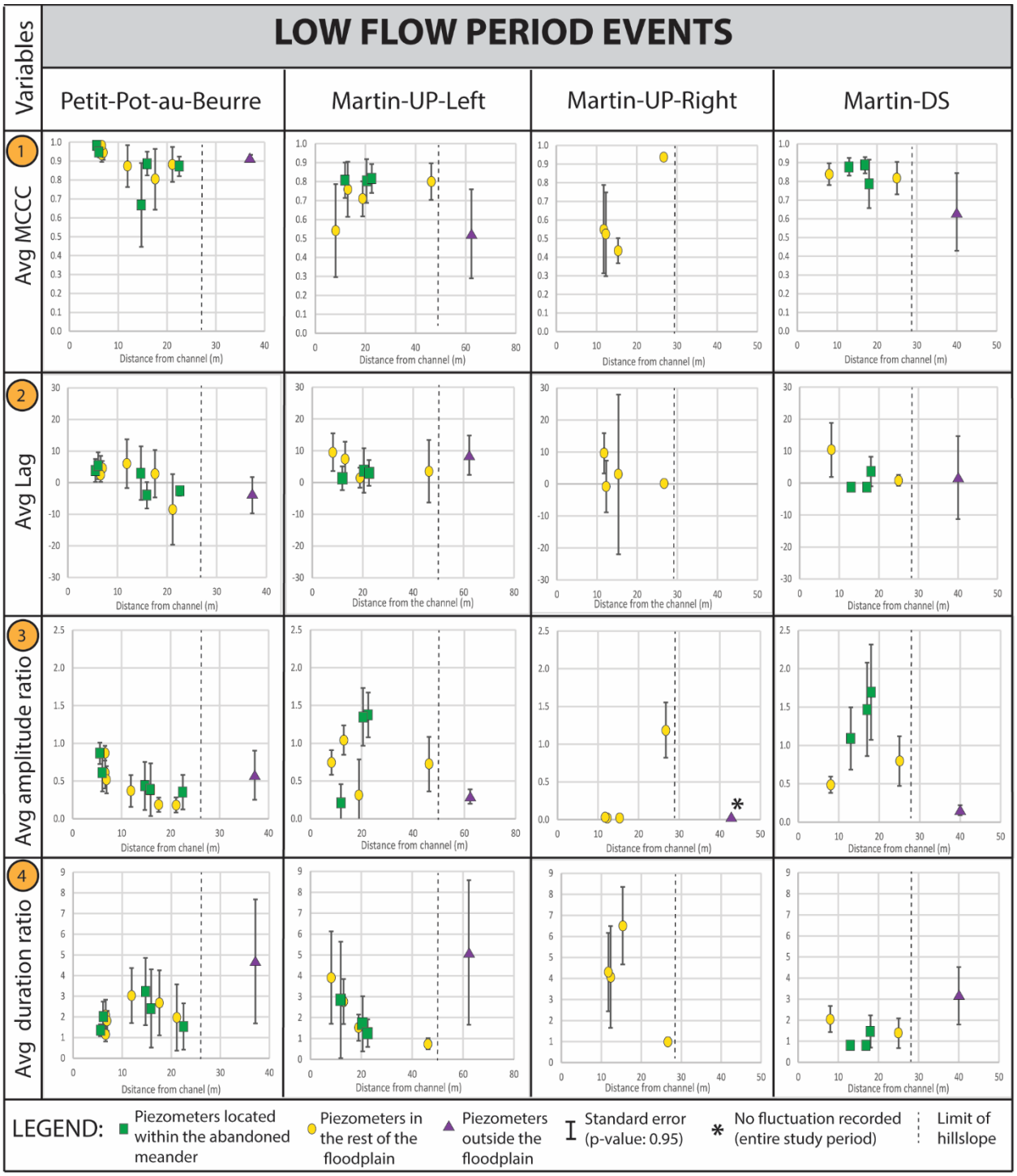


Figure 2.8. Cross-correlation analysis (MCCC (maximum cross-correlation coefficient), lag time) and hydrograph characteristics (peak amplitude ratio, peak duration ratio) for all piezometers at all studied sites for the low-flow period (mid-May to mid-October).

The hydraulic gradient at all sites during the low-flow period is generally stream oriented (Figure 2.9, see Appendix A, Figure D and E). At PB, short-duration gradient inversion occurs between

the stream and the piezometers close to the channel due to a slight delay between the head response in the piezometers near the channel and the fluctuation in the channel. This contrasts with the flood period where a hydraulic gradient inversion only occurred during overbank channel events. By the end of the summer at PB, groundwater levels eventually decrease below the piezometer, resulting in a net decrease of hydraulic gradients. At the RM sites, the decrease of the head on the hillslope never exceeded 1 m (Appendix : Figure D and E). Unlike PB, a strong hydraulic gradient from the hillslope to the floodplain thus remained throughout the study period. No overbank event occurred at both sites during the entire low-flow period (Figure 2.9 (B)). However, at the RM sites, water table elevations occasionally reached the surface elevation of the floodplain, specifically at the location of the abandoned meander apex (Appendix A: Figure D and E).

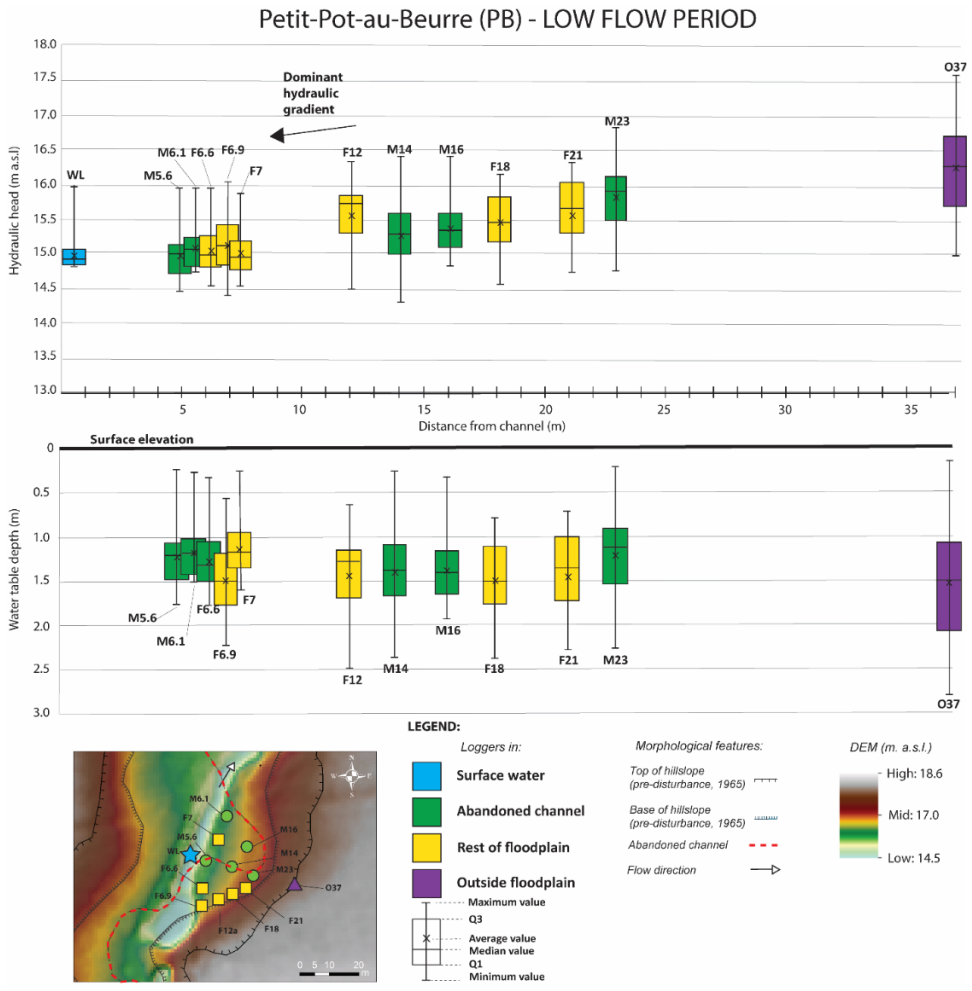


Figure 2.9. Box plot graphs showing A) hydraulic head elevation and B) water depth of piezometers installed at the PB site for the low flow period (mid-May to early October).

2.4. Discussion

2.4.1 The challenges of understanding subsurface hydrological processes in degraded alluvial environments

To the best of our knowledge, this study presents a first attempt to document with such high spatiotemporal resolution the groundwater-surface water interactions between straightened reaches and their historical floodplain and adjacent hillslopes. There are many challenges associated with the interpretation of these new data, in particular in terms of statistical analyses due to the intrinsically high level of variability in piezometric data in these complex degraded environments. Floodplain piezometers represent head fluctuations in a transitional geological area connecting surface water in the channel with the regional aquifer (Cranswick et al., 2015). This transitional area is subject to external controls such as stream water level and hillslope heads, precipitation and evapotranspiration. These controls can mask the influence of parameters intrinsic to the floodplain, such as effective porosity of the geological material, and morphology and stratigraphy of the deposits. This combination of influences can result in a high spatiotemporal variability of the piezometric response within the floodplain and increases the challenge of identifying significant differences in head fluctuation patterns at a given site.

Results from this study converge to support the idea that straightened lowland streams can still be hydrologically connected to their historic floodplain. For example, the generally high MCCC values and low time lag values indicate strong synchronicity between fluctuations in straightened lowland rivers and those in their historic floodplain. In addition, our findings provide evidence that abandoned meanders have a higher level of hydrological connectivity within the floodplains. This is particularly evident when events are analysed independently of each other. For example, the hydrograph for the event of August 8, 2019, at RM-UP (Figure 2.10) reveals that most fluctuations recorded in the floodplain were concentrated around the abandoned meander apex and near the hillslope (left and right), and that these fluctuations occurred slightly before those in the piezometers near the channel.

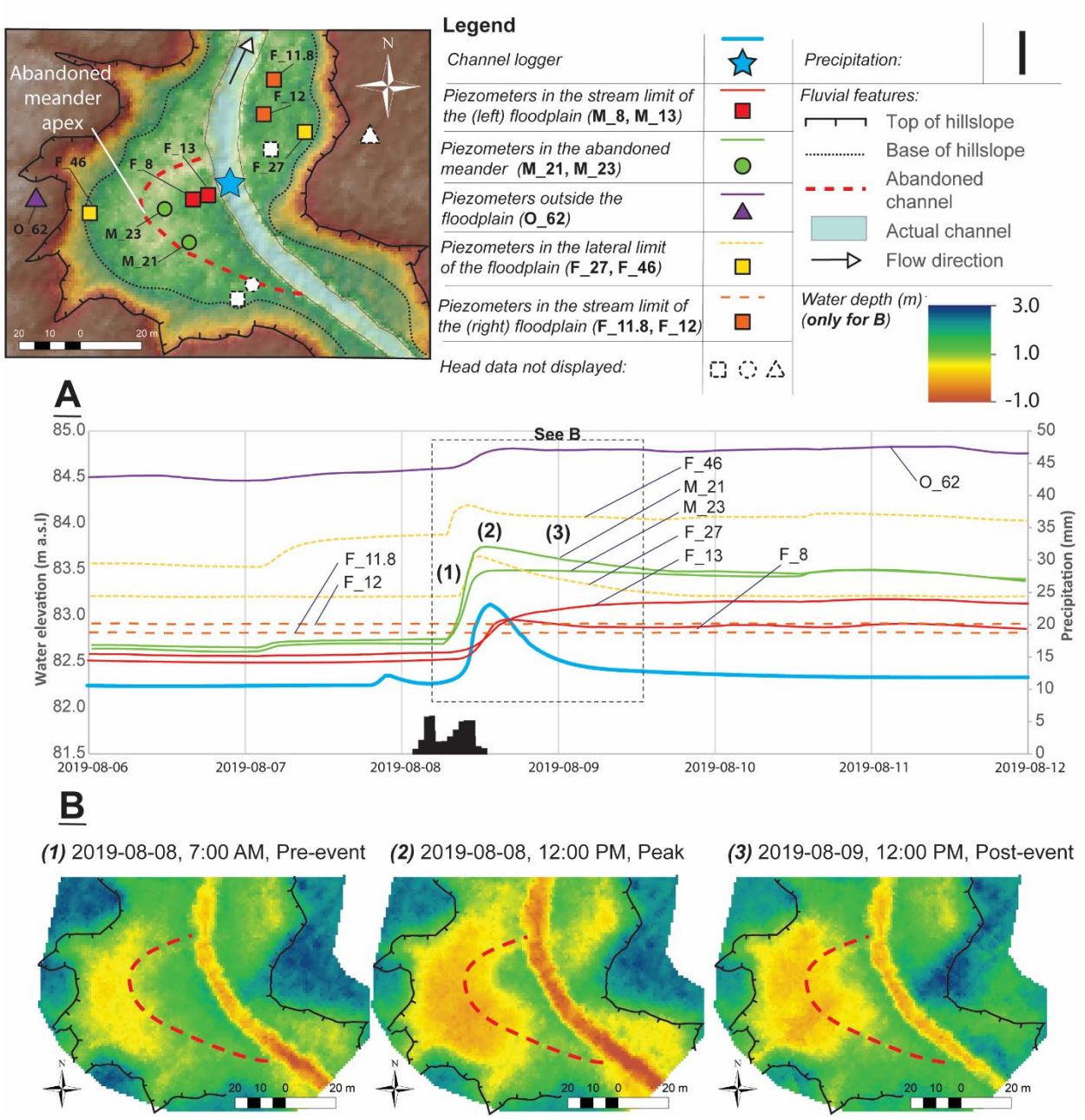


Figure 2.10. (A) Hydrograph for the August 8, 2019, hydrological event at the RM-UP site. (B) Piezometric maps representing three stages (pre-event, event peak, and post-event) of the August 8, 2019, event. Note that absolute elevations of hydraulic heads were converted to water depth from the surface before interpolation. Negative values (in the existing channel and in the abandoned channel apex) represent water levels above the ground.

2.4.2 Conceptual model of hydrologic connectivity in straightened lowland headwater streams

2.4.2.1 Hydrological controls

The combination of groundwater flows from the hillslope and the transient bank storage originating from the channel during a hydrological event are the main processes that appear to influence piezometric fluctuations in the floodplain of straightened lowland headwater streams. These original results contribute to better conceptualize the role of the floodplain in maintaining hydrologic connectivity between an agricultural stream and the neighboring aquifer (Figure 2.11). During the flood and low-flow periods at all three studied straightened meanders, stream stage fluctuations modify the hydraulic gradient between the stream and the floodplain. During the rising limb, the stream-oriented hydraulic gradient either decreases (Figure 2.11, point 1), which can induce the propagation of a pressure wave away from the channel (Lewandowski et al., 2009; Buffin-Bélanger et al., 2016), or is temporarily inverted (Figure 2.11, point 2), potentially resulting in subsurface flows toward the floodplain (Pinder & Sauer, 1971; Winter, 1999; Flipo et al., 2014; Van Stempvoort et al., 2021). Relatively rapid increases of piezometric levels in each studied floodplain reach, driven by stream stage fluctuations, are interpreted as transient bank storage (Cranswick & Cook, 2015; Winter, 1999).

The presence of higher heads in the hillslope at each study site can also control piezometric fluctuations in the historic floodplain of the straightened channels (Figure 2.11, point 3). At the RM sites, the relatively high hydraulic conductivity of the hillslope material probably contributed to higher hillslope heads and probably indicate groundwater flow toward the lateral limit of the floodplain (Vidon & Hill, 2004; Jencso et al., 2010). At PB, given the low hydraulic conductivity of the hillslope material, the elevated heads could result in limited groundwater flow between the hillslope and the alluvial deposits, especially during the flood period. The overall shorter time lags calculated in the piezometers located near the hillslope compared to those at the stream limit illustrate that flows originating from the hillslope and the channel are not of the same magnitude and are potentially not perfectly synchronized during a hydrological event. The only exceptions, when all floodplain piezometers fluctuate synchronously with the stream stage, occur during overbank flooding events (Figure 2.11, point 4). However, complete flooding of the floodplain only occurred at the RM sites, as the backfilling of the floodplain at the PB site considerably limits the extent of overbank flooding (Figure 2.11, point 5). Otherwise, with the dominant hydraulic

gradient oriented towards the stream, groundwater likely flows from the lateral limit to the stream limit of the floodplain (Figure 2.11, point 6).

During a hydrological event, both elevated heads in the hillslope and stream stage fluctuations thus contribute to a high level of hydrological connectivity with the floodplain, resulting in piezometric fluctuations that are larger within the floodplain than in the adjacent hillslope material. The results show that lag-time values can help differentiate signal propagation of regional groundwater (negative lag) from surface water-groundwater connectivity at the channel-bank interface (positive lag) (Figures 2.5 and 2.8).

Additional hydrological factors that may control the degree of correlation between surface water and piezometric fluctuations observed within the floodplain relate to local recharge from precipitation and antecedent head level. In the spring and late-fall flood periods, evapotranspiration over the floodplain should be relatively minimal, which allows precipitation to percolate through the alluvial deposits and induce head fluctuations (Figure 2.11, point 7). Antecedent high head level in the floodplain and especially along the lateral limit of the floodplain however may limit head fluctuation during hydrological events and affect MCCC values. By midsummer, during low-flow periods, local precipitation has hardly any influence on floodplain heads, as most precipitation is likely intercepted by vegetation or lost by evaporation (Gribovszki et al., 2010; Lalot, 2014; Van Stempvoort et al., 2021). At the PB site, the very fine texture of the backfilling unit placed upon the former meandering stream floodplain probably limits percolation, reduces recharge within the floodplain, and limits piezometric fluctuations from vertical inflows (Figure 2.11, point 8).

2.4.2.2 Geomorphic controls

The level of hydrologic connectivity between lowland straightened headwater streams, their former floodplain, and their hillslope is not spatially and temporally uniform, even within a given reach. For instance, the right floodplain at the RM-UP site suggests that very low hydraulic conductivity material in the hillslope and basal unit of the floodplain may influence piezometric fluctuations within the floodplain. The compact and low permeability till material on the right-hand hillslope (Figure 2.4) probably contributes to only very limited seepage toward the floodplain (Figure 2.11, point 9). The similar material and the configuration of the basal unit material on the right floodplain of the RM-UP site also likely explain why none of the piezometers along this stream limit react during summer hydrological events (Figure 2.11, point 10). Ultimately, the RM-

UP site highlights that marked contrasts in hydrologic connectivity occur at the scale of two opposing floodplains of the same straightened reach, with one of them comprising an abandoned channel.

Our results suggest that head fluctuations patterns are markedly different at the location of the abandoned meander apex than in the rest of the floodplain in specific hydrological periods. During the flood period, piezometric level near the former meander apex remains high, distinctively from fluctuations in the channel or in the rest of the floodplain. During the transition between flood and low-flow periods, the greatest amplitude of fluctuations along the hillslope during hydrological events is observed in the piezometers located near the abandoned meander apex. At RM, unlike at the PB site, greater piezometric fluctuations around the abandoned meander apex were observed for all low-flow period events, while hillslope heads remained above the adjacent floodplain.

These observations highlight the critical role of the abandoned meander apex in the complex spatiotemporal pattern of hydrologic connectivity observed between the straightened channel, its floodplain, and its hillslope. A higher degree of hydrologic connectivity at the location of the abandoned meander apex stems partially from the quasi-simultaneous but opposite pressure pulses from hillslope recharge and streamflow, although it remains difficult to identify the specific contribution of each process in the context of this study. Nevertheless, changes in the hydraulic gradient between the stream, the floodplain, and the hillslope as well as the hydraulic conductivity of the hillslope material and the antecedent floodplain heads cannot themselves explain the distinct piezometric fluctuation patterns observed near the abandoned meander apex.

Like their natural counterpart, abandoned meanders resulting from channel straightening potentially form surficial depressions within the floodplain. The lowest area of these abandoned channels generally corresponds to the apex of meanders where there used to be a pool. At the scale of one straightened meander, the former apex zone can converge surficial runoff from the adjacent hillslope (Figure 2.11, point 11) and from the surrounding floodplain (Figure 2.11, point 12) following a precipitation event (Mertes, 1997). At the RM sites, for instance, the surface depressions at the apex of the abandoned meander can still be observed and likely contribute to surface runoff toward these specific areas of the floodplain. The bottom contact of the alluvial floodplain material also generally displays an asymmetric and concave morphology, with a depression likely to form at the apex of meander bends toward which groundwater can be

temporarily oriented during hydrological events, therefore contributing to a larger amplitude of piezometric fluctuations in the apex of the abandoned meander (Figure 2.11, point 13) (Ali et al., 2011). It is also likely that the coarser material and the woody deposits associated with the former channel apex, as observed at the PB site, define high conductivity facies and therefore act on preferential flow paths, as suggested in lowland environment (Duval & Hill, 2006; Welch et al., 2014; Wallace & Soltanian, 2021).

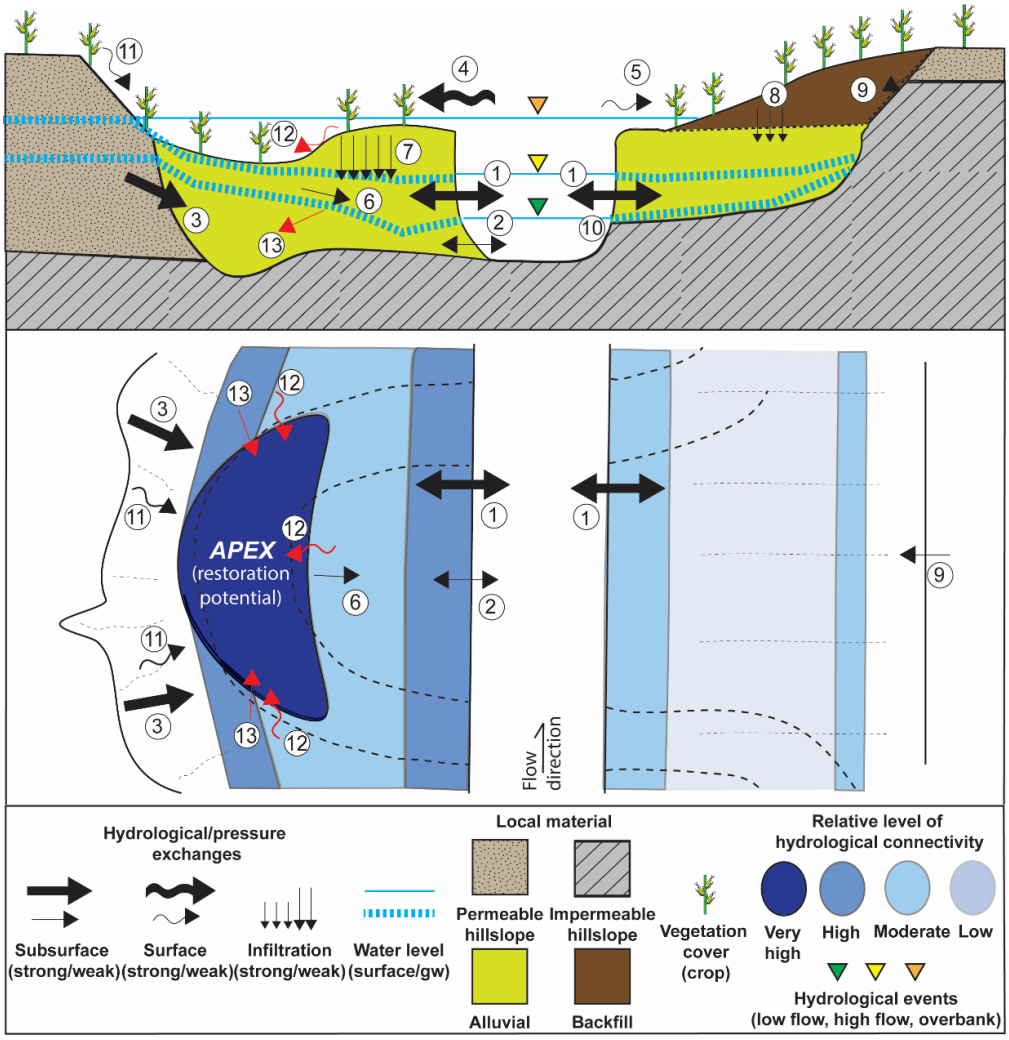


Figure 2.11. Conceptual model of surface and subsurface hydrological exchange mechanisms operating in straightened agricultural lowland streams: (1) bank transient storage during flood period and (2) during low flow period; (3) subsurface flows from permeable hillslope; (4) overbank flow on the undisturbed and (5) backfilled floodplain; (6) subsurface flows toward the stream limit of the floodplain when the stream-oriented hydraulic gradient re-establishes (7) infiltration into the undisturbed floodplain; (8) limited infiltration into the backfilled floodplain; (9) limited subsurface flows from impermeable hillslope; (10) limited surface-groundwater exchange due to the presence of an impermeable basal unit; (11) surface runoff from the hillslope; (12) surface runoff and (13) subsurface flows from the surrounding floodplain toward the meander apex depression during hydrological events. Overall, these mechanisms define zones of very high to moderately low hydrologic connectivity within the historical floodplain of straightened streams, with the focal zone being located at the apex of the abandoned meander. Red arrows represent exchange mechanisms directly associated with the presence of the former meander apex.

Because the experimental setting measured hydraulic heads, the results of this study only infer pressure exchanges and not directly hydrological fluxes. Also, with the available data, it is not possible to differentiate between precipitation events that occur at the study sites from those that occur upstream. Moreover, our findings must be interpreted in the context of straightened streams in lowland settings. In other settings, for example in a piedmont environment, hydrologic connectivity of straightened streams may differ. Nevertheless, it is worth noting that subsurface pressure transfers operating between the straightened stream and the stream limit of the floodplain, and between the hillslopes and the lateral limit of the floodplain, remain active at least for part of the year, which contrasts with findings by Lewandowski et al. (2009) in an abandoned meander of the lowland River Spree (Germany). This connectivity varies in time and space depending on the texture and configuration of the floodplain and hillslope material, the orientation and magnitude of the hydraulic gradients, and the antecedent saturation conditions, as observed in natural meandering lowland streams (Boulton et al., 1998; Cranswick & Cook, 2015; Biehler et al., 2020).

2.4.3 Implications for restoration planners and stakeholders

Increasingly, institutional and government stakeholders are raising concerns about the consequences of high levels of disturbance in low-order agricultural streams, resulting in rapid ecological degradation (Vidon & Hill, 2004; Colvin et al., 2019). Given their small drainage area and the absence of cumulative upstream sources of disturbance, headwater streams have greater potential to recover naturally from ecological degradation than higher-order streams. Headwater streams in agricultural setting are thus ideal sites for the restoration of ecological services that are likely to benefit at the watershed scale (Lowe & Likens, 2005; Nadeau & Rains, 2007; Creed et al., 2017; Schilling et al., 2018). Our results indicate that despite intense morphological perturbations, the historic floodplains of straightened headwater streams act as preferential areas of hydrologic connectivity in an agricultural lowland environment. While backfill material placed upon the floodplain limits the extent of surficial flooding, it appears they have no substantial effect on subsurface hydrologic connectivity. These findings thus provide useful arguments to put in place restoration programs targeting these environments.

This study also highlights that it is possible to interpret head fluctuations within historic floodplains of straightened headwater streams based on the pre-disturbance geomorphological configuration of these environments, as proposed by Larocque et al. (2016). Understanding the

nature of deposits and the hydrogeomorphological components (e.g., historical position of meanders and hillslopes) can help restoration planners classify the historic floodplains and the abandoned meanders according to their potential level of hydrologic connectivity. Using LiDAR images, historical photos, and maps of surface deposits, restoration planners can delineate, throughout a watershed, areas of strong hydrologic connectivity surrounding the apex of ancient meanders, along straightened headwater streams in agricultural environments.

Knowing areas of high hydrologic connectivity allows restoration projects to better align with the ecological services targeted for restoration (Phillips, 2013). For example, results from this study suggest that the transient water storage in the historical floodplain of straightened streams occurs during hydrological events. Therefore, active restoration measures such as removing backfilling material above abandoned meanders (ex. PB site) or removing embankments (Addy & Wilkinson, 2021) represent potential means of increasing water storage during hydrological events and can therefore contribute to flow regulation by reducing peak streamflow. Integrating the specific configuration of the historical floodplain in the planning of riparian buffers could also help improve their effectiveness in intercepting agrochemical pollution (Kaushal et al., 2008; Hénault-Éthier et al., 2017). The presence of revegetation at the RM site illustrates that, in the absence of floodplain backfilling and with a regional aquifer highly connected to the floodplain through the hillslope, passive restoration of the historic floodplain can lead to the recovery of various types of riparian wetlands. Evidently, for this passive restoration to significantly impact flow regulation, pollutant control, habitat diversification, and recreational uses at the watershed scale, many abandoned meanders along straightened channels must be restored.

However, large-scale restoration measures providing sufficient space for hydrogeomorphological processes to operate (e.g. Kondolf, 2012; Biron et al., 2014; Massé et al., 2020) can be complex in the context of lowland agricultural watersheds with many landowners along a given reach. As key residual components of the hydrologic connectivity of straightened headwater streams, the artificially abandoned meanders could be used to develop floodplain restoration strategies adapted to the scale of the land owned by farmers. Abandoned meanders are distinct, relatively small, and easily identifiable physical spaces that facilitate discussions with landowners to better understand the purpose of a restoration project. From a social acceptability perspective, it is also easier to initiate a restoration project at this scale than to limit agricultural activities indiscriminately along

complete portions of a stream. An abandoned meander of a degraded agricultural stream is therefore an excellent "feature" to popularize the concept of hydrologic connectivity in its simplest expression.

2.5. Conclusion

Like their lowland meandering stream counterparts, alluvial deposits that form the historic floodplain of straightened streams act as a continuum zone connecting surface water to shallow regional groundwater. Our high-resolution spatiotemporal piezometric dataset suggests that the abandoned meanders and, more specifically, their apex, exhibit a higher level of hydrologic connectivity than the rest of the historical floodplain. The hydrogeomorphological configuration of the former meanders, with a marked surface and subsurface depression at the meander apex, results in a convergence of hydrological flows from the hillslopes and the rest of the floodplain toward the apex zones during hydrological events.

Our findings suggest that the degree of alteration of subsurface hydrological exchanges in straightened lowland streams is relatively low compared with surface exchanges adversely impacted by channel incision and floodplain backfilling. It therefore follows that despite a drastic change in channel morphology and the floodplain features that limits surface exchanges, a straightened stream presents head fluctuation patterns within its historical floodplain that are relatively similar to those in a meandering lowland stream during hydrological events when the water level remains below bank level. It is reasonable to assume that the same potential to form diverse and sustainable riparian habitats in former meanders of straightened streams is similar to that of natural abandoned meanders. The Ruisseau Martin site provides useful evidence of this, with its abandoned meanders occupied by forested and shrub swamp and herbaceous marshes (unpublished data on vegetation surveys). There is therefore more than meets the eye in these degraded environments.

Further studies should focus on water exchanges operating within straightened streams, their historic floodplain, and the hillslopes at different spatial scales and under various hydrological regimes. Relevant questions need to be investigated concerning the role of local hydrological exchanges or pressure transfers in terms of surface water temperature regulation, solute transformation, and discharge regulation at the watershed scale. For example, it would be insightful to quantify transient water storage in the different apex zones bordering a straightened lowland

stream at the scale of a predominantly agricultural watershed. Hydrogeological or hydrogeochemical modelling of abandoned channels in lowland agricultural settings could potentially identify restoration approaches, active or passive, that maximize the functions of water storage and nutrient fixation. Filling this knowledge gap might contribute to help counter the rapid ecological degradation of agricultural watersheds in lowland settings by restoring ecological processes in their headwater streams (Lowe & Likens, 2005; Schilling et al., 2018). Developing restoration approaches centered around the remaining hydrologic connectivity occurring in these streams floodplains appears essential to increase their natural resilience, since they often lack the stream power to recover sediment-transport processes (Brookes, 1987; Kondolf, 2012; Kristensen et al., 2013).

With increased access to LiDAR data, combined with the analysis of historical aerial photos and surface deposits, it is possible to delimit historical floodplains of straightened lowland headwater streams and use this information as a critical first step in planning restoration strategies at the watershed scale. Where social acceptability exists among agricultural producers, it may then be possible to put forward a restoration plan for these streams, one abandoned meander at a time.

Liaison paragraph:

Taken together, these findings suggest that residual hydrological connectivity offers valuable opportunities for restoration, but their operational use requires a more explicit quantification of exchange dynamics. To this end, the following chapter introduces a conceptual MODFLOW model that explores how geomorphological context modulates groundwater–surface water fluxes in a degraded agricultural reach.

Chapter 3: Modelling subsurface hydrological exchanges between a straightened lowland agricultural stream and a degraded floodplain at the reach scale

Summary:

Lowland agricultural streams are often heavily modified by channel straightening and floodplain backfilling, which disrupt hydrological connectivity and degrade ecological functions sustained by surface–groundwater exchanges. In contexts where extensive mechanized interventions are costly and face low social acceptability, understanding residual subsurface processes is essential to support effective and scalable passive restoration. This study investigates groundwater exchange dynamics within a straightened and backfilled reach of an agricultural stream in southern Quebec using a three-dimensional conceptual hydrogeological model (MODFLOW). Twelve steady-state scenarios were used to evaluate the sensitivity of groundwater flow volumes and directions to variations in hydraulic conductivity, recharge, and material thickness across key geomorphological units. Results indicate that the structure of subsurface flow is strongly controlled by material heterogeneity, with coarse abandoned-meander sediments acting as disproportionately important nodes of groundwater exchange relative to their spatial extent. In contrast, the backfill unit exerts a strong modulatory effect on flow paths, where reduced hydraulic conductivity redirects groundwater toward underlying alluvium. These findings demonstrate that subsurface connectivity along straightened streams is highly variable and strongly conditioned by the legacy of past human interventions. By identifying the buried geomorphological features that retain high hydrological functionality, the modeling supports a more strategic placement of passive restoration measures, such as selective riparian revegetation and buffer expansion over abandoned meanders, thereby promoting ecologically meaningful outcomes while respecting the socio-economic constraints of agricultural landscapes.

3.1 Introduction

3.1.1 Rationale

In many lowland regions, small agricultural streams have been drastically altered by mechanical interventions, including channel straightening and dredging (Huang et al., 2010; Tockner & Stanford, 2002). Large areas of abandoned alluvial plains and meanders, resulting from channel straightening, have also been backfilled (Rousseau & Biron, 2009). Alluvial plain refers to the geomorphological form, relatively flat and elongated, formed of sediments transported and deposited by the contemporary flow of a stream (Wohl, 2021). These morphological modifications

have significantly altered hydrological exchanges, both surface and subsurface, between many small lowland rivers and their alluvial plains, and resulted in losses of ecological functions, such as hydrological regulation, habitat creation, and biogeochemical transformations of pollutants and nutrients(Kondolf et al., 2006; Graf et al., 2016; Díaz-Redondo et al., 2018; Petsch et al., 2023). Indeed, surface and subsurface hydrological exchanges between a river system and its alluvial plain control many other exchanges of materials impacting ecological processes, such as sediments, nutrients, organic matter including dead wood, as well as living organisms (Wohl, 2021). More and more institutional and governmental stakeholders are sounding the alarm about the consequences of high levels of disturbance in small lowland streams, particularly in agricultural settings (Hill, 2011; Colvin et al., 2019; Locke, 2024).

In parallel, several studies highlight the potential of restoring small lowland streams, including their floodplains, to enable the return of ecological functions(Lowe & Likens, 2005; Creed et al., 2017; Schilling et al., 2018; Couture et al., 2024). Studies have documented, for example, that the removal of riparian infrastructure, such as dikes or backfill deposits (Clilverd et al., 2016) or the excavation of wetlands (Mitsch et al., 2008) within the alluvial plains of lowland streams, favors surface hydrological exchanges (i.e. flooding), as well as exchanges between surface water and groundwater. However, the implementation of mechanical restoration measures in agricultural environments aimed at re-establishing surface hydrological connectivity can come up against significant obstacles, notably due to the high associated costs and sometimes limited social acceptability depending on the region (Boyer-Villemaire et al., 2021). Faced with these challenges, it is becoming imperative to consider restoration approaches for small, degraded streams in agricultural areas that limit mechanized modifications of the streams and their riparian environment and build on hydrological and hydrogeomorphological processes that are still active. To ensure the success and acceptability of such passive restoration actions, a thorough understanding of the persistent exchange processes between the surface waters of small lowland streams and the groundwater of riparian environments is essential (Middleton, 2002; Mitsch et al., 2008; Huang et al., 2010; Boano et al., 2014; Wohl, 2021).

3.1.2 Current understanding

Surface and groundwater exchanges within alluvial systems have been studied for decades (Pinder & Sauer, 1971; Lemon, 2020). The main objectives pursued by these studies have been to quantify

and understand the control mechanisms responsible for the high spatio-temporal variability of water exchange and water table fluctuations in various types of fluvial environments, particularly in small headwater streams in montane environments (Mueller Price et al., 2016) , on wide gravel rivers (Brunke et al., 2003; Cardenas, 2008) and on meandering rivers (Boano et al., 2006).

Three main types of subsurface hydrological exchange operating between a river, its riparian environment and its regional environment (Cranswick & Cook, 2015) have been documented, namely 1) hyporheic exchanges, which are relatively rapid movements of water between a river and the sediments of its bed or banks, induced by morphological variations 2) infiltration or exfiltration of water into the riparian environment, referred to as "bank storage" (Bates et al., 2000) which are generated by fluctuations in surface water levels, and 3) exchanges with shallow aquifers in the floodplain which are in turn connected to regional aquifers (Flipo et al., 2014; Winter, 1999). The hydraulic gradient between the river, its floodplain and its hillslopes generally dictates the direction of flow, either towards the river, towards the hillslope or even parallel to the flow of the river (Woessner, 2000; Kalbus et al., 2006). The intensity of groundwater flow is largely dictated by the hydraulic conductivity of riparian or bed materials (Bates et al., 2000). Various studies have also documented the influence of bank slope (Doble et al., 2012), bed morphology (Harvey & Bencala, 1993; Wu et al., 2024), channel sinuosity (Boano et al., 2006; Cardenas, 2008) or the shape of hydrographs (Ha et al., 2008) on the intensity and spatio-temporal variability of surface and groundwater exchange in alluvial environments.

Several studies have focused on the exchange processes and controlling parameters of groundwater fluctuations in alluvial plains (Winter, 1995; Jung et al., 2004; Flipo et al., 2014; Wohl, 2021). Alluvial plains are documented as hydrological convergence zones, collecting surface and groundwater from hillslopes and streams, as well as from local precipitation (Mertes, 1997; Woessner, 2000). They are generally characterized by shallow water tables with an upper unsaturated zone (vadose zone) usually close to the saturation point (Gillham, 1984; Burt et al., 2002). Rapid fluctuations in the water table can be linked to precipitation events (Lewandowski et al., 2009), but can also occur when surface water levels in the channel rise or fall rapidly, leading to pressure changes in the surrounding sediments (Jung et al., 2004). These pressure changes propagate rapidly through the saturated sediments, at velocities far greater than those of subsurface flows (Vidon, 2012; Buffin-Bélanger et al., 2016). The propagation velocity of these pressure

waves increases with the thickness of the aquifer, the hydraulic conductivity of the materials and the duration of water fluctuation in the channel (Lewandowski et al., 2009). It is also interesting to note the role of hydrogeomorphological processes responsible for the formation of alluvial plains on surface and groundwater exchanges, notably by influencing the thickness and size of alluvium (Sophocleous, 2002; Cabezas et al., 2008; Lehr et al., 2015; Larocque et al., 2016). For example, coarse alluvial deposits, forming the base of an alluvial plain formed by a formerly meandering river, can constitute zones of preferential groundwater flow (Duval & Hill, 2006). These same processes affect the spatial and temporal distribution of biogeochemical processes within alluvial plains, notably denitrification and phosphorus sorption processes (Noe et al., 2013, 2019; Wohl, 2021).

Several field and numerical methods have been employed to study these hydrological exchanges, at different spatial and temporal scales (Kalbus et al., 2006; Rosenberry & LaBaugh, 2008; Biehler et al., 2023). At the local scale down to the reach, the methods frequently employed are piezometric monitoring (Burt et al., 2002; Lewandowski et al., 2009; Vidon, 2012; Buffin-Bélanger et al., 2016; Marchand et al., 2022) and physico-chemical tracers, such as radon and water temperature (Cranswick et al., 2014; Biehler et al., 2020; Wilson et al., 2024). At the reach to regional (catchment) scale, hydrological and hydrogeological modelling, analytical methods (Pozdniakov et al., 2022) and distributed flow measurements (Biehler et al., 2023; Batlle-Aguilar et al., 2014) are more frequently employed.

Numerical models are frequently used to analyze the complex exchange of surface and groundwater in river environments (Pinder & Sauer, 1971; Frei et al., 2010; Karan et al., 2021; Li et al., 2024). Numerical modeling is the only global predictive analysis method, adaptable to a wide range of river and soil morphologies (Ferraz, 2022). The 3D finite-difference numerical model MODFLOW (McDonald & Harbaugh, 1988) is the most commonly used model for simulating surface and groundwater interactions in different alluvial environments, at different spatial scales (Ferraz, 2022). For example, MODFLOW has been used to quantify flood attenuation by *bank storage* in large gravel rivers at the reach scale (Squillace, 1996), to quantify the contribution of groundwater in a montane basin (Betterle & Bellin, 2024), to measure flows between a river and its alluvial plain in a lowland environment at the sub-basin scale (Krause et al., 2007; Schilling et al., 2012), as well as to quantify hyporheic exchanges within small streams

with steep slopes (Wondzell et al., 2009) or moderate slopes (Wroblicky et al., 1998), on a reach scale.

However, while MODFLOW is effective for modeling water flows, it has limitations when it comes to modeling thermal exchanges or biogeochemical transformations, due to the complexity of these processes. In particular, modeling the exchange of nutrients and geochemical compounds remains a challenge, often requiring couplings with specific models such as HydroGeoSphere or additional modules to capture chemical and biological interactions (Sudicky et al., 2008; Li et al., 2017). In the context of ecological restoration of degraded streams in agricultural environments, the main objective is to effectively model hydrological exchanges between surface and groundwater, as these exchanges play a crucial role in recharging aquifers and regulating water levels, thus directly influencing nutrient dynamics and thermal conditions conducive to increased biodiversity.

3.1.3 Gaps in understanding

Although current studies offer a relatively thorough understanding of surface and groundwater exchange in alluvial environments, most have been carried out in the context of coarse-grained streams and alluvial plains. There is a notable gap in research on these dynamics in fine-grained stream and floodplain (Lemon, 2020), including in agricultural lowland headwaters (Van Stempvoort et al., 2021). Alluvial plains generally present high complexity due to their heterogeneous structure, influencing groundwater dynamics significantly (Sophocleous, 2002).

Furthermore, the majority of studies focus on river environments with no or little alteration, resulting in gaps in our understanding of highly modified lowland streams, as found in agricultural environments (Schilling et al., 2004; Hénault-Éthier et al., 2017). Some studies have certainly modeled surface and groundwater exchanges within small straightened or incised lowland streams (Cey et al., 1998; Kasahara & Hill, 2008), but most have documented only hyporheic exchanges within these systems. To our understanding, very few field studies (Schilling et al., 2004; Marchand et al., 2022: Chapter 2) and no numerical modelling have so far been used to document the parameters controlling exchanges between straightened lowland streams, their modified alluvial plain and their hillslope.

A more detailed understanding of the parameters controlling subsurface hydrological exchanges within straightened lowland stream systems is essential to better understand the potential ecological gains from passive restoration measures (Stanford & Ward, 1993). This knowledge needs to be acquired on a reach scale, in line with the scale frequently considered for restoration projects in agricultural areas, given the high fragmentation of the territory between several landowners. This is a first step towards convincing funding agencies and landowners of the restoration potential of certain sites, which could play a pivotal role in the implementation of more sustainable, scientifically-based environmental management practices for small, degraded streams in agricultural areas.

3.1.4 Aim and objectives

This research aims to provide a scientific basis to support process-based restoration approaches for small straightened streams in lowland agricultural environments. The main objective is to study the exchange dynamics (volumes and directions) between surface and groundwater within a straightened stream reach, a backfilled alluvial plain and a regional lowland environment using a conceptual hydrogeological model (MODFLOW), which will enable these interactions to be studied in a complex environment with fine resolution (Schulz, 2023; Thompson et al., 2023). A straightened stream reach in the St. Lawrence lowlands of Quebec, already selected for a passive restoration pilot project (Marchand & Biron, 2025: Appendix D), is employed as a conceptual model to address the following specific objectives:

- Quantify hydrogeological flows, including their direction and intensity, between the different geomorphological units forming the alluvial plain of a straightened lowland stream, including its abandoned meanders.
- Analyze model sensitivity to variations in key parameters such as hydraulic conductivity, recharge and heterogeneity of geomorphic unit configuration
- Evaluate the relevance of the hydrogeological model to guide passive restoration strategies for small, degraded streams in agricultural areas.

3.2. Methodology

3.2.1 Study site

The Pot-au-Beurre River is located in the Montérégie-Est region of Quebec, Canada. It is a tributary of the Yamaska River, flowing exclusively over the lowland deposits of the St. Lawrence River valley. The studied reach, named Branch 13, is a second-order Strahler stream that drains a 12.8 km² watershed, made up mainly of cultivated fields (approx. 90%) with corn, soybean and forage crops. The study site is a 280 m-long stretch of the river at around 15 m above mean sea level. The current channel has an average width and depth of 4 m and 1.5 m respectively. Average annual flow is 0.2 m³/s, with peaks of just over 3 m³/s. Historically, the river was meandering. In the studied reach, the alluvial plain was between 31 and 57 m wide, with three meanders ranging in amplitude from 17 to 40 m (Figure 3.1 (A)). Prior to 1990, this reach was straightened, and fill material was added on top of the alluvial plain, significantly altering the original surface topography (Figure 3.1 (B)). Today, shallow, semicircular depressions mark the locations of the former meanders (Figure 3.1 (C)).

Since 2022, the site has been the focus of a pilot project to restore the stream and its alluvial plain (Marchand & Biron, 2025, Appendix D). Planned measures include passive actions, such as crop removal and non-assisted revegetation, as well as the replacement of an undersized culvert to promote sediment-transport processes (Figure 3.2). These restoration efforts aim to re-establish riparian wetland flora and fauna habitats, as well as reduce agricultural pollutant and nutrient inputs within the study reach, while retaining the support of the landowners.

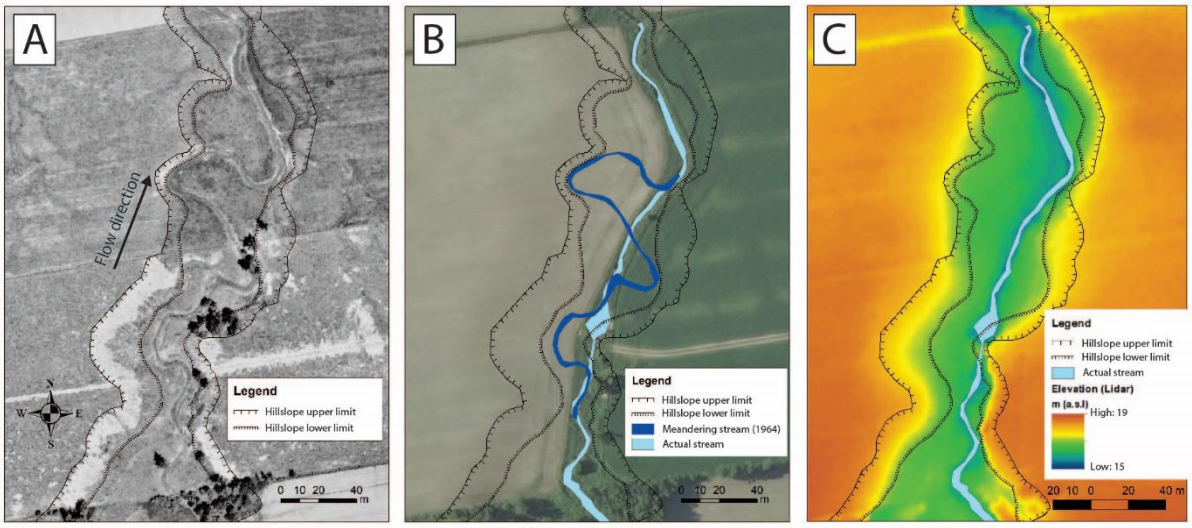


Figure 3.1: Historical photos of the Pot-au-Beurre River study reach (branch 13) with the location of the historic alluvial plain slopes: (A) as a meandering stream in 1964, (B) as a linearized stream in 2009 and (C) digital elevation model from a LiDAR survey (Photo credit: Gouvernement du Québec, 2024).

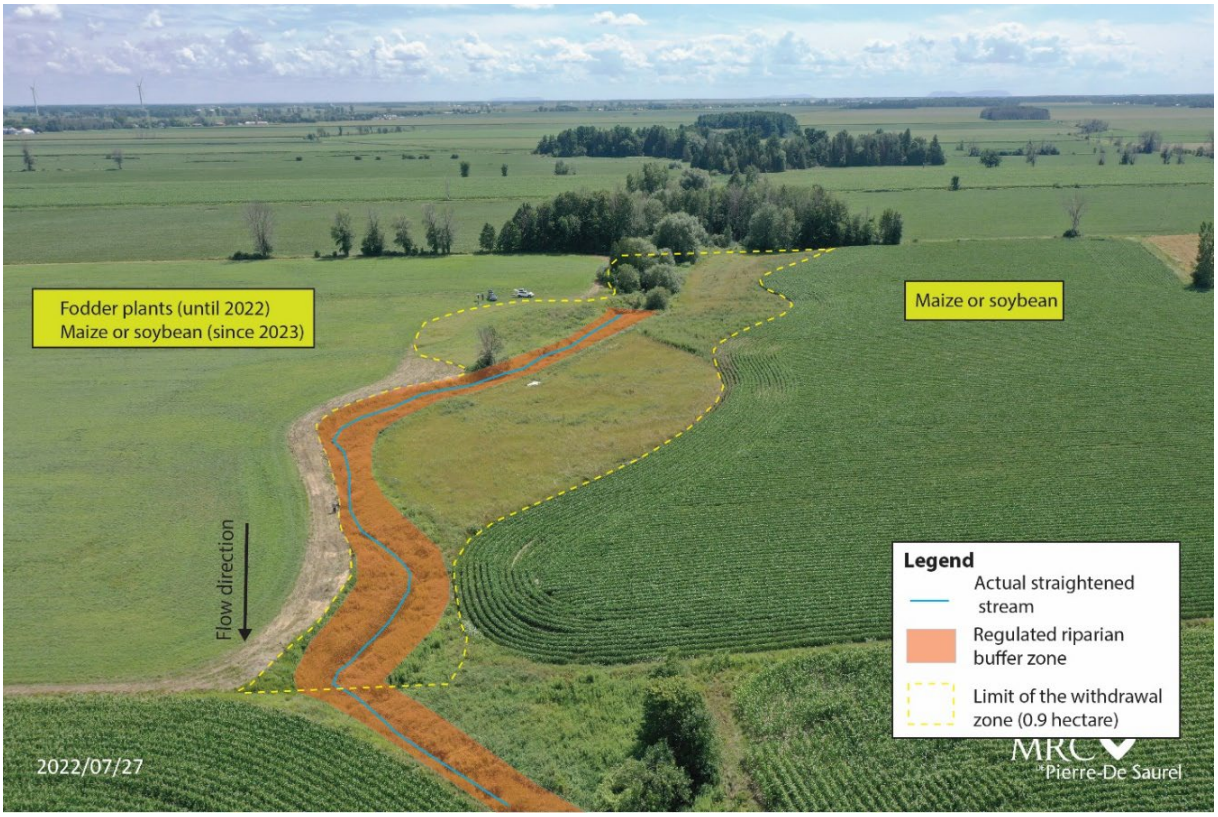


Figure 3.2. Aerial view (by drone) of the restoration site (July 2022). Photo credit: MRC Pierre de Saurel

3.2.2 *Field data*

Geological investigations, including a series of drilling, were used to characterize the stratigraphic architecture of the site (Marchand et al., 2022: Chapter 2). Over 40 boreholes between 1.75 and 2.80 m were drilled using a manual auger (Figure 3.3). Granulometric analyses were carried out on sediment samples collected at various depths during drilling. A sieve column was used to analyze the coarse fraction (> 2mm), while the fine fraction (2mm- 63 microns) was analyzed using a sedimentology column (Komar & Cui, 1984).

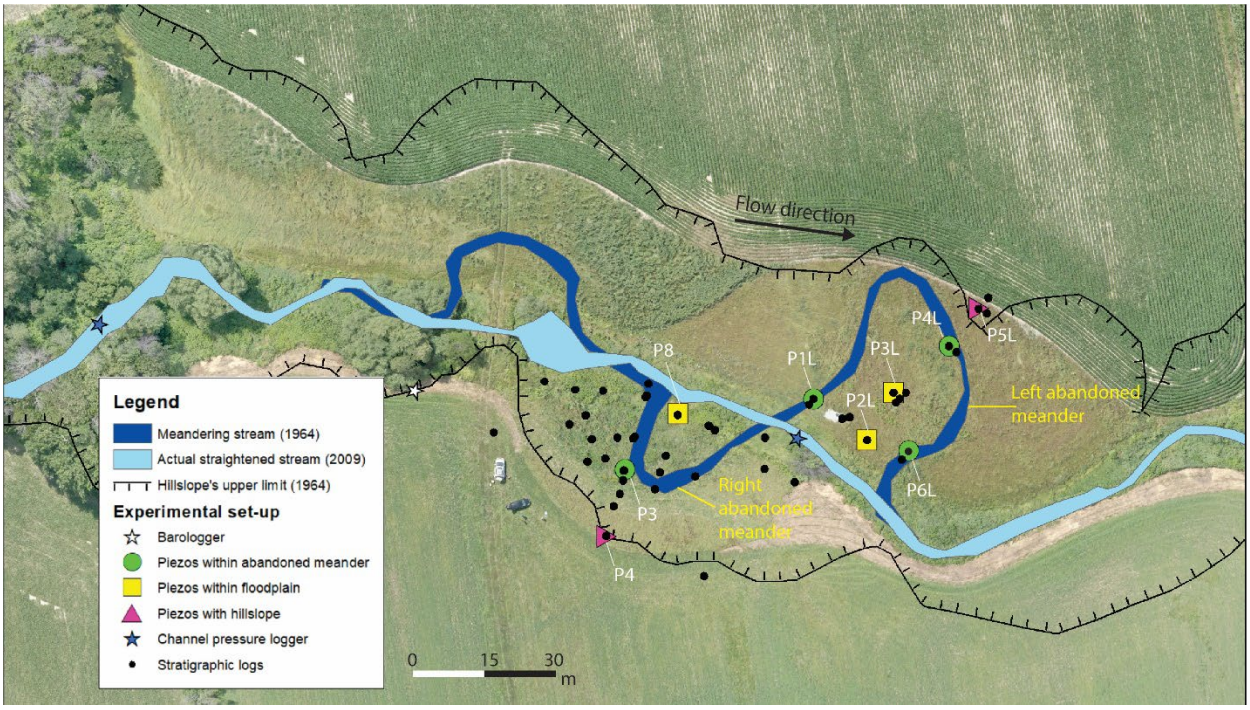


Figure 3.3. Experimental set-up at the restoration site on branch 13 of the Pot-au-Beurre River. The piezometers and pressure probes identified provided the observation data for calibration of the hydrogeological model. Stratigraphic borings, identified by a black dot, were carried out using a 2.8 m manual auger during the summers of 2018, 2019 and 2022. (Photo credit: MRC Pierre-de-Saurel)

The study site can be divided into six main stratigraphic units (Figure 3.4). (1) The alluvial plain is composed of graded alluvial sediments ranging from silty sand in the upper strata to medium sand in the lower portion of the deposit. Total alluvial thickness varies between 0.9 and 2 m. The thickness of the alluvium in the abandoned former meander beds is slightly greater. (2) In the former meanders, at the apexes, the bottom 30 to 50 cm is composed of coarser sands and a small proportion of small gravels. There is also a high proportion of dead wood in the former meander bends. The alluvial unit (the former alluvial plain) is covered by (3) silty loam fill, varying in

thickness from around 50 cm near the actual channel to around 1 m at the edge of the former hillslope. Backfilling work on the study site is known to have been carried out by mechanically reworking the local deposits. The alluvium and backfill material are thus embedded in a sandy loam forming (4) the regional superficial unit. This unit is approximately 2.5 m thick at the study site. It rests on a layer of gleyified silty clay, indicative of a quasi-permanent state of saturation. It should be noted that it was not possible to adequately sample (5) the lower regional unit, notably because the auger had a depth limit of 2.80 m, and because the clay material liquefied when the samples were brought up. The study by Carrier et al. (2013) suggests that in the study area, the regional unit corresponds to a shallow-water littoral deposit associated with the Champlain Sea, and that the thickness of the clay deposits varies between 20 and 25 m over bedrock. Finally, (6) the present bed of the straightened stream consists of fine sand and silt (similar to that found in the alluvial plain), with a thickness varying between 30 and 50 cm.

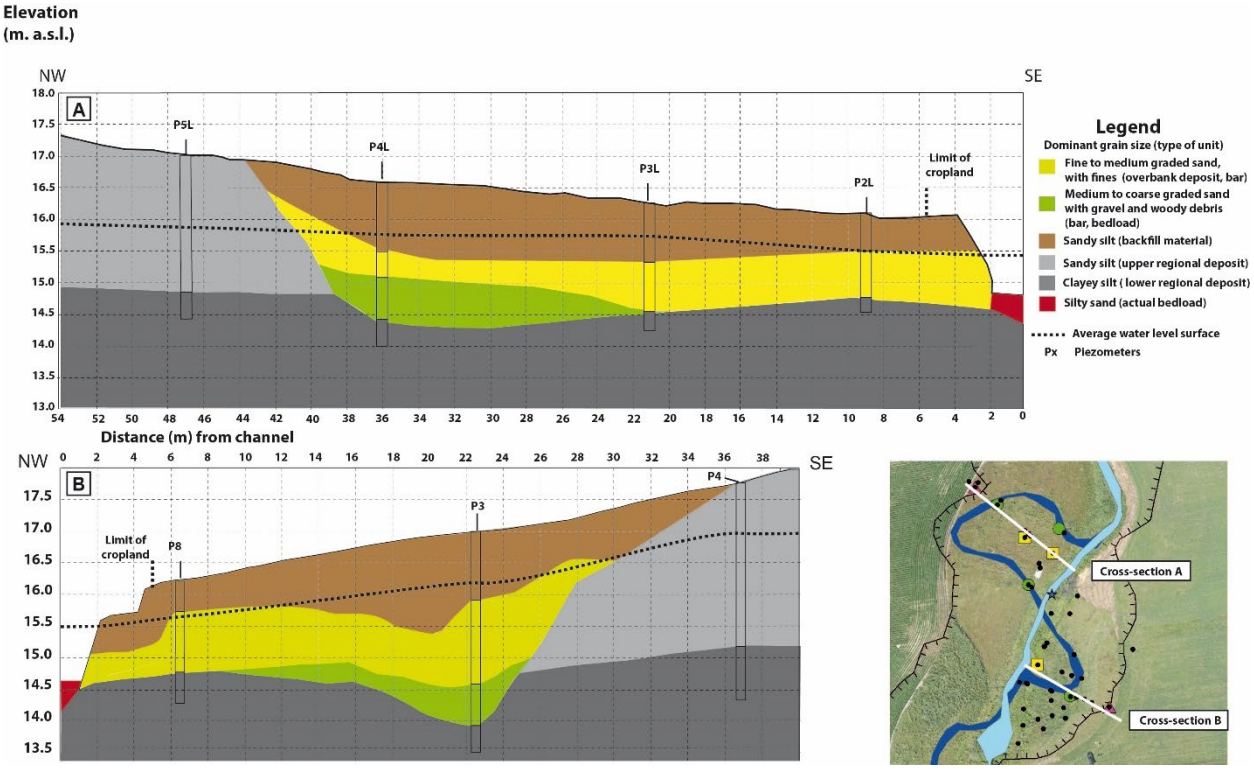


Figure 3.4. Cross-sectional stratigraphic profiles of the alluvial plain of branch 13 of the Pot-au-Beurre at the level of the abandoned meander on the left (A) and the abandoned meander on the right (B). The six main stratigraphic units are shown, along with the mean piezometric and surface water level, as established for the period October 2022-September 2023.

The restoration site has been the subject of high-resolution piezometric monitoring since 2017 (Marchand et al 2022: Chapter 2). Initially, seven piezometers were installed in the abandoned

meander on the right bank. In 2019, 4 new piezometers were installed within the same abandoned meander. At that time, the (voluntary) withdrawal of crops by farmers was limited to the abandoned meander on the right bank. The analysis of these piezometric series is discussed in Marchand et al. (2022: Chapter 2). In 2022, with the implementation of the passive restoration project, farmers agreed to withdraw their cultivation throughout the reach in exchange for financial compensation. As a result, 6 new piezometers were installed in the abandoned meander on the left, while only three piezometers were retained in the abandoned meander on the right. So, since 2022, nine piezometers have been recording, at hourly intervals, fluctuations of the shallow water table found within the site's historic alluvial plain (Figure 3.3). Of these, four piezometers are located directly in a former abandoned meander, three piezometers are located in what used to be the inner bank of these meanders, and two are located outside the alluvial plain, at the edge of what used to be the hillslope of the alluvial plain. These nine piezometers recorded water levels during the years 2022-2023 and provided the observational data used for calibration of the hydrogeological model. The first part of the Result section summarizes the main observations of this monitoring year.

3.2.3 MODFLOW modeling

3.2.3.1 Creating the conceptual model grid

A conceptual hydrogeological model based on the configurations of the study site was built in MODFLOW (McDonald, 1988) via the GMS interface software. The methodological guides provided by GMS and personal communications with hydrogeology professor Marie Larocque (UQAM, Montreal, Canada) provided the guidelines for this work. The main objective was to simulate groundwater fluctuations and exchanges between a small straightened stream, a backfilled alluvial plain and adjacent lowlands.

The model grid covers an area of 250 m x 200 m x 10 m, which encompasses approximately the dimensions of the stream drainage basin directly adjacent of the studied reach (Figure 3.5). The modeling grid comprises 10 vertical layers with horizontal cells measuring 1 m x 1 m and varying in thickness from 0.3 to 1 m. A digital elevation model derived from a LiDAR survey was used to model the grid surface, while a D-GPS survey was used to map the stream longitudinal profile. A fine spatial resolution was adopted to capture the relatively complex geometry of the alluvial materials, including fine sand and coarse sand alluvium in the abandoned meanders, as well as regional materials composed of an upper layer of sandy loam and a lower layer of loamy clay. This

strong material discretization aims to deepen our understanding of the roles played by the different geomorphological units in groundwater transfers between the stream and its riparian environment, in line with the recommendations of various studies (Bradley, 1996, 2002; Wondzell et al., 2009).

The conceptual hydrogeological model created in MODFLOW includes only two types of boundary conditions: a River condition to simulate surface water level fluctuations in the straightened channel, and a Recharge condition to simulate net recharge in the riparian zone. For the River condition, the longitudinal profile of the water surface in the stream was interpolated from the mean water levels recorded in the two pressure probes located upstream and downstream along the study reach (Figure 3.3) and then applied to a linear shapefile. A D-GPS-based topographic profile of the river channel showed that there were no significant breaks in gradient within the study section. Recharge values were discretized between three distinct surface shapefiles (Figure 3.5 (D)) representing the left bank regional environment, the right bank regional environment and the alluvial plain zone, in order to simulate the influence of farming practices and surface deposit texture, which are known to influence recharge values (Dubois et al., 2021).

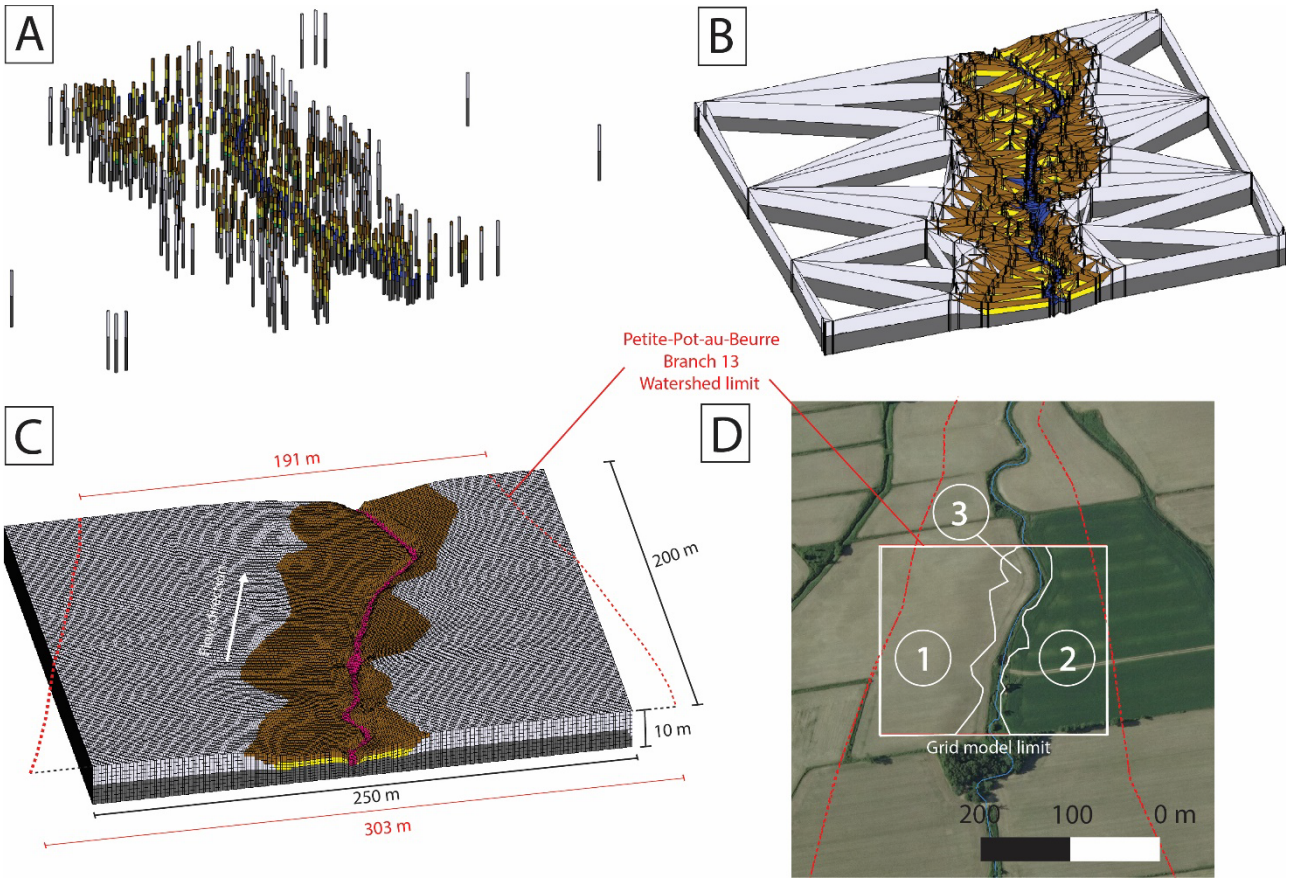


Figure 3.5: Construction of the model grid for the study site on branch 13 of the Pot-au-Beurre river: (A) creation of six conceptual stratigraphic column types, (B) creation of cross-sections using the GMS interpolation tool and (C) creation of the model grid, comprising six distinct stratigraphic units. The dotted red line indicates the approximate boundary of the river watershed adjacent to the studied reach. The model grid's boundary is shown in Box D. The recharge zones used as model boundary conditions are also shown, i.e. the regional environment on the left bank (1), the regional environment on the right bank (2) and the alluvial plain zone (3).

The three-dimensional architecture of the modeling grid is based on the thickness and spatial distribution of the stratigraphic units identified by drilling by Marchand et al. (2022). The modeling grid was created by initially establishing six typical boreholes or stratigraphic sequences that can be found on the study type (Figure 3.5 (A)). These conceptual boreholes were then spatially distributed using GIS software based on the interpretation of alluvial forms historically found on the site, obtained from historical aerial photos (pre-1990) of the site, among other sources. All conceptual boreholes were then transferred to MODFLOW, using the GMS interface software, from which cross-sections could be constructed (Figure 3.5 (B)). The GMS software was then used to build a three-dimensional model from these stratigraphic cross-sections (Figure 3.5 (C)).

The model grid therefore comprises six material units as follows (Figure 3.6): coarse alluvium at the location of the abandoned meanders (material ID #1), fine alluvium in the rest of the alluvial

plain (material ID #2), sandy silt in the upper regional unit (material ID #3), fine sand in the actual stream bed (material ID #4), silty clay in the lower regional unit (material ID #5) and silty sand in the backfill over the alluvial plain (material ID #6). To simplify the stratigraphy of the conceptual hydrogeological model, the lower regional unit (material ID #5) is considered to occupy all the bottom layers of the model grid. The strategy used to select the hydraulic conductivity values for each unit and to determine the recharge values to be used for the different areas of the model grid in the MODFLOW model calibration process is described below.

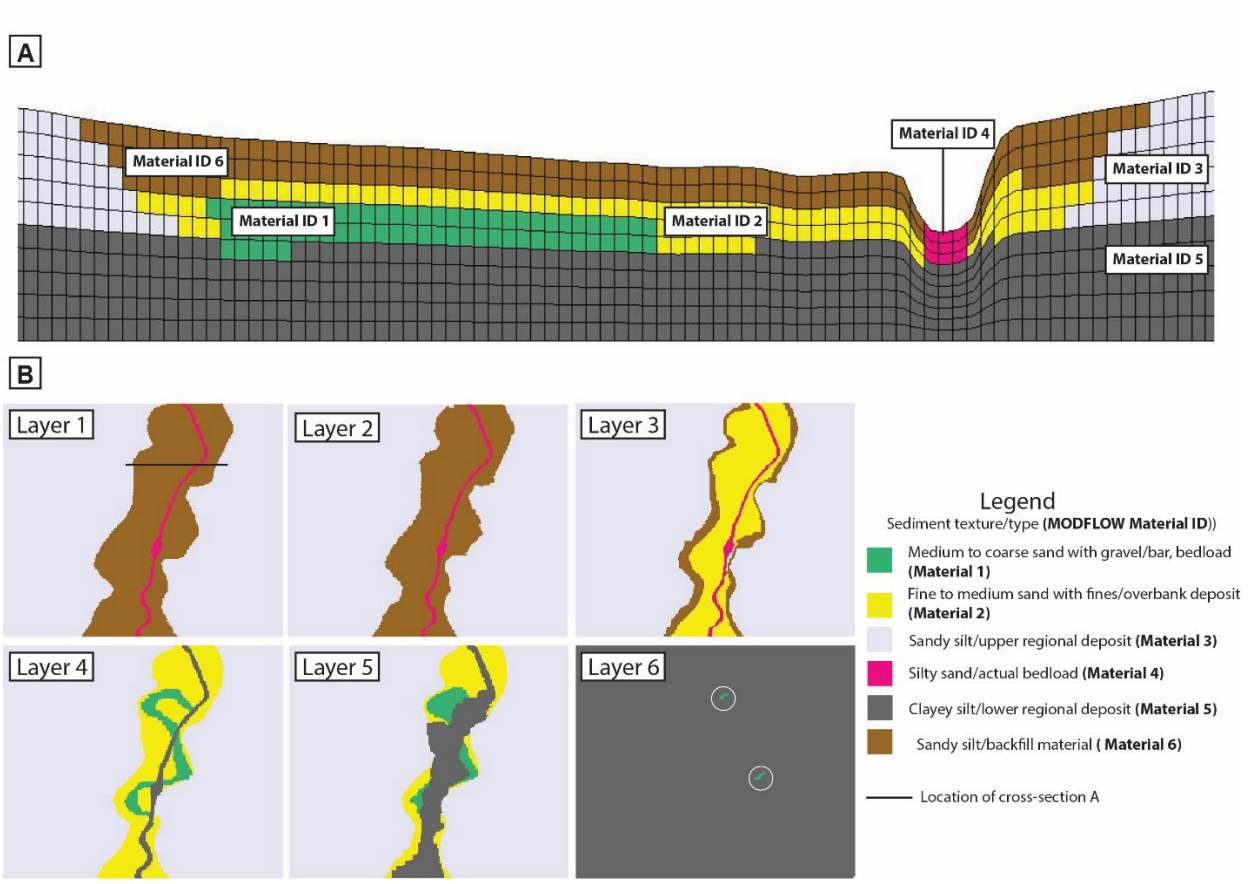


Figure 3.6. Spatial configuration of material units represented in the MODFLOW modeling grid: (A) cross-sectional view and (B) plan view in the first six layers of the modeling grid. Note in layer 6, circled in white, the presence of coarse alluvial material found in the apex of meanders. Layers 7 to 10 are entirely formed by the lower regional unit (silty clay) and are not shown here in Box B.

3.2.3.2 Model calibration

The calibration process represents a systematic method of adjusting model parameters so that simulations correspond as closely as possible to observed field data for given conditions. Recharge and hydraulic conductivity (K) are two of the main parameters modulated during the calibration

of a MODFLOW model. These parameters have a significant impact on the way water moves through the aquifer and interacts with the model's hydrogeological characteristics.

The process of calibrating a MODFLOW model, by modulating recharge and hydraulic conductivity (K) parameters, raises challenges mainly due to their interdependence (Wondzell et al., 2009). Indeed, recharge and hydraulic conductivity are linked by complex dynamics that directly affect simulated piezometric levels. An increase in recharge tends to raise these levels, illustrating an addition of water to the system, while an increase in hydraulic conductivity favours a faster flow towards streams or other outlets, which can reduce piezometric levels.

This inter-relationship can lead to ambiguities during calibration, as different combinations of recharge and conductivity values can produce similar results, making it difficult to identify the "true" values or the most likely parameters. To address these challenges, it is essential to establish ranges of values for recharge and hydraulic conductivity that are not only supported by empirical data and field observations, but also consistent with the type of hydrogeological environment being studied. These ranges must be flexible enough to accommodate natural variations, yet precise enough to effectively guide calibration.

On the other hand, the methods used to estimate recharge and hydraulic conductivity are often sources of great uncertainty (Condon et al., 2021). These uncertainties stem from the spatial variability of hydrogeological properties, the complexity of groundwater-surface interactions, and the limitations of models in terms of representing these complex processes. Consequently, calibration of MODFLOW requires a careful and considered approach, often involving successive iterations and critical evaluation of calibration results against available hydrogeological and environmental knowledge (Scanlon et al., 2002).

The strategy here employed to determine the net recharge and hydraulic conductivity values used in simulations under permanent and transient conditions in the MODFLOW software was therefore to establish ranges of values for the two parameters based on literature data and empirical methods (Andualem et al., 2021; Baker et al., 2022) and then to use these ranges as limits in an automated calibration process with the PEST module. This module is a model calibration tool that adjusts MODFLOW model parameters, such as recharge and hydraulic conductivity, with the aim of minimizing the difference between simulated results and actual measured data. Hourly water level data measured between October 2022 and September 2023 by the nine piezometers installed on

the alluvial plain and in the regional deposits of the study site were used to determine the observation values. The following sections detail the data used to establish the ranges of values employed in calibration.

Recharge estimates

Net recharge (estimated in mm per year) corresponds to the thickness of water reaching a groundwater table over the course of a year (Scanlon et al., 2002). Estimating recharge therefore initially requires quantifying precipitation water. Hourly precipitation data from the Pierreville Station, located 13 km from the study site, were used to quantify the volumes of water precipitated on the reach that are then available for infiltration or runoff (MELCCFP, 2023). It is possible that precipitation quantities and their temporality differ slightly between the study site and the meteorological station, but this variability is considered negligible. Precipitation data from the Pierreville station puts annual precipitation at 1305 mm at the study site between October 2022 and September 2023. It is important to note that July 2023 was a particularly rainy month, with a total of 266 mm of precipitation compared with a climate normal average of 105.6 mm.

Estimating net recharge from precipitation volumes requires more data, some of which can be highly variable at the scale of the study site (Healy & Cook, 2002). This is due in part to the fact that a portion of precipitation does not infiltrate the soil, but rather runs off the surface. Catchment characteristics (topography, vegetation cover and soil conditions), rainfall event characteristics and soil saturation levels are all variables that influence surficial runoff (Merz & Blöschl, 2009). Also, a second portion of precipitation water, which does not run off, is returned to the atmosphere via evapotranspiration processes (Van Stempvoort et al., 2021). Several parameters can also influence the amount of water evaporated or transpired by vegetation on an annual and daily scale (R. Allen et al., 1998): climatic conditions, precipitation characteristics (duration, intensity), soil characteristics including current and historical uses, and vegetation characteristics. However, it is common practice to base evapotranspiration estimates on simplified methods, such as that of Oudin et al.(2005), which is based on average daily temperature values. Finally, precipitation water that does not run off or is not intercepted by evapotranspiration processes will migrate towards the aquifer at variable speeds depending on the texture of the deposits, their state (compaction, indurated layer) and the thickness of the unsaturated soil layer (Scanlon et al., 2002). Indeed, the granulometric composition (grain size distribution) and degree of compaction of surface deposits

will influence porosity and therefore the retention capacity of water infiltrated by the soil. This retention capacity corresponds to a soil's ability to retain a fraction of the infiltrated water subject to gravity in the unsaturated zone of the soil. The thickness of the unsaturated zone (known as the vadose zone) will influence the amount of water that can reach the recharge zone in a given time (Labrecque et al., 2020).

In the context of this study, the data required to accurately estimate net recharge at the scale of the study site would have required an experimental set-up deemed too complex and costly. Indeed, on the Branch 13 study site, the history of land use and mechanical disturbance is complex, suggesting very high spatial variability in runoff conditions, evapotranspiration and retention capacity in the face of various precipitation events. With regard to the role played by the thickness of the vadose zone, this variable is not considered by the MODFLOW software (Ntona et al., 2022) and therefore cannot be used to accurately estimate the net recharge value.

The regional groundwater study by Carrier et al. (2013) defines recharge values at the level of the underlying bedrock for various hydrogeological units in the Montérégie-Est region, including the hydrogeological unit at the site of the present study (St. Lawrence South Platform). Carrier et al. (2013) used the HELP model (Schroeder, 1994) to estimate evapotranspiration, surface runoff, subsurface runoff and storage over the 1979-2010 climatic period.

The study by Carrier et al. (2013) establishes the quantities of water infiltrating the soil, but not reaching the rock, which is referred to as subsurface runoff. This runoff corresponds to subsurface runoff that eventually reaches the fluvial system before being discharged into the St. Lawrence River. It is conceivable that this type of subsurface runoff could be used to estimate the recharge of shallow groundwater that feeds the hydrology of small streams and lowland wetlands in the St. Lawrence. It can therefore be used to estimate the recharge value at the study site, which corresponds to a shallow water table adjacent to a stream. For the study area, Carrier et al (2013) set the ratio of subsurface runoff to total annual precipitation at between 11 and 25%, depending on the year. Applying these ratios to the total precipitation value at the study site for the period October 2022 to September 2023 (1305 mm), we can reasonably estimate that subsurface runoff and therefore recharge varies between **144 and 327 mm** per year.

This range of recharge values is broadly similar to that of Dubois et al. (2021), who set the recharge to precipitation ratio for the study site area at between 10 and 15%. Dubois et al. (2021) based their

estimate on the use of a distributed hydrogeological modelling software (HydroBudget), which provides recharge values distributed over a spatial matrix with a 10 km^2 mesh (the study site is located at the level of their cell #2604). For the calibration period from October 2022 to September 2023, this equates to a range of recharge values between **131 and 196 mm**, at the lower end of the values estimated from Carrier et al. (2013).

The maximum and minimum annual recharge values established by the studies for the study area are **131 mm (0.00036 m/day) and 327 mm (0.00090 m/day)** respectively**.** It should be borne in mind, however, that the recharge estimates provided by the aforementioned studies are on a regional scale, and that they represent surfaces that are not exclusively used for agricultural purposes. It is therefore possible that the nature and intensity of agricultural interventions on the fields may enhance surface runoff, resulting in lower recharge values on a local scale. It was therefore decided to lower the minimum threshold value for automated calibration (PEST) in MODFLOW. The final threshold values used for automated recharge calibration for the three model zones were **55 mm (0.00015 m/d) and 327 mm (0.00090 m/d**) (Figure 5D).

Estimating the hydraulic conductivity of materials

Hydraulic conductivity (K) is a physical property of porous materials, such as sediments, which quantifies the ability of these materials to transmit water through their pores when a hydraulic gradient is applied. In this study, the estimation of the hydraulic conductivity of materials was carried out in much the same way as for the estimation of recharge values. Reference documents were compared with empirical estimation methods to establish the threshold values used for automated calibration (PEST) in MODFLOW.

Granulometric analyses (coarse and fine fractions, Marchand et al., 2022) of sediment samples collected from the study site were used to estimate hydraulic conductivity using HydrogeSieve software (Devlin, 2015). Hydrogeosieve software enables conductivity values to be calculated from the characteristics of particle size distributions based on 16 different methods. In this study, the results of particle size analysis were used to define hydraulic conductivities based on 5 distinct methods (Krumbein & Monk, 1943; Shepherd, 1989; Vukovic & Soro, 1992; Alyamani & Sen, 1993; Barr, 2001) (Table 3.1). K threshold values from the scientific literature, including for surface fluvial deposits (first 100 cm) from the Yamaska unit, which lies within a 20 km radius of the study site (Gagné et al., 2013), are also presented in Table 1. Finally, hydraulic conductivity

could be estimated from water level data using slug tests based on an exponential decay model built in R from the NLS package (Table 3.1).

Table 3.1. Range of hydraulic conductivity values (K, in m/s) for the different materials of the conceptual model for different empirical sources or extracted from scientific literature.

		Material ID # 1	Material ID # 2 and 4	Material ID #3 and 6	Material ID # 5
Method or reference	Distribution	Coarse alluvium (medium to coarse sand with gravel)	Fine alluvium and actual bedload (fine to mediun sand with fines)	Upper regional unit and backfill material (silty sand)	Lower regional unit (clayey silt)
HydrogeoSieve	Min	1.96E-06	1.07E-07	1.49E-08	
	Max	4.63E-05	2.98E-05	1.42E-06	
Domenico and Schwartz (1990)	Min	9.00E-07	2.00E-07	1.00E-09	1.00E-11
	Max	6.00E-03	5.00E-04	2.00E-05	4.70E-09
Gagné et al.	Min		6.70E-06		
	Max		1.29E-06		
Slug test (august 2018)	Min	1.93E-06		9.45E-06	
	Max	2.50E-03		9.55E-06	

The sediment samples identified as belonging to the upper regional deposits and backfill (material ID # 3 and 6, see Figure 3.6) show very similar particle size distributions and conductivity values and were therefore considered indistinguishable. The range of values associated with the historical alluvium was used as a guide for calibrating the conductivity values of the actual riverbed. For the underlying clay unit (material ID # 5), considering the inability to collect quality sediment samples, calibration of the hydraulic conductivity value for this unit was therefore carried out by combining threshold values from the literature for silts and clays (Domenico & Schwartz, 1990).

The ranges of K values for each type of deposit are very wide, from 2 to 4 orders of magnitude depending on the method and material (Table 3.1). The threshold values used for PEST calibration in MODFLOW correspond to the minimum and maximum values and are as follows:

Coarse alluvium (ID # 1): between 9×10^{-7}m/s (0.08 m/day) and 6×10^{-3}m/s (518 m/day)

Fine alluvium (ID # 2) current alluvium (ID # 4): between 1×10^{-7}m/s (0.009 m/day) and 5×10^{-4}m/s (60 m/day)

Upper regional deposit (ID # 3) and fill (ID # 6): between 1×10^{-9}m/s (0.00009 m/day) and 2×10^{-5}m/s (1.73 m/day)

Lower regional deposit (ID # 5): between 1×10^{-11}m/s (0.00000095 m/day) and 2×10^{-5}m/s (1.73 m/day)

3.2.3.3 Error validation and evaluation

Model evaluation was carried out by comparing simulation results with observed data, in order to assess the quality of calibration under permanent conditions. The simulation using the hydraulic conductivity (K) and recharge values obtained by PEST calibration was compared with the data observed in the various piezometers on the study site for the period 2022-2023. The residual error was calculated by comparing the simulated piezometric heights with the average annual observed heights for this period. At the same time, the balance of the hydrological budget was analyzed by comparing inflows (recharge) and outflows (river limit condition), to ensure that the difference between these flows remains minimal (under 3%).

In addition, an independent validation of the model was carried out by simulating the hydrological year 2023-2024 using the K values obtained by PEST calibration and an estimate of recharge derived from precipitation measured during this period. To do this, the recharge/precipitation ratio determined during the PEST calibration was applied to the annual precipitation observed in 2023-2024. The simulated piezometric levels were then compared with observations over the same period, enabling us to assess the model's stability and its ability to reproduce hydrological conditions at the site beyond the calibration year.

This dual approach, combining error assessment under steady-state conditions and independent validation based on a different hydrological period, ensures that the model is robust before it is used to analyze hydrogeological scenarios.

3.2.3.4 Types of analysis

To better understand the influence of key hydrogeological parameters (hydraulic conductivity (K), recharge and material thickness) on groundwater flows within a modified lowland alluvial plain, twelve steady-state simulations were carried out. These are grouped into six categories of exploratory scenarios:

- Scenarios 1 and 2: varying the hydraulic conductivity of alluvial units, to modulate the contrast between fine (ID #2) and coarse (ID #1) alluvium.

- Scenarios 3A and 3B: joint modification of the K values of the upper (ID #3) and lower (ID #5) regional units, enabling two limit cases to be tested: an increase (3A) or a decrease (3B) compared with the base scenario.
- Scenarios 4A and 4B: combined variation in hydraulic conductivity and recharge in the backfill unit (ID #6).
- Scenarios 5A and 5B: widespread modification of alluvial unit thickness across the entire plain.
- Scenarios 6A and 6B: localized variation in coarse alluvial thickness, specifically targeting the former meanders identified in the model.

It should be noted that the conductivity, recharge and thickness values used in the different scenarios were not selected to faithfully represent real local conditions, but rather to consistently test the directional effect (upward or downward) of these parameters on the structure of underground flows. The amplitudes of variation selected are based on plausible values for lowland environment but remain conceptual. In some cases, K values were adjusted to match those of other units, while thicknesses were modified by adding or removing a layer in the model grid. All simulations were calibrated to maintain a balanced water balance (inflows ≈ outflows), thus ensuring the comparability of scenarios within an exploratory logic. A detailed summary of the assumptions specific to each scenario, in relation to the expected effects on flow redistribution, is presented in Table 3.2.

Table 3.2. Summary of simulation scenarios used in MODFLOW-GMS

Group	Scenario	Description	Assumptions
Group 1 & 2 (Modification of alluvial K contrast)	1A	Increase K of fine alluvium (Unit 2) to match that of coarse alluvium (Unit 1)	↑ fluxes between alluvial units, ↑ flux from upper regional unit to fine alluvium, and ↑ proportion of flux reaching the river bed (Unit 4) from fine alluvium (Unit 2)
	1B	Decrease K of coarse alluvium (Unit 1) to match that of fine alluvium (Unit 2)	↑ fluxes between alluvial units (Unit 1-2), ↓ flux from upper regional unit (Unit 3), and ↓ the proportion of flux reaching the river bed (Unit 4) from fine alluvium (Unit 2)
	2A	Decrease K of fine alluvium (Unit 2), while the coarse alluvium (Unit 1) K value remains unchanged	↑ proportion of flux from the coarse alluvium (Unit 1) to fine alluvium (Unit 2), and ↓ the proportion of flux reaching the river bed (Unit 4) from fine alluvium (Unit 2).
	2B	Increase K of coarse alluvium (Unit 1), while the fine alluvium (Unit 2) K value remains unchanged	↑ flux from upper regional (Unit 3) unit to coarse alluvium (Unit 1), and ↑ proportion of flux from the coarse alluvium (Unit 1) to fine alluvium (Unit 2).
Group 3 & 4 (Modification of regional units K and recharge)	3A	Increase K for regional units (3, 5) and increase recharge in the regional area.	↑ proportion of flux reaching the river bed (Unit 4) from lower regional unit (Unit 5), while ↑ proportion of fluxes between the lower regional deposits (Unit 5) and the alluvial units (1-2)
	3B	Decrease K for upper regional units (Unit 3) and decrease recharge in the regional area.	↓ proportion of fluxes between the regional deposits (Unit 3-5) and the alluvial deposits (Unit 1-2)
	4A	Increase K for the backfill unit (6) and increase recharge in the floodplain area.	↑ fluxes between the backfill material (Unit 6) and the fine alluvium (Unit 2) and ↑ proportion of flux from the the backfill (Unit 6) to the stream bed (Unit 4)
	4B	Decrease (K) for the backfill unit (6) and decrease recharge in the floodplain area	↓ fluxes between the backfill material (Unit 6) and the fine alluvium (Unit 2) and ↑ proportion of flux from the fine alluvium (Unit 2) to the stream bed (Unit 4)
Group 5 & 6 (Modification of alluvial unit configuration)	5A	Increase thickness of fine alluvium (Unit 2) and coarse alluvium (Unit 1) by one grid layer	↑ fluxes between the alluvial units(Unit 1-2) and the upper regional deposit (Unit 3) , while ↑ proportion of fluxes reaching the river bed (Unit 4) from the alluvial units (Unit 1-2)
	5B	Reduce thickness of fine alluvium (Unit 2) and coarse alluvium (Unit 1) by one grid layer	↑ fluxes between the upper (Unit 3) and lower regional deposit (Unit 5), while ↓ proportion of fluxes reaching the stream bed (Unit 4) from the alluvial units (Unit 1-2)
	6A	Increase thickness only for coarse alluvium (Unit 1) by one grid layer	↑ fluxes between coarse (Unit 1) and fine alluvial unit (2), and ↑ volume of fluxes passing through the coarse alluvium (Unit 1)
	6B	Reduce thickness only for coarse alluvium (Unit 1) by one grid layer	↓ fluxes between coarse (Unit 1) and fine alluvial unit (2), and ↓ volume of fluxes passing through the coarse alluvium.

3.3. Results

3.3.1 Field observations

Piezometric monitoring (2018-2024) enables us to characterize fluctuations in surface water levels in the river channel and groundwater in the alluvial plain, as well as in the former hillslope (Figure 3.7). The river has a nivo-pluvial regime, with a relatively regular spring flood period from mid-March to mid-April, and a low-magnitude autumn flood period beginning in early October. High water levels can also persist through autumn and winter, in response to thawing of the snow cover. The low-water period generally extends from mid-June to mid-October. Complete droughts were observed in the summers of 2018, 2019, 2020 and 2021, while intense summer floods occurred in 2023 and 2024. These observations reflect strong inter- and intra-annual variability, in terms of the intensity, duration and frequency of hydrological episodes.

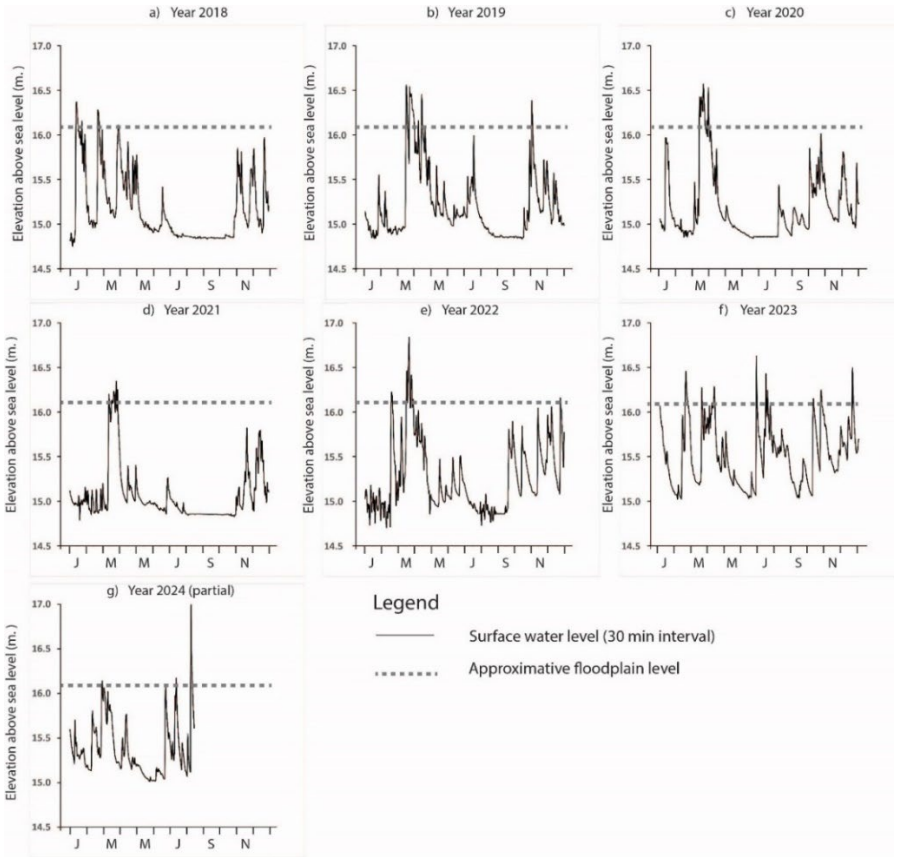


Figure 3.7. Interannual variability of surface water level at the study site. The year 2021 represents drastic low water level between July and end of October. The year 2023 represents relatively high level in January and summer high level reached between June to August. The year 2022 represents a normal year. At the study site, surface water level above 16.10 m (a.s.l.) approximately represents overbank flooding events.

In the subsurface, a hydraulic gradient oriented from the hillslopes towards the channel is observed almost constantly throughout the year. On average, piezometers on the left-hand hillslope of the alluvial plain record piezometric levels 0.5 m higher than those in the channel, while those on the right-hand show differences of up to 1.5 m. Subsurface water levels within the alluvial plain are closer to those of the river, with a vertical difference of around 15 cm. This gradient diminishes during severe low-water or high-water periods, even reversing briefly (from the channel to the alluvial plain) for a few hours or days. These inversions occur without overbank flow, but some events lead to surface flooding, during which groundwater and surface water levels align in a horizontal plane.

High-resolution data can also be used to analyze piezometric responses at event scale. For example, during the rainfall event of September 19, 2023, groundwater level fluctuations followed surface water variations almost synchronously, with a varying time lag depending on distance from the

channel (Figures 3.8 and 3.9). Piezometers close to the channel react more quickly than those located at distance. This creates temporarily a bell-shaped hydraulic gradient, with flows converging both from the hillslope and from the channel. This type of dynamic response is similar to the phenomenon of groundwater ridging, well documented in the bank storage literature (Abdul & Gillham, 1989; Cloke et al., 2006). Visual analysis of the data suggests that the intensity and duration of rainfall influence the persistence of this gradient inversion: the more intense and brief the rainfall, the shorter the inversion. At the site scale, only small differences in piezometric response are observed between the areas corresponding to the abandoned meander and those of the former alluvial plain, mostly during the transition between the flood and the low-flow period (Marchand et al., 2022).

In short, these observations underline the temporal and spatial complexity of surface and groundwater interactions. They provide an essential framework for calibrating and interpreting the hydrogeological scenarios simulated in MODFLOW.

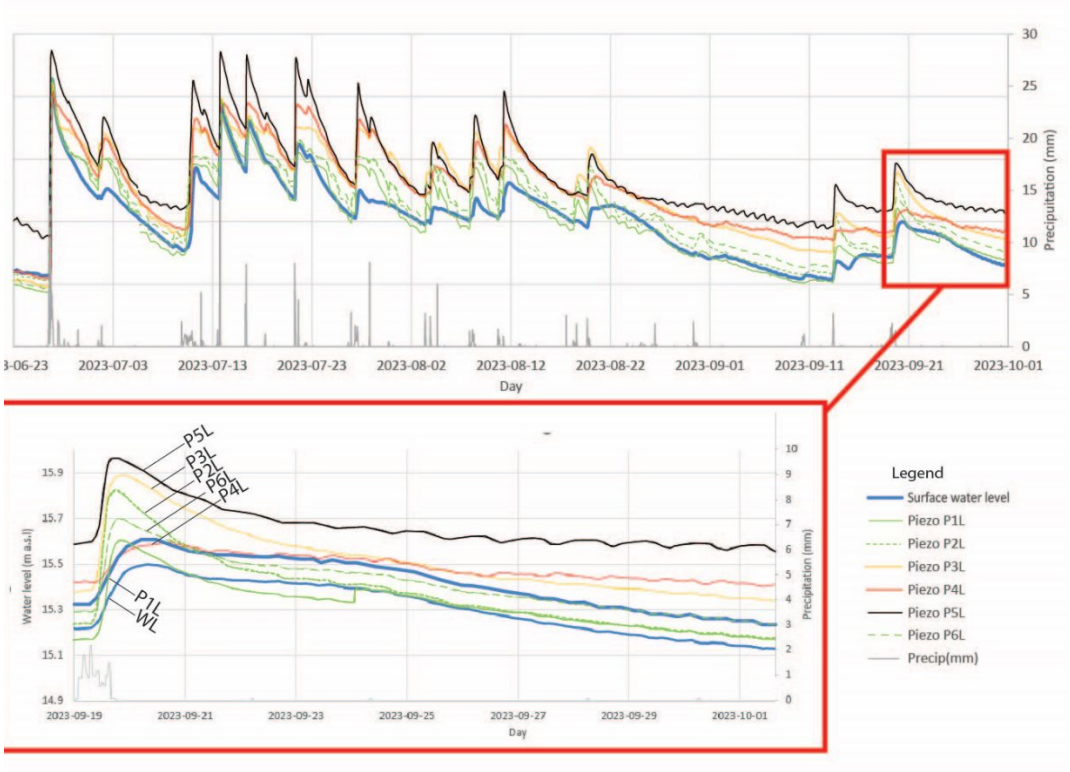


Figure 3.8. Fluctuations in surface water levels and in piezometers located in the left abandoned meander during the summer period (June to September) 2023 (A). The hydrological event of September 19 (B) illustrates the hydraulic gradient inversion occurring between the piezometers located on the alluvial plain near the channel (P1L-P2L-P3-P6L) and the one located in the plain, but furthest from the channel (P4L). See figure 3.3 for piezometers spatial location.

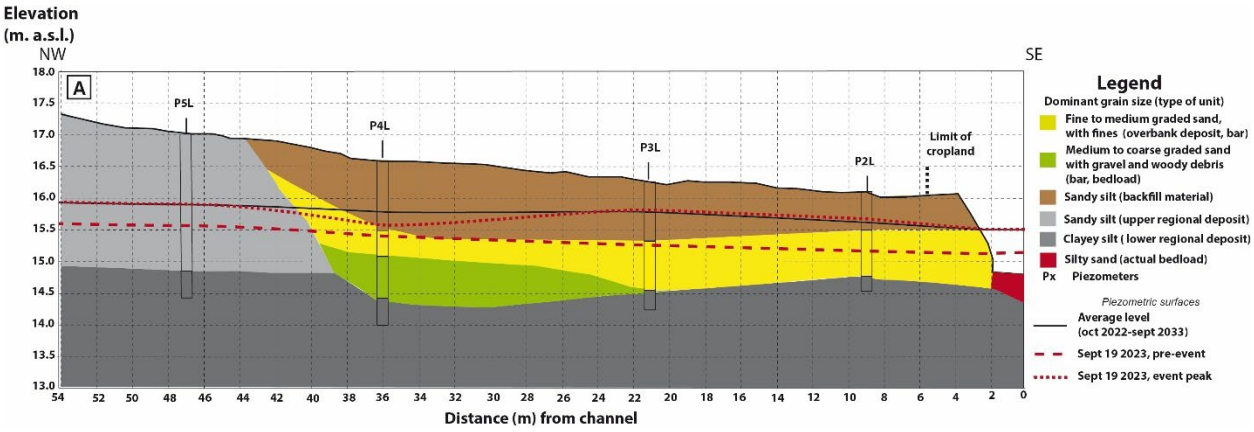


Figure 3.9. Cross-section showing the piezometric surface in the alluvial plain and regional environment adjacent to the study site during the hydrological event of September 19, 2023 (see Figure 3.8B). The solid black line indicates the average water level in the piezometers over the period October 2022 to September 2023. The dashed line indicates the water levels in the various piezometers prior to the hydrological event, while the dotted line shows the levels reached in the piezometers when the maximum level was reached in the channel.

3.3.2 PEST calibration results: optimum K and recharge values

Automated calibration using the PEST module in MODFLOW enabled us to estimate optimum values for recharge in the model's three main zones (Figure 3.5 (D)), as well as for hydraulic conductivity (K) in the six geomorphological units represented in the grid (Figure 3.6). The conductance applied to the River condition was set at 5 m^2/day/m, a value representative of the bed thickness and permeability of the underlying sediments. In MODFLOW, this parameter controls the exchange capacity between the channel and the aquifer via the River module.

Table 3.3 shows the calibrated parameters. The results show a clear differentiation between recharge on the alluvial plain and in regional environments. Estimated recharge on the alluvial plain reaches 327 mm/year, three to six times higher than in the regional zones (Table 3.3). This value represents the plain as a preferential recharge zone at the scale of the studied reach, an observation which is consistent with the coarser grain size of its sediments compared with regional deposits.

Table 3.3. Hydraulic conductivity and recharge values established by automated calibration (PEST) in MODFLOW for the conceptual model of branch 13 of the Pot-au-Beurre river.

PEST simulation (Test 801C)		
Hydraulic conductivity (K) (material ID)	**(m/day)**	**(m/s)**
Coarse sand (abandoned meander) (Unit 1)	32.32	3.74E-04
Fine sand (floodplain, overbank deposit) (Unit 2)	0.96	1.11E-05
Silty sand (upper regional deposit) (Unit 3)	0.15	1.72E-06
Fine sand (actual bedload) (Unit 4)	1.84	2.13E-05
Clayey silt (lower regional unit) (Unit 5)	0.002	2.31E-08
Silty sand (backfill material) (Unit 6)	0.95	1.10E-05
Recharge	**(m/day)**	**(m/year)**
Left regional zone (1)	0.00015	0.06
Right regional zone (2)	0.00027	0.10
Former alluvial zone (3)	0.0009	0.33
Annual precipitation (m) Oct 2022-Sept 2023	1.305	
Average residual error with observed data (m) (std error)	0.05 m (± 0.05 m)	
Hydrologic budget error: FLUX IN/FLUX OUT (%)	1.42	

Despite the fact that this value reaches the upper limit of the range initially defined, it has been retained in the final simulation. It remains physically realistic and is supported by observations from comparable studies (Carrier et al., 2013; Dubois et al., 2021). Based on discussions with Dr. Marie Larocque (pers. comm., 2024), recharge above this threshold would have been considered unlikely.

Calibration also revealed a recharge asymmetry between the two banks of the river: 55 mm/year on the left bank versus 99 mm/year on the right bank. This difference can be explained by contrasting land uses, in particular the predominance of corn on the left bank, compared to forage crops on the right bank, which potentially favours better infiltration.

Finally, the hydraulic conductivity values obtained are consistent with the hydrogeological environments of the St. Lawrence lowlands. In particular, the K values simulated for the fine

alluvium and the fill are close, supporting the hypothesis that the materials used for the backfill come from the stripping of local sediments.

3.3.3 Evaluation of residual error and hydrological budget

Calibration was assessed by comparing simulated piezometric levels with field observations. The simulation carried out with the optimum hydraulic conductivity (K) and recharge parameters obtained by the PEST module shows a mean residual error of 0.05 m, with a standard deviation of ± 0.05 m (Figure 3.10).

Greater discrepancies are nevertheless observed in the alluvial plain on the left-hand side, particularly at piezometers P2L, P3L, P4L and P6L (see Figure 3.3). This local over- or under-estimation could be explained by the simplification of applying a single recharge value to the entire plain, with no spatial distinction between the two banks. On the other hand, simulated levels correspond well to observations in adjacent regional environments, notably at piezometers P4 and P5L, suggesting a good representation of hydrogeological behavior outside the plain.

In terms of overall balance, the simulation shows a hydrological budget difference of 1.42%, which is considered very satisfactory for a model under permanent conditions (Reilly & Harbaugh, 2004).

To assess the robustness of the calibrated parameters, a second simulation was carried out using water levels observed during the year 2023-2024. The results show an almost identical average residual error of 0.05 m (± 0.03 m), and a water balance difference of 1.71%. These results confirm the stability of K and recharge values over two distinct hydrological periods, reinforcing confidence in the steady-state model for subsequent scenario analyses.

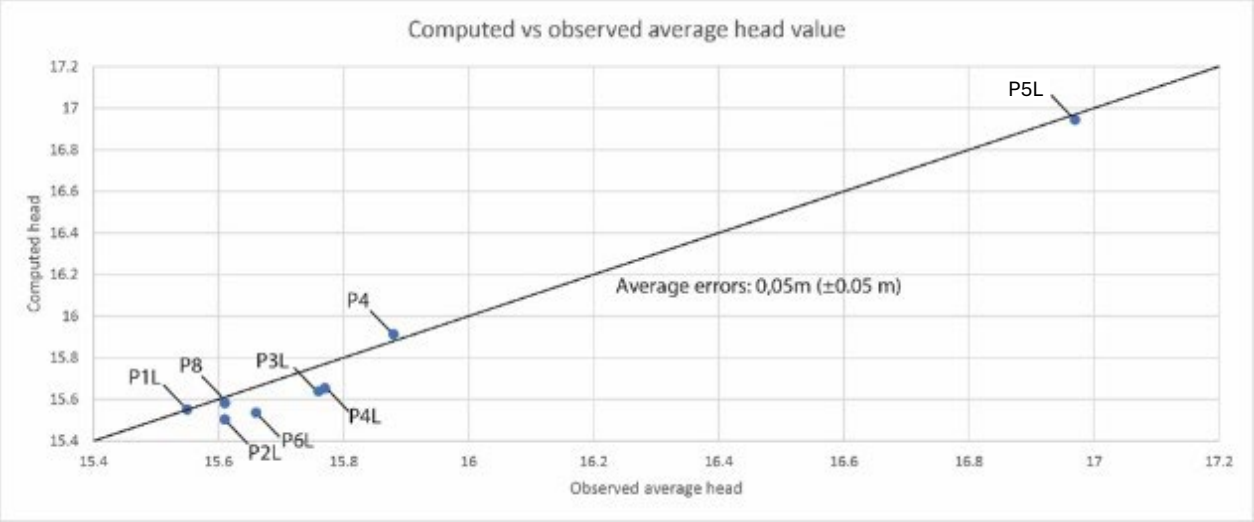


Figure 3.10. Computed (MODFLOW calibration) versus observed value for the average water levels in the different piezometers installed at the Pot-au-Beurre's restoration site.

3.3.4 Findings for constant simulation conditions

The steady-state simulation, based on the calibrated parameters, indicates that hydrological flows are predominantly oriented from the terrestrial environment towards the stream. As observed on the piezometric map (Figure 3.11), the main hydraulic gradient is oriented perpendicular to the stream axis, towards the channel from adjacent regional deposits. A decrease in the hydraulic gradient can be detected at the transition between the regional unit and the alluvial plain, as evidenced by the increased spacing between the piezometric isolines (Figure 3.11).

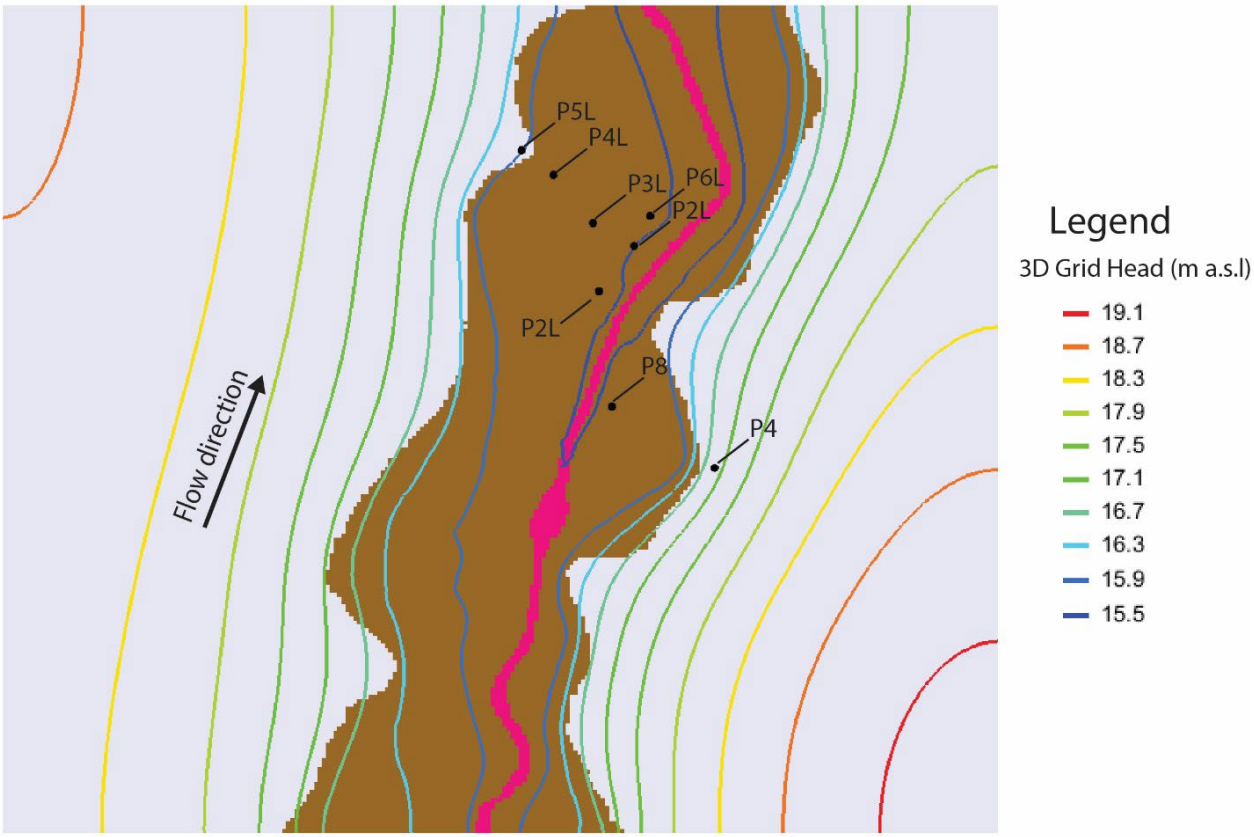


Figure 3.11: Piezometric map showing the position of groundwater at the study site according to the PEST calibration performed in MODFLOW.

The hydrogeological budget shows that the study area supplies approximately 16 m³/day of groundwater to the river, mainly from recharge (15.88 m³/day). The difference is explained by a very low volume of water exchange (0.11 m³/day) between the stream (River condition) and the actual bed unit (Material ID #4). It should be noted that this exchange volume is strongly influenced by the conductance parameter assigned to the River condition, according to the approach proposed by Harbaugh (2005).

Given that recharge and conductance parameters have been defined using a simplified methodology, the following analysis focuses less on absolute volumes of water exchanged than on the relative distribution (in %) of hydrological flows between the different geomorphological units in the model.

The percentages presented in this section are calculated on the basis of gross flows exchanged between units, i.e. taking into account all volumes transferred in each direction, without distinguishing between net inflows and outflows. This method highlights the internal dynamics

and hydrological connectivity of the system, illustrating the intensity of exchanges and the functional role of the various units, even in a context where the net steady-state volume balance is theoretically zero. This approach aims to avoid any confusion as to the significance of the flows presented: these are not "new" volumes feeding the system, but preferential flow routes and relative shares of groundwater between the different geomorphological units.

Figures 3.12 to 3.19 illustrate the absolute volumes exchanged (in m^3/day), in order to visualize more clearly the differences in intensity between the scenarios. These visual representations complement the percentage analyses, highlighting the magnitude of changes, without altering the functional interpretation of hydrogeological dynamics. All flow values (in % and m^3) are available in Appendix B.

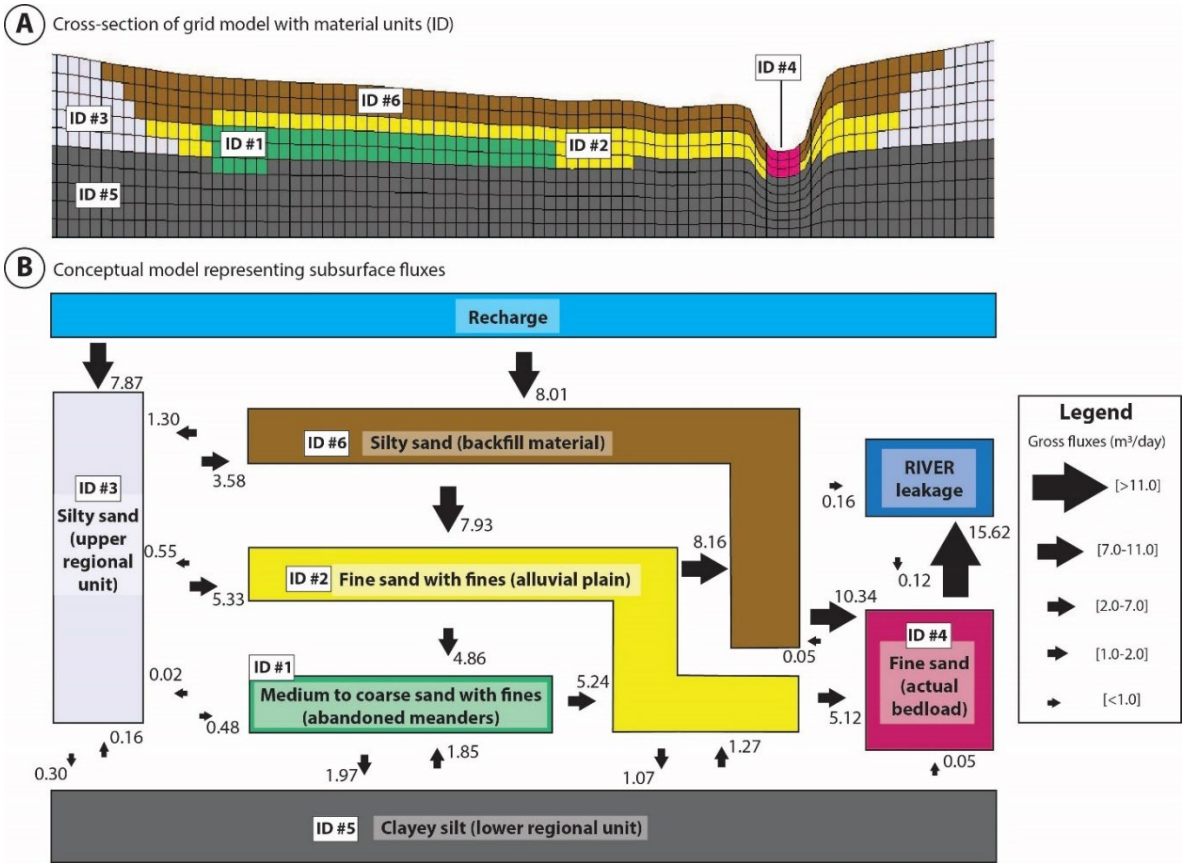


Figure 3.12. Diagram of gross hydrogeological flows between geomorphological units in the conceptual model of the studied reach on branch 13 of the Pot-au-Beurre River. Each box represents a distinct unit: (1) coarse alluvium (abandoned meanders), (2) fine alluvium (alluvial plain), (3) upper regional deposit (silty sand), (4) current riverbed, (5) lower regional deposit (silty clay), and (6) fill (silty sand). Arrows indicate gross flow volumes (in m^3/day) exchanged between units, under steady-state conditions. The size of the arrows is proportional to the volume transferred. Bilateral exchanges are represented by separate arrows for each flow direction. These flows reflect the dynamic circulation of groundwater in the modeled system, with no net change in storage in the units, in accordance with steady-state conditions. Cumulative gross flow volumes exceed total system recharge due to internal hydrological recirculation.

In a typical year, shallow groundwater recharge at the study site is distributed almost equally between the regional deposits and the alluvial plain. Analysis of the gross inflows and outflows for each of the six geomorphological units modelled provides a better understanding of the internal dynamics of the hydrogeological system (Figure 3.12).

The upper regional unit (Material ID #3), made up of sandy silt, acts mainly as a lateral transit zone of subsurface flows towards the adjacent alluvial plain. The majority of its outflows are directed towards fine alluvium (ID #2, 55%) and backfill material (ID #6, 37%). A minority flows into the coarse alluvium (ID #1, 5%) and the lower regional unit (ID #5, 3%). In return, this unit receives input from the backfill unit (ID #6, 64%) and fine alluvium (ID #2, 27%), indicating bidirectional hydrological exchanges between the regional unit and the alluvial plain.

The lower regional unit (Material ID #5), composed of silty clays, functions as a secondary source, transferring water mainly to the coarse alluvium (ID #1, 56%) and fine alluvium (ID #2, 38%). A small fraction (1%) reaches the actual riverbed (ID #4) directly, while 5% of the subsurface water is exchanged with the upper regional unit. In return, it receives significant inputs from coarse alluvium (59%), fine alluvium (32%) and the upper regional unit (9%), suggesting complex lateral and vertical subsurface exchanges.

The backfill unit (Material ID #6), composed of locally sourced sandy silt, acts as a main transit area of subsurface water towards the actual channel. More than half (52%) of its outflow flows to the existing riverbed (ID #4), while 40% is directed to the fine alluvium (ID #2). A small proportion (7%) flows into the upper regional unit, and 1% reaches the channel directly (River leakage). Most of the inflow comes from the fine alluvium (69%) and, to a lesser extent, from the adjacent upper regional unit (30%).

The fine alluvium (Material ID #2), which forms most of the historic alluvial plain, ensures a significant redistribution of hydrogeological flows. Its outflows are distributed mainly towards the backfill unit (ID #6, 41%) and the current riverbed (ID #4, 26%). A significant proportion (25%) is transferred to the coarse alluvium (ID #1), while 5% flows to the lower regional unit (ID #5) and 3% to the upper regional unit. This unit receives contributions evenly distributed between the fill (40%), the coarse alluvium (27%), and the upper regional unit (27%), reflecting strong lateral and vertical subsurface connectivity.

The coarse alluvium (Material ID #1), located at depth at the apex of abandoned meanders, acts as an intensive bidirectional exchange zone with the fine alluvium material. Most of their outflow (72%) feeds the fine alluvium (ID #2), while 27% reaches the lower regional unit (ID #5). Inflows are mainly from the fine alluvium (67%), followed by the lower regional unit (25%) and the upper regional unit (7%).

Finally, the actual riverbed (Material ID #4) is the system's main outlet. Almost all of its outflows (~100%) are discharged via the River boundary condition. It receives inputs mainly from the backfill unit (66%) and fine alluvium (33%), with a negligible contribution (<1%) from the lower regional unit.

Taken together, these exchanges illustrate complex subsurface hydrological exchange pathways between the different geomorphological units, dominated by subsurface flows between the deposits forming the upper regional environment, the modified alluvial plain (including the backfill unit), and moderate contribution from the lower regional unit.

3.3.5 Results of scenarios

In order to account for the most significant effects, only variations in hydrological flow proportions greater than ±5% are generally reported. However, smaller variations may be reported if they alter the dominant direction or functional role of a unit.

3.3.5.1 Scenarios Groups 1 and 2: K variation between alluvium (Units 1 and 2)

Group 1 and 2 scenarios test the effect of hydraulic conductivity of fine (Material ID #2) and coarse (Material ID #1) alluvium on groundwater flow distribution. Scenario 1A (Figure 3.13 and 3.14, blue bars) explores a situation where the hydraulic conductivity of the fine alluvium unit is increased to match that of the coarse alluvium unit, while Scenario 1B (Figure 3.13 and 3.14, green bars) simulates a lower coarse alluvium conductivity, equivalent to that of the fine alluvium. Scenarios 2A and 2B (Figure 3.13 and 3.14, orange and grey bars) examine the impact of a more pronounced conductivity contrast between the two alluvial units, respectively decreasing the hydraulic conductivity of fine alluvium or increasing it for coarse alluvium.

In scenario 1A, the results show that increasing the hydraulic conductivity of the fine (lowland) alluvium to match that of the coarse (old meander) alluvium leads to an increase in the volumes of water exchanged between these two alluvial units. Indeed, compared to the baseline scenario, the

proportion of incoming and outgoing volumes from the coarse alluvial unit to the fine alluvial unit rises from 67% to 79% and from 72% to 85% respectively. There is also an increase in the volume of water exchanged between fine alluvium and regional geological units (upper and lower) (Figure 3.14), but a decrease in the proportion of exchanges between coarse alluvium and regional units (Figure 3.13), to the benefit of fine alluvium.

For the fine alluvium unit, in addition to higher volumes of water exchanged, the proportions of volumes exchanged with the other units remain more or less the same, with the exception of exchanges with the backfill unit, which decrease. Furthermore, compared to the initial scenario, a higher volume of groundwater is transferred from the fine alluvium to the actual riverbed under these conditions (Figure 3.14). In sum, in this scenario, a higher total volume of groundwater circulates within the alluvium in general, but particularly within the fine alluvium.

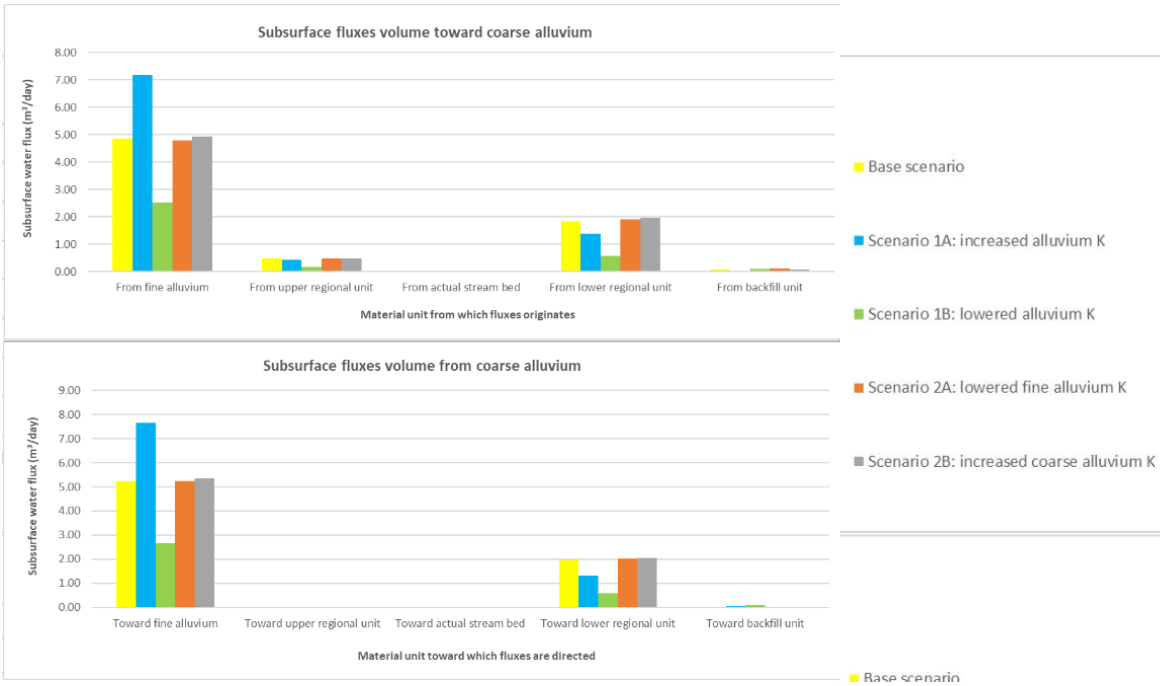


Figure 3.13 Hydrological inflows and outflows from Unit 1, the coarse alluvium of the old meanders, for scenarios 1A, 1B, 2A and 2B.

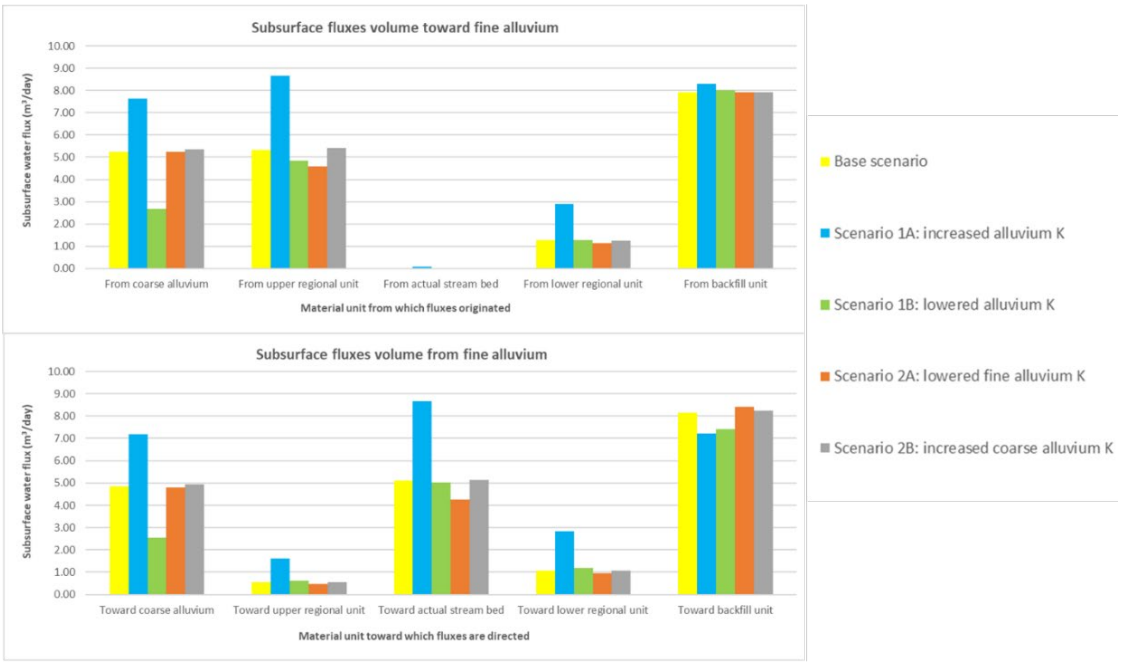


Figure 3.14. Hydrological inflows and outflows from Unit 2, the fine alluvium of the alluvial plain, for scenarios 1A, 1B, 2A and 2B.

Conversely, a reduction in the hydraulic conductivity of the coarse alluvium to match that of the fine alluvium (Figure 3.13 and 3.14, scenario 1B, green bars) reduces the total volumes of water exchanged between the two alluvial units. This is particularly striking for the fine alluvium unit (Figure 3.14), where the proportions of water coming from (entering) and going to (leaving) the coarse alluvium unit drop (compared to the base scenario) from around 27% to 16%. The volume of water exchanged between coarse alluvium and regional units also weakens (Figure 3.13), as flows in the coarse alluvium are highly dependent on the volume of water coming from the fine alluvium. Exchanges between the fine alluvium and the regional units, the backfill unit and the actual riverbed, remain relatively stable despite the decrease in hydraulic conductivity. In short, in a context of generally low hydraulic conductivity of the alluvium, it is exchanges within the coarse alluvium unit, which underlies the fine alluvium, that are decreasing the most.

Scenarios 2A and 2B (Figure 3.13 and 3.14, orange and grey bars), which accentuate the K contrast by modifying the hydraulic conductivity of either type of alluvium, do not induce significant changes in the proportions of inflow or outflow between geomorphological units. The variations observed (generally less than ±3%) do not alter the functional structure of hydrological exchanges on the alluvial plain.

3.3.5.2 Scenarios Groups 3 and 4: Effects of modifying the contrasts and hydraulic conductivities of regional units and backfill

Scenarios 3A, 3B, 4A and 4B (Figure 3.15 and 3.16) aim to assess the combined impacts of removing the hydraulic conductivity contrast between the upper (Material ID #3) and lower (Material ID #5) regional units, and of changes in hydraulic conductivity and recharge applied to the backfill (Material ID #6).

Scenarios 3A and 3B test standardized regional configurations:

- 3A: high regional permeability (Figure 3.15 and 3.16, blue bars and Figure 3.17),
- 3B: low regional permeability (Figure 3.15 and 3.16, green bars).

In scenario 3A, there is a marked redistribution of outflows from the upper regional unit (ID #3) (Figure 3.17). The proportion of transfers to the lower regional unit (ID #5) rises sharply, from 3 % to 79 %, while the proportion of outflows to fine alluvium (ID #2) decreases from 55% to 16%. Flows to the backfill unit (ID #6) also dropped from 37% to 2%. These changes indicate a redirection of regional groundwater towards depth, reducing inflows to surficial units of the alluvial plain.

Outflows from the lower regional unit (ID #5) are also modified (Figure 3.17): transfers to the riverbed (ID #4) increase sharply, from 2% to 59%, making this unit the main contributor to groundwater flow entering the riverbed in the studied reach. At the same time, the proportions of water exiting to the fine alluvium (ID #2) and coarse alluvium (ID #1) decreased, but the absolute volumes of water exchanged with these alluvial units increased (Figure 3.17). This suggests increased exchange at the level of the deep regional unit, but with a dominance of exchanges with the bed unit, thus reducing the buffering (or transitional zone) role of the alluvium.

Finally, the proportion of outflows from fine alluvium (ID #2) to the streambed decreased (Figure 15) from 26% to 14%, and those to the embankment from 41% to 27%, confirming a general reduction in the contribution of alluvial units to the hydrographic network.

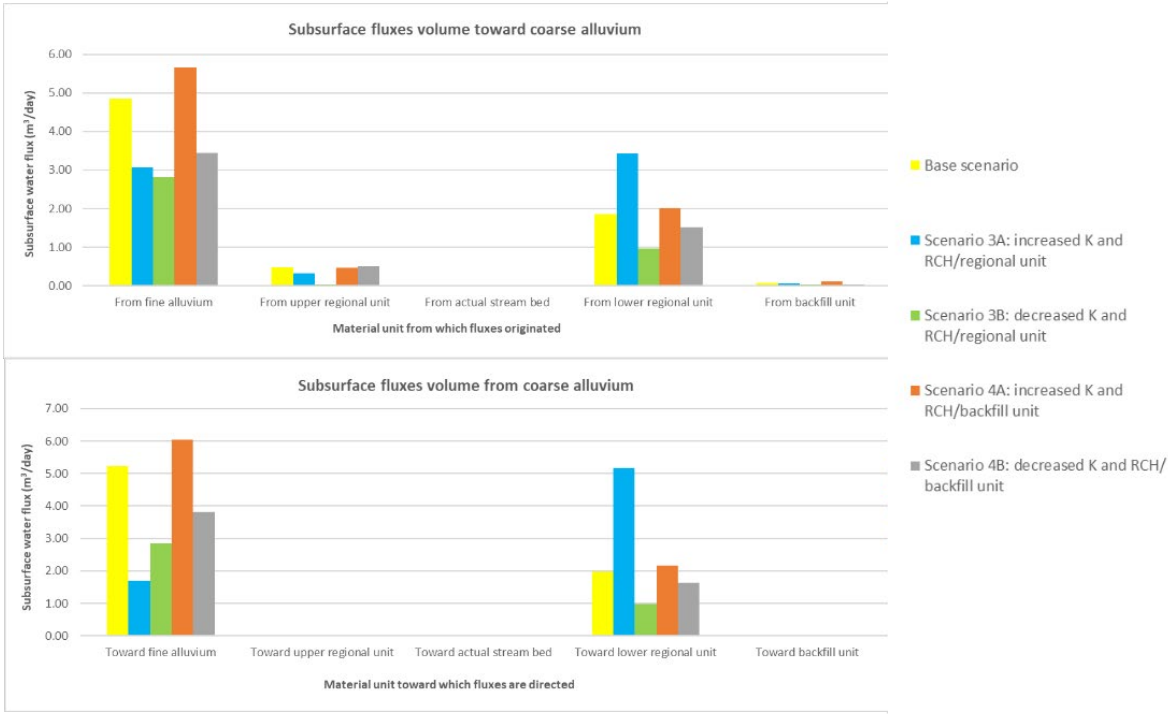


Figure 3.15 Hydrological inflows and outflows from Unit 1, the coarse alluvium of the old meanders, for scenarios 3A, 3B, 4A and 4B.

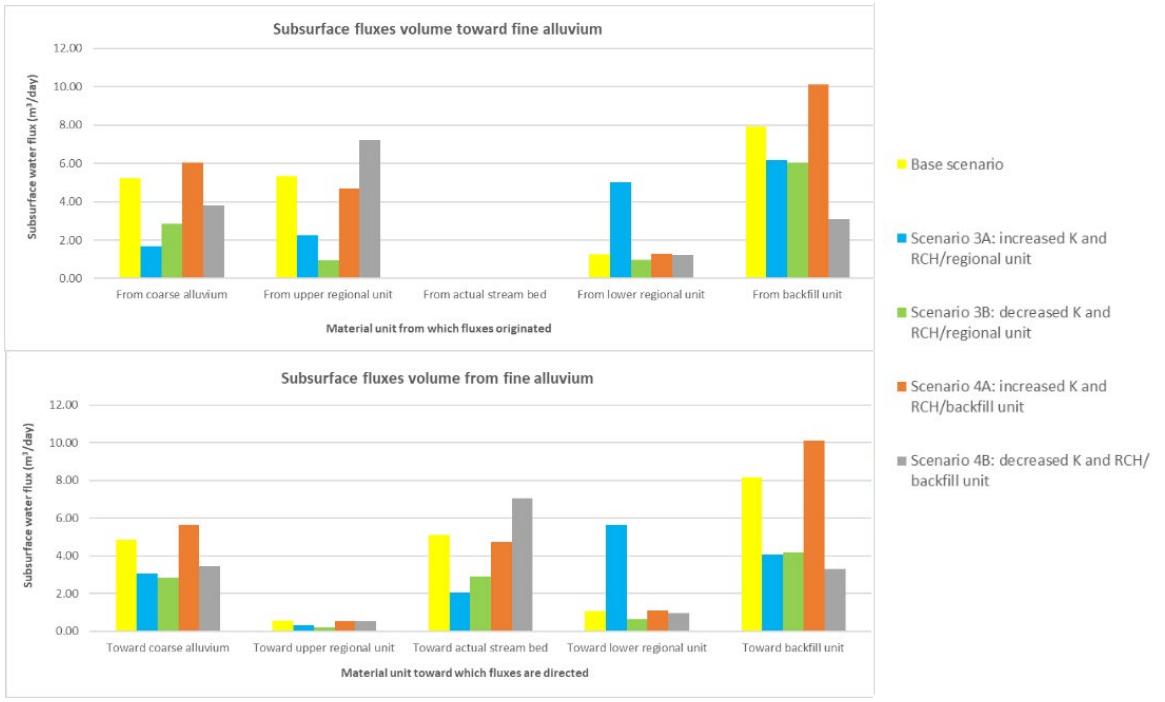


Figure 3.16. Hydrological inflows and outflows from Unit 2, the fine alluvium of the alluvial plain, for scenarios 3A, 3B, 4A and 4B.

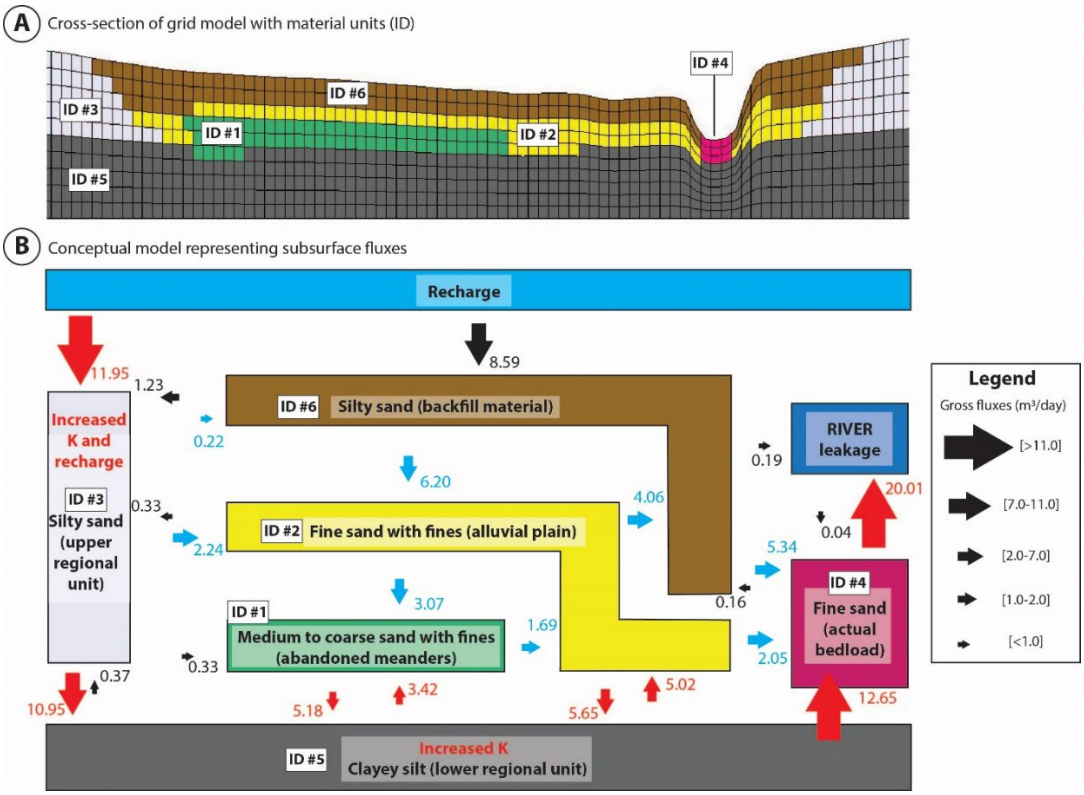


Figure 3.17. Diagram of gross hydrogeological flows between geomorphological units in the conceptual model of the studied reach on branch 13 of the Pot-au-Beurre River for Scenario 3A. Scenario 3A represents a case where the hydraulic conductivity (K) of the regional units (ID # 3 and 5) is increased to the K value of the fine alluvial unit. The red and blue arrows represent flows that have respectively increased or decreased significantly compared to the baseline scenario.

In scenario 3B, hydrological exchanges generally decrease. The proportion of outflows from the upper regional unit (ID #3) to the lower regional unit (ID #5) remains relatively high (41%), but transfers to the fine alluvium (ID #2) and fill (ID #6) are lower than in the base scenario (30% and 28% respectively, compared with 55% and 37%). This reflects a general weakening of lateral exchanges between the alluvial plain and regional deposits.

Outflows from the lower regional unit (ID #5) also show a relatively low contribution to the riverbed, at 5% (compared to 1.5% in the base scenario, but much lower than 59% in 3A). The proportions of exchanges with alluvium, 34% to fine alluvium and to coarse alluvium, as well as the absolute volumes exchanged between the lower regional unit and alluvial units are down compared to initial conditions (Figure 3.15 and 3.16, green bars). This confirms a reduction in the role of these units in groundwater exchange.

On the other hand, the alluvium retains an internal exchange structure relatively similar to that observed in the base scenario. The proportions of outflows from fine alluvium to the riverbed

(27%, versus 26%) and to coarse alluvium (26%, versus 25%) show little variation. However, the absolute volumes of water exchanged daily between the different alluvial units are decreasing, consistent with the lower recharge values applied to the regional units in this scenario (Figure 3.15 and 3.16, green bars).

Scenarios 4A and 4B explore the effect of varying hydraulic conductivity and fill recharge:

- 4A: increase in K and backfill recharge (Figure 3.15 and 3.16, orange bars),
- 4B: decrease in K and backfill recharge (Figure 3.15 and 3.16, grey bars).

High hydraulic conductivity in the backfill material (Scenario 4A) favours subsurface transfer from the upper regional unit to this zone at the expense of the underlying fine alluvium. The proportion of outflows from the upper regional unit to the backfill unit goes from 37% (in the base scenario) to 43% in scenario 4A, while it falls from 55% to 49% to the fine alluvium. Exchanges between the backfill unit and the fine alluvium unit also intensify, with the proportions of incoming and outgoing flows increasing from 40% in the base scenario to 46%. In addition, the proportion of flows entering the actual river bed from the backfill unit increases from 66% (base scenario) to 74%.

Conversely, in scenario 4B, as the hydraulic conductivity of the backfill material decreases, lateral transfers from the upper regional unit are redirected to the fine alluvium unit (increase in the proportion of outflows to the fine alluvium from 55% to 72%) at the expense of transfers to the backfill (37% to 19%) (Figure 3.16, grey bars). The proportion of exchanges between the fine alluvium unit and the backfill unit also decreased, down by around 20 percentage points in both directions. Finally, the proportion of inflow to the actual stream bed from the backfill unit falls sharply, from 66% (base scenario) to 30%, while the contribution of fine alluvium to the river bed rises from 33% to 67%.

Overall, changes in hydraulic conductivity and recharge applied to the backfill unit overlying the alluvium (Figure 3.15 and 3.16, scenarios 4A and 4B, orange and grey bars) have a limited impact on the proportions of hydrological exchanges between the fine and coarse alluvial units.

3.3.5.3 Scenarios Groups 5 and 6: variation in thickness of alluvial units

Scenarios 5 and 6 (Figures 3.18 and 3.19) aim to assess the effects of a variation in alluvial unit thickness on hydrogeological exchanges. Two types of modification were tested: a generalized

variation in thickness across the alluvial units (scenarios 5A and 5B) and a localized variation in the coarse alluvium at the apex of former meanders (scenarios 6A and 6B). The assumptions were that an increase in thickness would promote internal alluvial exchanges and lateral connectivity with regional units and the riverbed, while a reduction in thickness would limit them.

In scenarios 5A (Figure 3.18 and 3.19, blue bar) and 6A (orange bar), the increase in alluvial thickness leads to an intensification of exchanges from fine alluvium (ID #2) to coarse alluvium (ID #1), the proportion of which rises from 67% in the base scenario to 86% (5A) and 85% (6A). At the same time, exchanges in the opposite direction (coarse to fine) decrease from 72% to 63% (5A) and 60% (6A). This dynamic reflects a strengthening of the drainage role of coarse alluvium as its thickness (and hence storage capacity) increases.

Subsurface hydrological exchanges between the upper regional unit (ID #3) and the fine alluvium (ID #2) also increased: the proportion of outflows from the upper regional unit to the fine alluvium rose from 55% to 62% (5A) and 58% (6A). This trend is accompanied by a slight drop in transfers to the backfill (from 37% to 30% in 5A and 34% in 6A), suggesting that the increased thickness of the alluvium favors its role in intercepting lateral groundwater flows from the regional environment. This also translates into lower vertical exchanges between the alluvium and the lower regional unit (ID #5), both in proportion and absolute volume.

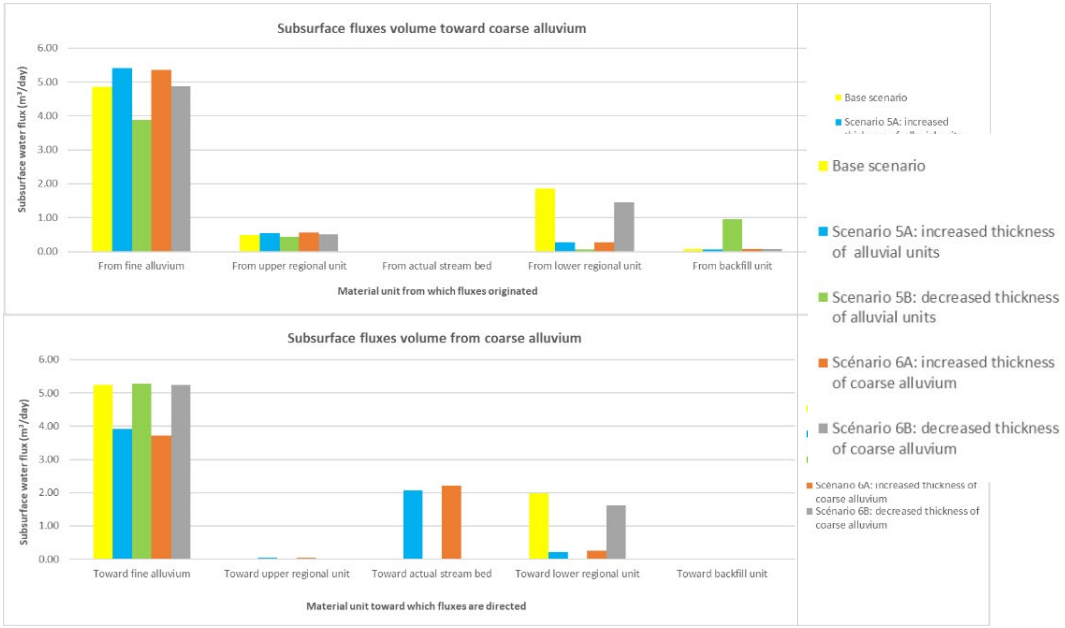


Figure 3.18. Hydrological inflows and outflows from Unit 1, the coarse alluvium of the former meanders, for scenarios 5A, 5B, 6A and 6B.

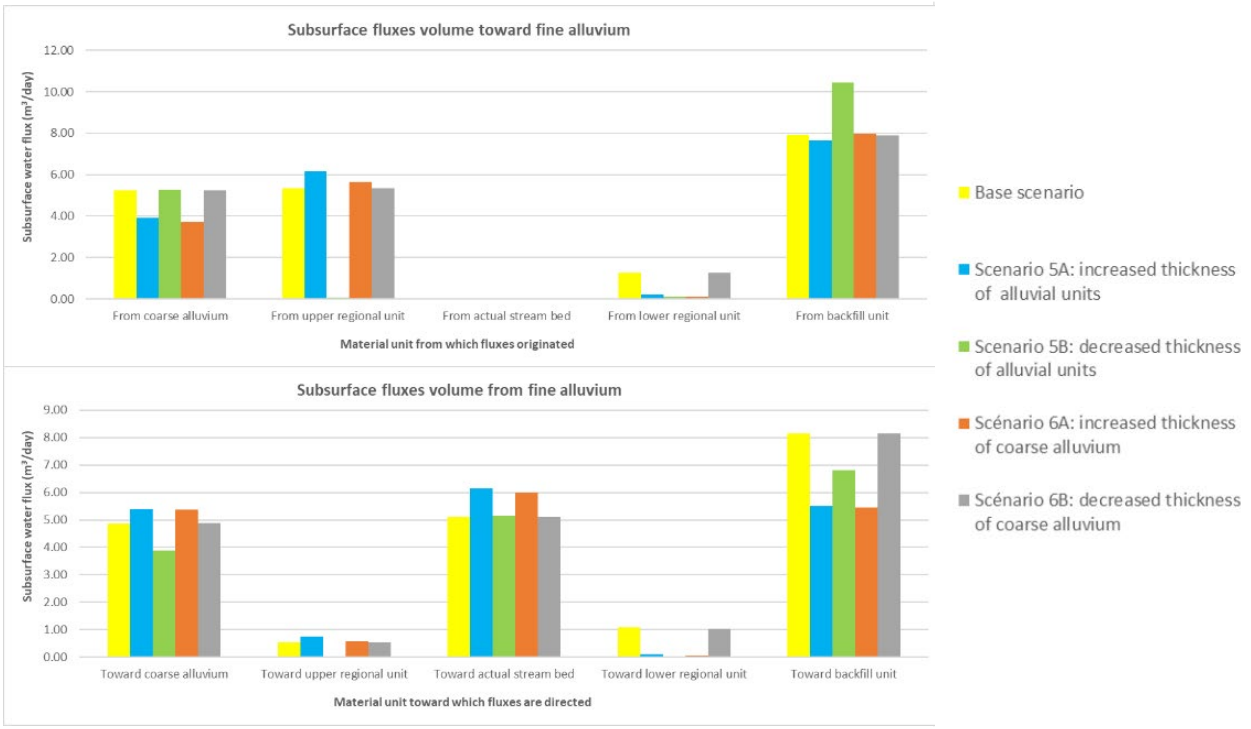


Figure 3.19. Hydrological inflows and outflows from Unit 2, the fine alluvium of the alluvial plain, for scenarios 5A, 5B, 6A and 6B.

Contributions to the riverbed are also modified. In the base scenario, the coarse alluvium has little or no direct contact with the riverbed, resulting in a negligible contribution (<1%). In contrast, in scenarios 5A and 6A (Figure 3.18 and 3.19, blue and orange bars), their increased thickness results in substantial contact with the bed: their contribution rises to 13% (5A) and 14% (6A). At the same time, the contribution of fine alluvial deposits (ID #2) increases slightly (from 33% to 39% in 5A and 38% in 6A), while the contribution of the backfill unit decreases (from 66% to 47% in both scenarios).

In scenarios 5B (Figure 3.18 and 3.19, green bar) and 6B (Figures 3.18 and 3.19, grey bar), a reduction in alluvial thickness alters the overall exchange dynamics. Scenario 5B shows a marked redirection of flows from the upper regional unit (ID #3): transfers to the fine alluvium drop from 55% to 1% (Figure 3.19, green bars), while those to the backfill unit increase from 37% to 88%. This reorganization of the flow regime leads to a significant increase in the backfill's share of fine alluvial inflows (from 41% to 66%), to the detriment of direct inflows from the regional environment (Figure 3.20).

In the lower regional unit (ID #5), there is a significant change in the origin of inflows. In scenario 5B, around 90% of the water entering this unit now comes from the upper regional unit, a situation that contrasts with the base scenario where flows were more diversified (including alluvium). On the other hand, the proportions of outflows from the lower regional unit to fine alluvium (from 38% to 18%) and to coarse alluvium (from 56% to 12%) decrease.

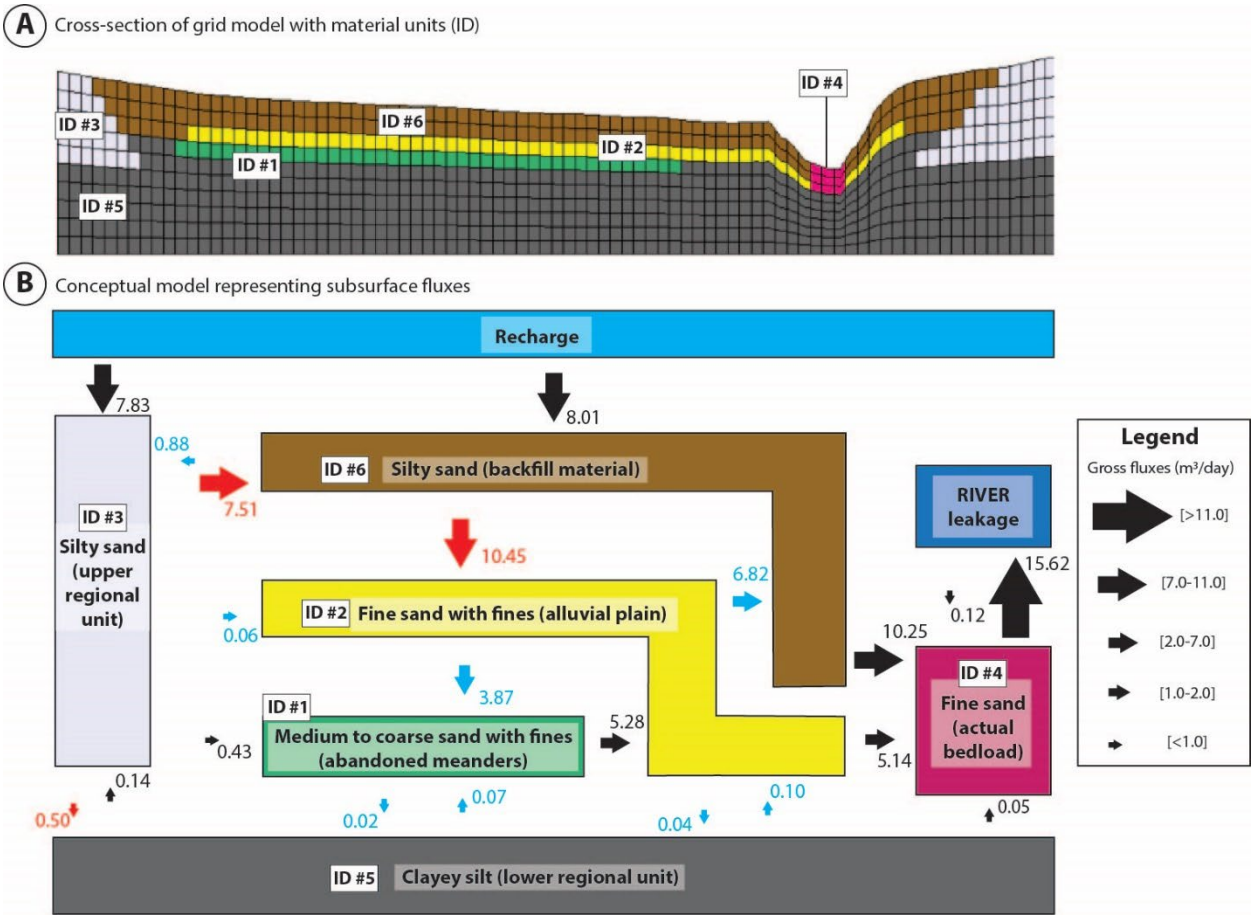


Figure 3.20: Diagram of gross hydrogeological flows between geomorphological units in the conceptual model of the studied reach on branch 13 of the Pot-au-Beurre river for Scenario 5B. Scenario 5B represents a case where alluvial thickness (fine and coarse) is reduced by one layer in the conceptual model. The red and blue arrows represent flows that have respectively increased or decreased significantly compared to the baseline scenario. Note that the figure does not represent an inflow (0.95 m³/day) from the backfill unit to the coarse alluvial unit, nor an outflow (0.19 m³/day) from the lower regional layer to the embankment.

In scenario 6B, although only the thickness of coarse alluvium has been reduced, the proportions of intra-alluvial exchanges remain relatively stable (Figure 3.18 and 3.19, grey bars), as do the volumes of water exchanged daily between fine and coarse alluvium. In scenario 5B, the generalized reduction in alluvial thickness affects intra-alluvial exchanges to a greater extent.

Although the proportions of exchanges between fine and coarse alluvium remain close to those of the base scenario, the absolute volumes of water exchanged decrease significantly.

In scenarios 5B and 6B, despite the reduction in alluvial thickness, the contributions to the actual riverbed remain similar to those of the base scenario, both in proportion and absolute volume. The contributions of fine alluvium, coarse alluvium and backfill remain relatively stable. This suggests that even a thinned alluvial layer remains functional as a transfer zone toward the streambed, at least under simulated conditions. This stability may reflect a minimum threshold of thickness or connectivity beyond which the hydrogeological role of alluvium is maintained, even in the presence of reduced material thickness (and hence storage volume).

Scenarios for modifying the thickness of alluvial units show that increasing their thickness generally favors an intensification of intra-alluvial exchanges, particularly in coarse alluvium. Conversely, a reduction in thickness diminishes their role in subsurface lateral exchanges, in favor of a reorganization of flows towards other units such as the upper backfill deposits. Thus, the spatial configuration of alluvial deposits strongly influences the structure of groundwater exchanges in the floodplain. The next section situates the modeling results in the context of the assumptions made and existing knowledge of surface and groundwater interactions in alluvial environments.

3.4. Discussion

3.4.1 Consistency of modeling results with our understanding of groundwater flow control parameters in alluvial environments

The steady-state simulation (base case scenario) adequately represents a hydraulic gradient within the modelled stream reach, oriented perpendicularly from the regional environment towards the stream, in line with field observations. The model also reveals the impact of transitions in material hydraulic conductivity values on the profile (slope) of the hydraulic gradient. An inflection of the hydraulic gradient is visible at the transition between regional units and alluvium (Figure 3.11), suggesting an influence of alluvial materials adjacent to the stream on groundwater flows, in agreement with observations made in other lowland alluvial plain environments (Poole et al., 2002; Lewandowski et al., 2009). This type of configuration corresponds to what is termed a "*gaining reach"*, typical of lowland environments where groundwater flows are mainly directed towards the stream and aquifers are well connected to the streambed (Winter, 1995; Sophocleous, 2002).

The alluvial corridor along the river, despite channel straightening, favours significant subsurface exchanges, both with regional units and between alluvial units. In the steady-state simulation, the fine alluvium unit receives over 55% of the outflows from the upper regional unit and around 40% of those from the overlying backfill unit. The coarse alluvium, although occupying only approximatively 5% of the total volume of the plain, accounts for 25-27% of exchanges (inflow and outflow) with the fine alluvium, underlining its role as a nodal zone for bidirectional exchanges. By comparison, the backfill unit, which accounts for 59% of the floodplain's volume, captures around 40% of exchanges with fine alluvium. These results show that the geometry and distribution of alluvial materials structure underground flow paths. This disproportionate role of certain high hydraulic conductivity units is consistent with observations made by several studies (Cardenas, 2008; Stanford & Ward, 1993; Van Stempvoort et al., 2021) on the importance of granulometric discontinuities in structuring hyporheic flows in alluvial environments.

Assessment of the assumptions associated with scenarios 1 and 2 shows that they are only partially confirmed, with the expected effects on exchange patterns often proving to be more limited or different than anticipated. For example, in scenario 1A, the increase in conductivity of fine alluvium did lead to a rise in flows exchanged between alluvial units, as well as an increase in their contribution to the stream bed, as anticipated. In scenario 1B, on the other hand, the reduction in the K of coarse alluvium reduced its relative weight in exchanges with fine alluvium, without however affecting the proportion of flows from fine alluvium to the stream. Scenario 2A confirmed a decrease in the contribution of fine alluvium to the channel, but did not alter the structure of exchanges between alluvial units. As for scenario 2B, the increased K of coarse alluvium did not increase its role in exchanges with regional or alluvial units as anticipated.

It is rather the contrast-reduction scenarios (1A and 1B) that lead to significant reorganization of the exchange structure within the plain, favoring a more homogeneous distribution of flows. However, this redistribution reduces the distinct role played by coarse alluvium in exchanges with adjacent units. Whereas they previously performed a specific hydrological function, serving as a preferential transit zone with fine and regional alluvial units, their relative importance diminishes when conductivity contrasts are levelled, making them less differentiated from the rest of the plain. This is in line with the work of Poole et al (2002) and Cardenas (2008), who emphasize that areas of high hydraulic conductivity can act as nodes of hydrological connectivity within a

heterogeneous alluvial system. Conversely, the scenarios accentuating contrasts (2A and 2B) induce little change, suggesting a relative inertia of the exchange structure in steady-state simulation.

Modelling results for scenario group 3 suggest that when the regional environment is composed of materials with low hydraulic conductivity (3B) compared to floodplain materials, the latter can concentrate almost 100% of groundwater before transferring it to the streambed. Conversely, with high hydraulic conductivity of the regional environment (3A), a high proportion (over 60% in the scenario tested) of hydrological flows reach the riverbed via deeper subsurface inflows from the lower regional unit. This scenario therefore validates the hypothesis that the increase in conductivity of the lower regional unit increases the relative proportion of flows exchanged with the alluvial units. This redistribution of flows illustrates the transition from a system dominated by subsurface shallow inflows to one fed mainly by deep subsurface inflows, depending on the properties of the alluvial plain and hillslope material (Winter, 1999). These results suggest that regional units neighboring an alluvial plain may become locally the main underground source of water to the stream when their hydraulic conductivity is high relative to plain deposits. These results also suggest that analysis of the restoration potential of alluvial corridors adjacent to degraded lowland streams requires a sound analysis not only of the nature of the alluvium of the former floodplain, but also of the nature of the regional deposits forming the hillslopes and basal unit underlying the streambed (Lewandowski et al., 2009; Gurrieri, 2023; Wymore et al., 2023).

Scenarios 4 also confirm the hypotheses formulated concerning the effect of the backfill unit on the structuring of shallow subsurface hydrological exchanges. Increasing hydraulic conductivity and recharge of the backfill unit (4A) increases the relative contribution of this unit to underground exchanges, both with fine alluvium and with the adjacent riverbed. Conversely, their reduction (4B) slows down infiltration toward fine alluvium and accentuates the role of the latter as the main vector of riverbed recharge. These results underline the fact that backfill properties can modulate the trajectory of subsurface flows within the floodplain, but also the dynamics of subsurface exchanges with the hillslopes and with the stream bed, an effect already observed in other contexts of low-permeability substrates acting as hydraulic control layers (Bouma, 1981; Greco, 2002; Doble et al., 2012; Berghuijs & Kirchner, 2017). Indeed, in some lowland alluvial plains, where the upper fine alluvium unit is very clayey, groundwater exchanges can be concentrated within

networks of macropores that may be hydrologically disconnected from each other and from the stream, resulting in highly spatially heterogeneous piezometric fluctuations asynchronous with the channel (Lemon, 2020; Van Stempvoort et al., 2021)

Modelling scenario groups 5 and 6 reveal that alluvial thickness has an upward or downward influence on intra-alluvial hydrological exchanges and interactions with the regional environment, as does hydraulic conductivity (scenarios 1 and 2). The simulation results validate the hypotheses formulated, in particular that increasing thickness favours the contribution of flows originating from the alluvium, whereas reducing thickness accentuates the role of deep regional units or the upper backfill unit.

Overall, the results obtained show that localized variations in hydrogeological properties such as hydraulic conductivity, deposit thickness or recharge rates can significantly modulate the spatial and functional structure of subsurface exchanges within a modified alluvial plain of a small straightened lowland river. The different scenarios tested illustrate that even subtle contrasts between adjacent units (e.g. fine vs. coarse alluvium, backfill vs. alluvium, plain vs. regional units) can lead to significant reorganizations of subsurface flow trajectories in the alluvial plain, while maintaining a general stream ward hydraulic gradient. These findings confirm the relevance of a fine-tuned, integrated approach to characterizing hydrological connectivity in modified lowland environments.

This conceptual modelling also highlights the function of alluvial corridors as major hydrological transit zones for groundwater flows, specifically in lowland environments. The alluvial plain of a straightened river, albeit backfilling, could therefore be part of the hyporheic corridor (or hydrological continuum) that links surface water to groundwater in the shallow aquifers of natural alluvial plains, as described by Stanford and Ward (1993). This study affirms the role of degraded alluvial plains as flow regulation zones in lowland areas, as already shown by other studies (Burt et al., 2002; Lewandowski et al., 2009). A better understanding of the three-dimensional architecture of alluvial corridors could improve our estimates of intra-alluvial water exchange and interactions with the regional environment. This knowledge is essential for optimizing the location of restoration projects in agricultural areas.

3.4.2 Implications for the design/objective setting of projects to restore degraded agricultural streams.

In small lowland agricultural streams, restoration projects generally pursue nutrient and sediment input reduction objectives, with the aim of improving water quality (Wohl, 2017). There is also a growing interest in the restoration of riparian and aquatic habitats, in response to the loss of biodiversity associated with the degradation of agricultural environments (Addy et al., 2016; Ngom, 2021). These objectives frequently direct interventions towards mechanized bed, bank or floodplain management aimed at slowing runoff, increasing water retention and promoting biogeochemical processes (Kasahara & Hill, 2008; Kristensen et al., 2012; Polvi et al., 2020). However, these active approaches represent major investments, often incompatible with the scale of the agricultural hydrographic network to be restored (Rousseau & Biron, 2009). They can also raise issues of social acceptability, due to the heavy interventions required on agricultural land.

In this respect, passive restoration approaches, such as removal of agriculture and non-assisted vegetation of the riparian zone, appear to be relevant solutions, both for their lower cost, their low level of mechanical intervention required, and their ability to restore the natural functions of riparian environments (Rhoads & Herricks, 1996; Wohl et al., 2015; Wohl, 2025). However, these approaches are still poorly supported by detailed knowledge of residual hydrological connectivity between surface water and groundwater in degraded river systems, particularly in lowland agricultural environments.

The results of the conceptual model presented in this study propose some key considerations for the planning of passive restoration projects, particularly in small, degraded lowland agricultural streams where interventions have to cope with significant economic, spatial and social constraints. Firstly, conceptual hydrogeological modelling delineates zones of converging groundwater flow toward the channel, allowing passive restoration measures to be targeted based on subsurface connectivity. In the agricultural context of lowlands, where extended riparian buffer strips are increasingly proposed to producers as a means of restoring the ecological functions of riparian environments, this information is crucial. Modelling results indicate that subsurface exchanges are not uniform along a straightened stream, and that certain portions of riparian corridor, notably former meander deposits that are still functional, may play a central role in subsurface exchanges. Their coarse, well-connected sediments allow significant exchanges between local shallow alluvial aquifer, regional aquifer and the channel, reinforcing their role as subsurface flow convergence

zones. Model results suggest that these features could sustain higher hydroperiods and promote conditions favorable to wetland establishment and biogeochemical processing within the riparian corridor. As such, the presence of abandoned meanders provides a strong justification for locally expanding riparian buffers or prioritizing natural revegetation efforts in their vicinity, even when spatial constraints limit interventions elsewhere along the reach.

With this in mind, the modeling approach allows us to go beyond a fixed-width riparian buffer logic and adopt an adaptive approach that takes into account the historical width and depth of the alluvial corridor, the nature of the materials and the relative position of different geomorphological units in regard to the stream. It thus provides a basis for directing crop removal or revegetation projects towards areas with high functional potential, and for avoiding costly or ineffective interventions in less suitable areas.

Secondly, the scenarios tested in this study enable us to assess the nature of the potential gains expected from passive restoration, depending on the geomorphological context. In former alluvial corridors that remain well connected to the regional system, more intense hydrological exchanges create favorable conditions for spontaneous wetland revegetation, nutrient retention and shallow groundwater recharge (Bernhardt et al., 2005; Kool et al., 2014; Newcomer Johnson et al., 2016; Allen et al., 2016; Van Stempvoort et al., 2022). In contrast, where surface deposits restrict vertical exchanges with the underlying alluvium, the potential for passive recharge and riparian wetland recovery may be more limited. In this sense, modeling does not replace field measurements, but it anchors restoration objectives in a realistic understanding of the system's subsurface processes.

Thirdly, hydrogeological modelling can also support the targeted identification of complementary active measures, aimed at optimizing the ecological benefits of passive restoration while reducing costs and the need for non-essential mechanized interventions. For example, in areas where the backfill material is highly compacted or made up of very fine materials, actions such as mechanical decompaction or organic matter amendment can promote vertical exchanges between the surface and the underlying alluvium, thereby increasing the potential for recharge and support for hygrophilic vegetation (Shaheb et al., 2021; Dong et al., 2022).

Among these targeted measures, the removal of mechanical backfill deposits could represent a complementary lever to passive restoration in certain geomorphological settings. The model results show that when the backfill layer is cohesive or poorly permeable, it reduces groundwater

transfer into the historical alluvium, thereby potentially limiting the development of riparian wetlands and the filtration and transformation of nutrient-rich agricultural waters. Removing this material would re-establish preferential exchanges through the alluvial matrix, increasing residence time, hydroperiod, and the buffering of short flood peaks. However, such interventions often require heavy mechanized earthworks, leading to high implementation costs and lower social acceptability, which are two major constraints in agricultural settings. Backfill removal should therefore be considered selectively, where expected ecological gains are high and feasibility conditions are favorable.

Furthermore, when modeling reveals that the regional environment has high hydraulic conductivity, a significant proportion of the groundwater flow can bypass the alluvial plain and feed directly into the riverbed. In this context, riparian zones partially lose their role as biogeochemical filters, and it becomes essential to intervene at the field scale, relying on effective agri-environmental practices to limit nutrient and pollutant transfers (e.g. upstream buffer strips, vegetation cover, fertilizer management). In this way, understanding preferential subsurface flow trajectories will enable us to better calibrate the combination of passive and active interventions, so as to achieve restoration objectives while maintaining a high level of social acceptability among the growers concerned.

Finally, this study highlights the relevance of developing a hydrogeological knowledge bank at the regional scale, integrating data on alluvial morphology, material thickness, and permeability, while accounting for the location of former floodplains. These features can be readily identified using historical aerial photographs and increasingly accessible digital elevation data. Such a database could support multi-stakeholder decisions on which sites to restore, which measures to prioritize, and what realistic objectives to set in different contexts. This approach would contribute to more strategic and functional restoration, targeting reach to watershed scale areas with high potential for hydrological and biogeochemical regulation in agroecological landscapes. Such an approach resonates with the recommendations of Magliozzi et al. (2019), who emphasize the need for scalable methods to prioritize sites for restoring surface–groundwater interactions, particularly in contexts where hydrological and hydrogeological data are uneven or limited.

3.4.3 Perspective on hydrogeological modelling in degraded lowland stream environments

Conceptual hydrogeological modelling, as conceived in this study, has significant methodological limitations. The very wide calibration threshold values can lead to several combinations of hydraulic conductivity (K) and recharge values, making calibration complex and interpretation of absolute water exchange volumes difficult. Calibration with PEST tends to over- or underestimate recharge values, a particularly sensitive parameter (Lewandowski et al., 2009). Furthermore, to facilitate calibration, separate recharge values were assigned for the left and right portions of the alluvial plain and regional environment. Although this distinction is potentially valid (linked to differences in crop type, fill thickness or soil types), it is difficult to verify, which constitutes another modelling bias.

Finally, as Van Stempvoort (2021) points out, compartmentalized models can artificially reproduce subsurface hydrological boundaries that are, in reality, diffuse. The approach adopted here, based on six distinct geomorphological units, although useful for structuring the interpretation of flows, can be perceived as a conceptual simplification that mitigates the dynamic and continuous nature of hydrological exchanges within the system under study.

Hydrogeological models built with MODFLOW alone cannot adequately model processes in the vadose zone, nor the recharge of alluvial plains by surface flooding (Doble et al., 2012). This inability to simulate flooding or processes in the unsaturated zone, such as runoff, evapotranspiration and retention capacity, limits the ability to realistically represent surface and groundwater interactions in alluvial plain environments. It is this shortcoming in particular that may explain the inability of this study to calibrate a model under transient conditions, despite many efforts. Another important constraint, raised by Brunner et al. (2010), is that MODFLOW does not adequately represent the spatial and temporal transitions between different types of hydraulic connections (complete, partial or disconnected) between a river and the water table, as modeled via the RIVER boundary condition. Furthermore, as Ghysels et al. (2019) have shown, the conventional MODFLOW approach tends to oversimplify bed and bank structure, neglecting vertical and lateral substrate heterogeneity, as well as lateral flows across banks. This can lead to an incomplete representation of groundwater-river exchanges and, in contexts such as that of this study, to an underestimation of the volumes of water transferred laterally from lowland units (e.g. fine alluvium and fill) to the channel, to the benefit of the vertical inflows simulated by the bed.

To overcome these limitations, the use of a coupled model could have been considered. Models such as HydroGeoSphere (Brunner et al., 2010; Frey et al., 2016) or SWAT-MODFLOW (Bailey et al., 2016) are designed to integrate fluxes between saturated and unsaturated zones, as well as surface interactions. HydroGeoSphere simulates flows across the vadose zone and aquifer systems, while SWAT-MODFLOW combines surface and subsurface hydrological processes in watersheds. For river-bank exchanges, the study by Ghysels et al. (2019) proposes an alternative method in MODFLOW using the Horizontal Flow Barrier (HFB) package. These combined tools could offer a better understanding of complex hydrological processes and improve the accuracy of simulations.

That said, it's important to stress the considerable effort in terms of time, skills and resources required even for a simple conceptual model under permanent conditions. In addition to the modeler's skills, the costs associated with field data collection, model structuring and calibration are high. These constraints are amplified when modeling transient conditions or using coupled models. As noted by Ntona et al. (2022), it is essential to consider these limitations in any restoration planning approach, especially in agricultural environments, where resources are often limited.

Despite these constraints, hydrogeological modelling offers a number of interesting prospects. In particular, it enables us to validate, on a quantitative basis, hydrological hypotheses that are often formulated theoretically. In this study, modelling revealed the structure of hydrological exchanges in a backfilled alluvial plain, notably the differentiated role of geomorphological units in the transit of groundwater. It also highlights the importance of hydraulic conductivity contrasts and unit thickness in structuring flows. These results enrich our understanding of hydrological dynamics in small degraded lowland streams, systems often neglected in modeling efforts due to their morphological complexity and historical alteration.

Modelling is also a useful tool for strategic restoration planning. As discussed in the previous section, it can help identify priority areas, target geomorphological units with the greatest potential for recharge or denitrification, and test the effect of management scenarios. In this way, it helps to better align restoration objectives with the physical reality of the environment. It can also facilitate dialogue between disciplines and stakeholders, by providing a visual and quantitative representation of the processes involved (Ntona et al., 2022; Fredericks et al., 1998). In this sense,

even if it cannot be applied on a large scale, high resolution hydrogeological modelling could contribute to a regional knowledge bank on the links between alluvial structure, land use and hydrological connectivity, which is a valuable basis for guiding future passive restoration projects.

3.5 Conclusion

The aim of this chapter was to explore the exchange dynamics between surface water and groundwater in a highly transformed agricultural stream, using conceptual hydrogeological modelling calibrated to permanent conditions. This approach validated certain hypotheses formulated on the basis of field data, while revealing flow structures that are difficult to perceive in any other way. Despite the simplifications inherent in this type of model, the results obtained shed original light on the differentiated role that geomorphological units can play in hydrological connectivity, even in an environment of backfilled alluvial floodplains and straightened streams.

Simulations show that the alluvial plain, despite its transformation, retains an active function in regulating subsurface flows, particularly through certain nodal zones such as the abandoned meanders formed of coarse alluvium. The importance of hydraulic conductivity contrasts, unit thickness and stratigraphic configuration appears to be decisive in the organization of subsurface flows, directing exchanges between regional units, alluvium and the stream bed. These results confirm that agricultural lowland environments are not hydrologically homogeneous, and that their restoration should be based, among other things, on a detailed understanding of the structure and dynamics of subsurface flows.

From an operational point of view, modelling enables us to identify locations with high potential for groundwater recharge, denitrification or preferential transfer. This integrated reading can support the design, prioritization and optimization of passive restoration projects. It also shows the importance of adapting interventions, such as the establishment of wider vegetated riparian buffers or the removal of crops, to the geometry, connectivity and physical composition of the riparian environment.

Finally, although the technical limitations of the model (notably the lack of coupling with the vadose zone and surface flooding inputs) restrict interpretation results in absolute terms, the exploratory scenarios confirm the relevance of such an approach to support informed decision-making. From this perspective, hydrogeological modelling can be used as a lever to strengthen the

link between scientific knowledge and the strategic planning of agricultural stream restoration projects.

Liaison paragraph:

The next chapter will focus on the practical implementation of a passive restoration project in a heavily reworked lowland environment, based on the retreat of cultivation from a former alluvial plain. It will highlight the challenges, trade-offs and lessons learned in translating hydrogeomorphological and hydrogeological principles and observations into concrete restoration action in the field.

Chapter 4: One Meander at a Time: an innovative project to restore a straightened stream in an agricultural area

Planned to be submitted in the journal Vertigo (in French)

Summary:

In agricultural areas, in Quebec province, stream restoration remains limited, mainly due to severe modifications to streams, land constraints, and an unsuitable regulatory framework. This article documents the *Un Méandre à la fois* project, the first process-based restoration initiative targeting a straightened stream and its freedom space on farmland in the Montérégie region (Quebec). The project, which grew out of a research initiative, has become a showcase for restoration with minimal mechanical intervention, based on a detailed understanding of hydrological connectivity and close collaboration with a family of crop producers. Using a combination of piezometric, hydraulic, geomorphological, and ecological analyses, the project highlights the conditions conducive to the return of natural processes. Initial monitoring (3 years) shows gains in flora, bird, and insect diversity, despite limited interventions. The discussion highlights the levers for success: intersectoral consultation, co-construction of measures, and simplified monitoring. It also highlights the institutional constraints hindering the implementation of effective sustainability tools. In conclusion, this project illustrates the potential of passive restoration that is rooted in the territory and replicable, relying on complementary knowledge, trust between partners, and gradual adjustment to local realities. It thus paves the way for a new generation of projects integrating social, agricultural, and hydrogeomorphological dimensions that are better adapted to the challenges of ecological resilience in agricultural environments.

4.1 Introduction

In Quebec, as elsewhere, the degradation of wetlands and stream environments in agricultural contexts is an increasingly pressing issue that is recognized in public policy (Biron et al., 2018; Gariépy-Girouard et al., 2025). In the St. Lawrence lowlands, streams have been profoundly altered to allow for intensified agricultural production: channels have been straightened (linearized), banks and beds have been incised, and floodplains (or alluvial plains) have been filled and/or drained (Rousseau & Biron, 2009; Couture et al., 2024). These interventions have led to a marked reduction in geomorphological processes (erosion, transport, accumulation of sediments and wood) and hydrological exchanges, compromising the filtering, buffering and biological refuge roles that these environments play in the functioning of agroecosystems.

In recent years in Quebec, programs such as the Program for the Restoration and Creation of Wetlands and Water Environments (PRCMHH) and the Regional Wetland and Water Environment Plans (PRMHH) have called for intensified conservation and restoration efforts, including on private land. However, existing technical and regulatory instruments are still poorly adapted to the social, economic, and land tenure realities of agricultural areas. In many regions, the streams that cross these areas are still subject to intensive maintenance practices financed in part by the Financière Agricole du Québec. At the same time, legal protection measures (e.g., mandatory 3-meter riparian buffers, no backfilling or excavation within stream littoral zone) are often difficult to enforce (Ruiz et al., 2021). The coexistence of the agricultural production objectives and the ecological functions of wetlands and streams is often conflictual and leaves little room for experimentation or innovation in restoration.

There is broad scientific consensus that restoring riparian vegetation and partially reconnecting floodplains, when compatible with land uses, can lead to measurable gains in water quality, groundwater recharge, and biodiversity. Process-based restoration approaches (Beechie et al., 2010) do not aim to restore a pre-degradation ideal form of stream, but rather to recreate the conditions necessary for ecosystem self-regulation, in particular through the restoration of hydrological connectivity (Marchand et al., 2022; Wohl et al., 2024; Mason et al., 2025). In this perspective, several authors emphasize the relevance of passive, low-mechanization interventions that can be integrated into fundamentally constrained contexts, provided they are rigorously designed and monitored over time. One of the levers for supporting the resilience and restoration of the hydrogeomorphological functions of streams is the concept of freedom space, which combines floodplain space (including riparian wetlands) and the natural mobility of a stream (Biron et al., 2014) .

In Quebec, truly promising stream restoration projects, i.e., those that are functional, replicable, and compatible with agricultural constraints, remain rare (Gariépy-Girouard et al., 2025). This scarcity is particularly marked with regard to process-based restoration approaches. Most of the interventions identified aim instead at targeted improvements to fish habitat, particularly for brook trout, through measures such as the creation of pools or spawning grounds (Biron et al., 2018; Gariépy-Girouard et al., 2025). This type of restoration favors an approach focused on certain

species or structures, to the detriment of an integrated ecosystem view of streams and their floodplains.

It is therefore with a view to innovation that the *Un Méandre à la fois* (*One Meander at a Time*) project was implemented. This is a passive restoration initiative for a straightened stream reach in an agricultural area in Montérégie (Petit Pot-au-Beurre, PPAB), in close collaboration with a family of farmers (Ferme Parentall). The intervention, carried out without landscaping or reprofiling, aims to restore hydrological connectivity through the gradual removal of crops from the river's freedom space, corresponding to the former backfilled floodplain, the spontaneous revegetation of the river's freedom space, and the replacement of an undersized culvert.

This article draws on this case study to analyze the ecological and social effects of the passive restoration of a small reach of the PPAB, with a perspective to its feasibility and transferability to other watersheds. It looks at both the measurable results obtained in the first three years and the socio-economic conditions that made this project possible, with a view to replicability on a larger scale.

4.2. Conceptual framework and critical perspective

4.2.1 Understanding hydrological connectivity in agricultural environments

In fluvial environments, hydrological connectivity refers to the exchange of mass and energy between the different components of a river system (channel, water table, floodplain, wetlands, lake, pond, hillslopes) in response to hydrological flows (Bracken et al., 2013). It typically manifests itself in three dimensions: longitudinal (upstream-downstream), lateral (between the channel and the floodplain), and vertical (between the riverbed and the groundwater table) (Stanford & Ward, 1993; Wohl, 2017a). This connectivity plays a central role in nutrient transport and transformation (Harvey et al., 2019), thermal regulation (Hannah et al., 2009), groundwater recharge (Doble et al., 2012), flood dissipation (Wohl, 2021) and the maintenance of biodiversity adapted to fluvial dynamics (Ward et al., 1999; Pander et al., 2018).

Numerous studies have highlighted the existence of preferential exchange zones within river systems, i.e., portions of the river where exchanges between the channel, saturated banks, and the surface water table are amplified. Depending on the authors and contexts, these zones are referred to by various terms: river corridors (Harvey & Gooseff, 2015; Wymore et al., 2023), river freedom

space (Biron et al., 2014), or river beads . These preferred exchange zones share several functional characteristics: gentle slopes, widened channels, low riparian zones composed of permeable materials, and vegetation cover typical of wetlands. When sufficiently intact in terms of morphology and land use, alluvial plains can be considered large-scale preferential exchange zones (Opperman et al., 2010; Wohl, 2025). Their temporary activation, even partial, makes it possible to modulate floods, recharge the shallow groundwater table, and support plant regeneration dynamics (Amoros & Bornette, 2002; Ferraz, 2022; Petsch et al., 2023). Alluvial plains facilitate bidirectionnal exchanges between surface water and saturated riparian areas, thus playing an essential buffering role in seasonal water balances (Maharjan & Donovan, 2016; Zimmer & McGlynn, 2017; Mason et al., 2025).

In agricultural watersheds, the three dimensions of connectivity and the extent of preferential exchange areas are often altered simultaneously (Wohl, 2019), limiting exchanges with the water table and isolating the channel from its floodplain (Burt et al., 2002; Schilling et al., 2004). Several cross-structures and water retention structures, like weirs and dams, also hinder longitudinal connectivity, particularly the free movement of aquatic organisms. Restoring hydrological connectivity in these contexts cannot therefore be reduced to simple physical reconnections: it requires re-establishing a dynamic functioning, where the nature and intensity of exchanges evolve according to seasonal variations in water level and across the different components of the river system (Beechie et al., 2008; Wohl et al., 2024). The challenge is therefore not only to physically reconnect the channel to its floodplain, but to restore conditions conducive to slow, diffuse, and reversible water flow, which is favorable to ecosystem services such as groundwater recharge, denitrification (i.e transformation of nitrate), and resilience to hydrological extremes.

In the context of a process-based restoration approach, the concept of hydrological connectivity is not viewed as a binary state (connected/disconnected), but as an emerging property that depends on hydraulic flows, existing materials, riparian vegetation, and land use (Bosworth et al., 2025). Restoring connectivity in a restored stream in an agricultural environment therefore involves recognizing the importance of residual exchange zones, reducing physical barriers, and promoting processes that allow the free movement of water, sediments, dead wood, and living organisms.

4.2.2 Process-based restoration approaches and the distinction between active and passive interventions

Over the past two decades, a consensus has emerged on the need to shift river restoration interventions from a morphology-centric approach to a process-based approach (Kondolf et al., 2006; Beechie et al., 2010; Powers et al., 2019; Wohl et al., 2024). The "process-based" approach aims to recreate the conditions necessary for the natural expression of hydrological, sedimentary, biological, and geochemical dynamics, rather than artificially reproducing target river forms deemed ideal. This paradigm shift is based on the idea that ecological functions emerge from dynamic processes (groundwater recharge, material transfer, plant regeneration) that cannot be sustained without adequate physical conditions.

In this context, the authors generally distinguish between two main types of intervention: active restoration, which relies on planned physical improvements (e.g., reprofiling, landscaping, directed planting), and passive restoration, which aims instead to remove anthropogenic pressures and allow natural processes to resume their course (Wohl et al., 2015). While active approaches may be necessary in highly artificial environments, they require significant financial resources, rigorous technical supervision, and social acceptability that is often more difficult to achieve, particularly in agricultural settings (Palmer et al., 2005; Campeau et al., 2023) .

Conversely, passive or semi-passive approaches are particularly suitable when land, technical, or social constraints limit the scope of possible interventions (Jones et al., 2018; Rohr et al., 2018; Chazdon et al., 2024). In several contexts, they can offer an effective compromise between feasibility, costs, and ecological benefits, particularly when local conditions allow for partial natural regeneration or when anthropogenic pressures are limited (Aleeje et al., 2025). Cost-benefit analyses conducted in New Zealand by Daigneault et al., 2017 have shown that such passive projects, when well targeted, can generate ecological benefits comparable to or even greater than active projects, while significantly reducing initial costs and land use conflicts.

This approach is particularly suited to agricultural environments, where land constraints, production objectives, and limited budgets make it difficult to implement civil engineering-based projects. Several studies have shown that low-mechanical-intensity interventions, such as the removal of human activities in riparian wetlands, natural channel stabilization, or the reintroduction of dead wood, can lead to measurable ecological gains, particularly in terms of

groundwater recharge, water temperature, nutrient retention, and wildlife habitat structure (Weigelhofer et al., 2012; Forget et al., 2013; Martens et al., 2019; Sanders et al., 2020) .

Among the most effective structuring elements are wooded riparian strips, which play a central role in restoring ecological functions. According to O'Huallacháin et al. (2025), these strips outperform herbaceous strips for most of the ecosystem services assessed, including water quality, biodiversity, carbon storage (due to their greater longevity, higher biomass and denser roots system) and even landscape perception. However, their effectiveness depends on their connectivity with the floodplain and the channel, in contexts where periodic flooding can stimulate plant succession processes and enhance soil fertility.

While these process-based restoration approaches have gained international recognition, their implementation remains marginal in Quebec, particularly in agricultural areas, where constraints are numerous.

4.2.3 Quebec constraints and levers for action for restoration in agricultural areas

In Quebec, the restoration of wetlands and stream environments in agricultural contexts is part of a changing institutional framework. The Program for the Restoration and Creation of Wetlands and Water Environments (PRCMHH-MELCCFP, 2025), the Regional Wetland and Water Environment Plans (PRMHH-MELCCFP, 2022) and various environmental organizations (e.g., Fondation de la Faune du Québec) now offer support for interventions on private land. However, their implementation in the field faces many obstacles: significant artificialization of streams, significant land constraints, the rigidity of certain agricultural practices, and a lack of consistency between the objectives pursued by the various ministries concerned. These institutional tensions limit the scope of collaborative projects, particularly in areas characterized by intensive agriculture.

At the same time, the concept of freedom space (Biron et al., 2014), although absent from legislation and regulations, has gradually been incorporated into several national strategic documents and guidelines, particularly in relation to the analysis and mapping of river hazards (Dy et al., 2018; Quebec Government, 2023). Since 2022, the concept of river mobility zones has been formally recognized in the Environment Quality Act (LQE, art. 46.0.4.2), where it is mainly used to regulate certain developments on rivers in the context of fluvial hazards. However, this

recognition remains marginal in the field of ecological restoration, and even more so in the restoration of streams in agricultural areas.

In the St. Lawrence lowlands, the riparian zone of agricultural streams is often reduced to a narrow strip, saturated with technical, agricultural, and economic issues: the presence of underground tile drains, the immediate proximity of crops, productivity requirements, and high land values. As shown by the work of the Lake Saint-Pierre Littoral Expertise Pole (Campeau et al., 2023), these constraints hinder the adoption of even modest restoration practices. Agricultural producers anticipate economic losses (Gariépy-Girouard et al., 2025), technical support is sometimes insufficient, and conservation measures are often perceived by farmers as external impositions or forms of disguised expropriation by the governments.

In this context, even flexible, iterative, or passive restoration approaches struggle to gain traction due to a lack of documented examples recognized by institutions. Furthermore, as highlighted by Arsénio et al. (2020), the lack of immediate visibility of ecological benefits can reduce the perceived value of these projects in the eyes of local communities, particularly agricultural producers. However, studies show that co-constructed projects, adapted to agricultural rhythms and monitored over time, can generate tangible transformations, even in fragmented or constrained contexts (Daigneault et al., 2017; Schumann et al., 2021).

It is therefore crucial to document realistic and transferable initiatives, even modest ones, that demonstrate through practice the feasibility of restoring the hydrological and ecological functions of streams in agricultural areas without requiring a complete break with the needs and requirements of the agricultural world. With this in mind, our study proposes to examine these concepts on a implemented project, combining a passive restoration approach, collaboration with a family of producers, and ecological monitoring in a heavily modified stream reach in an agricultural area. The project *Un Méandre à la fois (One Meander at a Time)* is part of this approach.

4.3 Site context and genesis of the *Un Méandre à la fois* project

4.3.1 Location and physical characteristics

The *Un Méandre à la fois* project is being carried out in the municipality of Saint-Robert, in the Montérégie region, within the St. Lawrence Lowlands (Figure 4.1). The project site is located in

the watershed of the Pot-au-Beurre River, a sub-tributary of the Yamaska River, which flows into Lake Saint-Pierre, a UNESCO biosphere reserve.

The targeted reach, approximately 300 m long, corresponds to branch 13 of the Petite Pot-au-Beurre, a headwater second-order (Strahler) stream, characterized by a bank full channel discharge of approximately 1.5 m^3/s and a bank full width of approximately 4 m. This reach crosses land operated by Ferme Parentall, which is used for conventional corn and soybean cultivation.

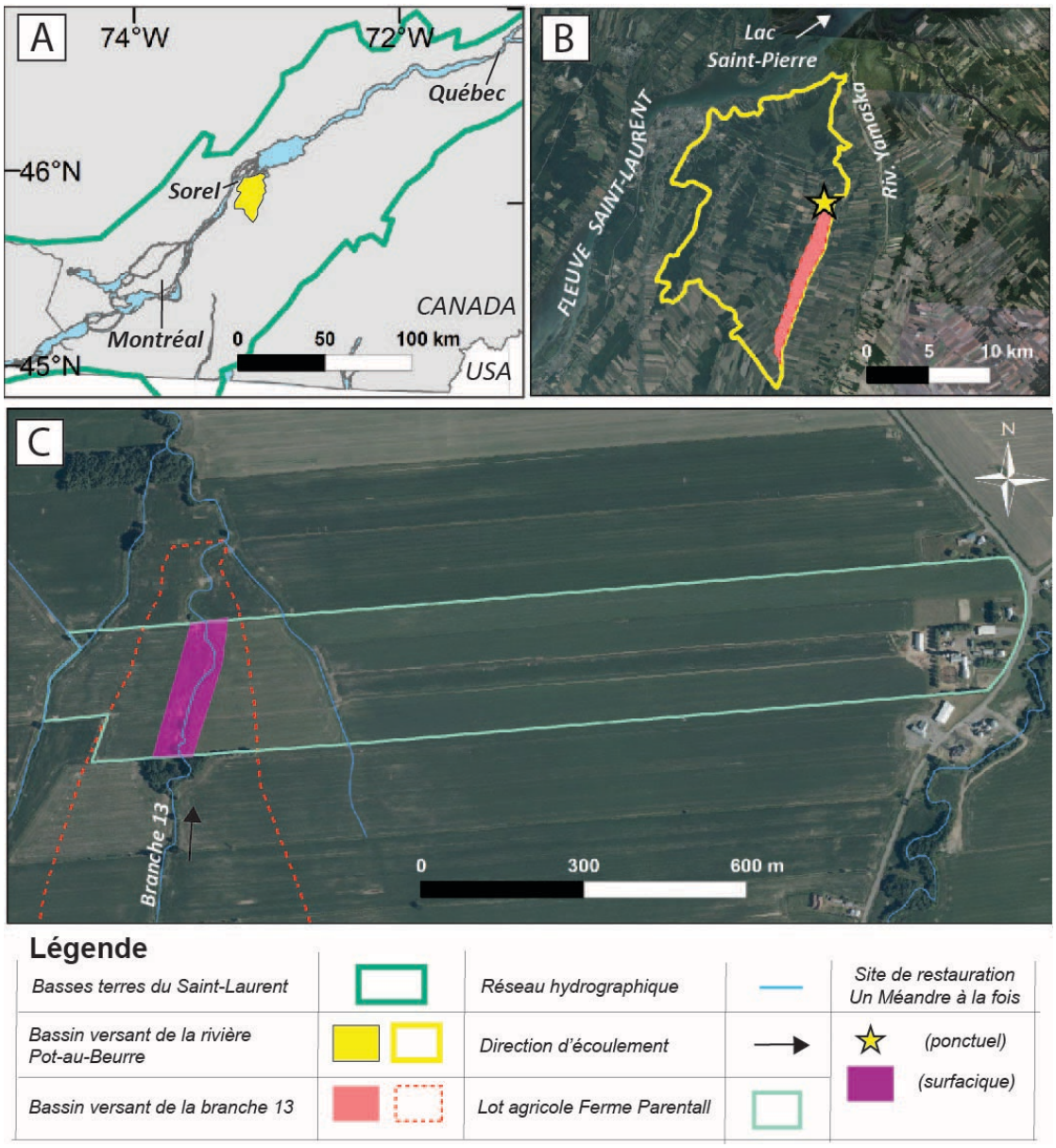


Figure 4.1. Location map of the restoration site One meander at a time

Historically, the stream had a meandering river style, with meanders reaching a maximum amplitude of approximately 60 meters (Figure 4.2). A well-developed floodplain occupied the margins of the stream. Stratigraphic surveys have confirmed that the original alluvial material is still present below the surface (Marchand et al., 2022). In 1983, the channel was mechanically straightened and the floodplain was backfilled with local materials. The alluvial plain consists mainly of fine loamy sand, grading to medium to coarse sand, with a thickness varying from 0.70 m to 1.5 m depending on the area. The coarsest and thickest alluvial deposits are found at the apex locations of the former meanders. The regional substrate, adjacent to the alluvium, is formed by shallow marine deposits, mainly composed of clayey silt.

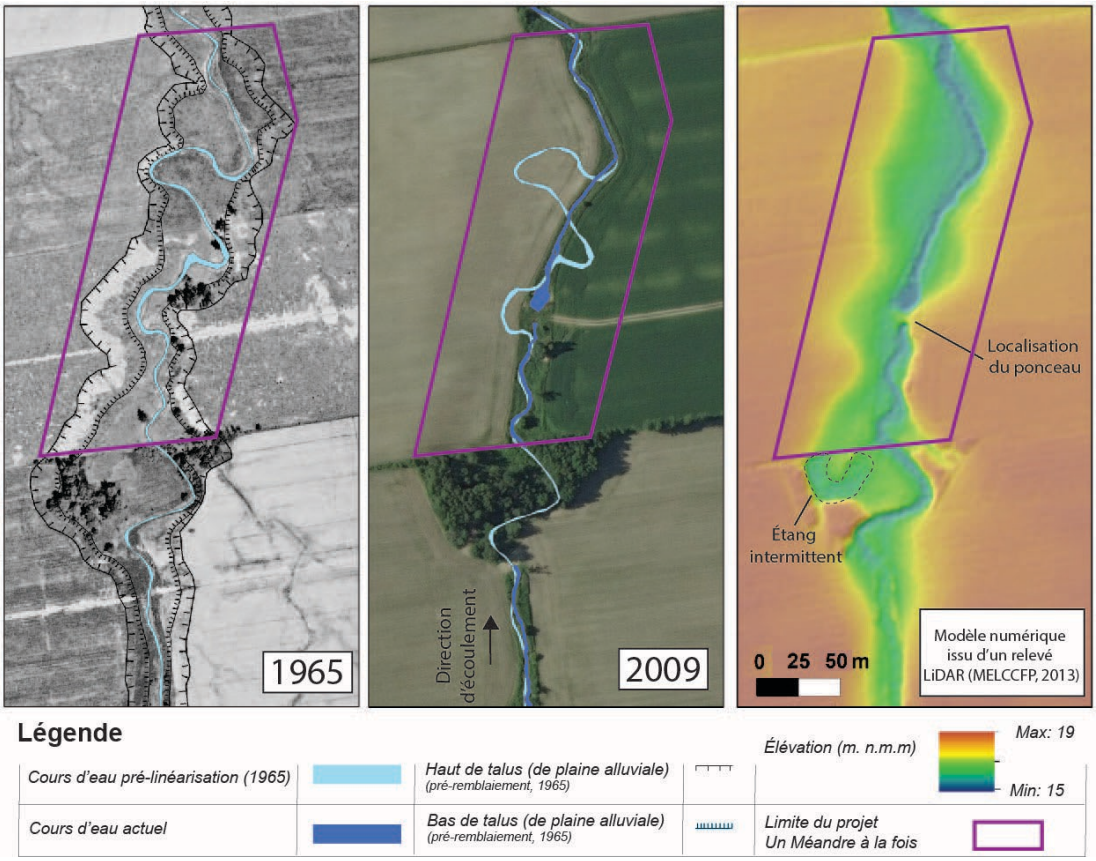


Figure 4.2. Historical evolution of the restoration site: (A) historical aerial photo of the site in 1965 showing the morphology of the site prior to the straightening and backfilling work, (B) aerial photo of the site in 2009, prior to the restoration project, and (C) digital elevation model based on a LiDAR (Light Detection and Ranging) survey showing the current morphology of the site.

Until recently (2021), the backfilled floodplain was cultivated up to the immediate vicinity of the regulatory 3-meter riparian strip. An agricultural subsurface drainage network is present on both sides of the stream, although only the implementation plans for the left bank are available. The network consists of 10 cm diameter crepinated pipes, spaced approximately 15 m apart and buried between 30 and 70 cm in the ground. An undersized culvert (diameter: 1100 mm) in terms of flow area also crosses the site in the center of the reach. It should be noted that an unmodified segment of the stream remains immediately upstream, with a wooded floodplain and even an intermittent pond occupying a former meander bend (Figure 4.2).

4.3.2 From a research project to a restoration initiative

The *Un Méandre à la fois* project took root in a scientific study initiated in 2017 and funded by Environment and Climate Change Canada about the hydrological connectivity between straightened lowland streams and their former meanders (Massey et al., 2019), which included the Ferme Parentall site. Pressure probes installed in piezometers in straightened channel reaches and in former abandoned meanders made it possible to compare fluctuations in surface water levels between the channel and shallow riparian aquifer during different precipitation events.

As part of a doctoral research project (Marchand, 2025), monitoring of surface and groundwater levels has documented the existence of a groundwater response that is almost synchronous with surface fluctuations in the channel, despite the presence of backfill material covering the historic floodplain. Stratigraphic surveys carried out using hand augers have characterized the grain size and stratification of alluvial deposits across the site, which has been used both to position piezometers and to formulate hypotheses on the dynamics of lateral and vertical subsurface water exchange between the channel and the backfilled meanders. These empirical observations, detailed in Marchand et al. (2022), suggest that the reworked alluvial materials may retain significant subsurface hydrological connectivity with the straightened channel, giving the historic floodplain a high restoration potential.

These field observations were supplemented in subsequent years by two complementary modeling exercises: one-dimensional hydraulic modeling with HEC-RAS (Marchand & Biron, 2025) and hydrogeological modeling with MODFLOW in steady state (Marchand, 2025, chapter 2). The HEC-RAS model confirmed reduced lateral connectivity between the main channel and its riparian environment, accentuated by historical channel straightening and partial backfilling of the

floodplain. It also identified a break in longitudinal connectivity at the undersized culvert, illustrated by an asymmetry in flow velocities upstream and downstream of the culvert. During floods, a reservoir formed upstream of the culvert, limiting any possibility of sediment or dead wood being transported by the flow, which was reduced to a virtually stagnant environment. Downstream, under the narrowing effect at the culvert, a pressurized flow formed, leading to the scouring of an erosional pool. Over time, this accentuated erosion under the culvert's bed led to a disconnection of the flow during low water periods, also limiting the passage of aquatic organisms. The MODFLOW model suggested the existence of preferential groundwater flows from the regional environment to the alluvial material composing the floodplain before reaching the riverbed. The model determined that these preferential flows are particularly pronounced at the interfaces between materials with contrasting conductivities, particularly between the coarse alluvium of the former meanders and the fine marine sediments forming the regional deposits.

In summary, this methodological crossover (summarized in Figure 4.3) confirmed the relevance of the site for restoration focused on hydrological connectivity, providing a robust diagnosis of the physical barriers to be removed and the nodal role played by the backfilled floodplain in surface water-groundwater exchange dynamics.

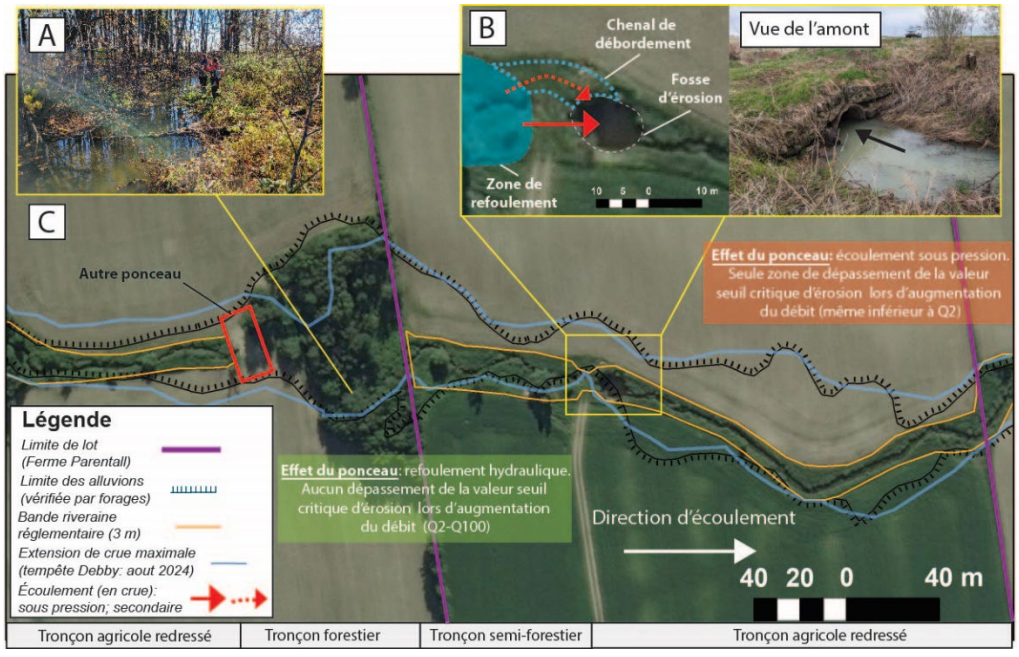


Figure 4.3. Summary of the hydrological connectivity components studied in the context of agricultural stream restoration: (A) forested section upstream of the restoration site with potential to supply the stream with dead wood and sediments, (B) flow dynamics at the undersized culvert, and (C) overview of the hydraulic and geomorphological features identified in the freedom space.

4.3.3 Genesis of the project One meander at a time

The restoration project emerged in the wake of the research on hydrological connectivity conducted on branch 13 between 2017 and 2021. In 2017, Ferme Parentall initially agreed to remove an initial area of 0.3 hectare, corresponding to one former meander bend, from cultivation to allow the installation of a network of piezometers. In return, they were paid compensation equivalent to the estimated net loss of agricultural income. This initial arrangement, which respected agricultural interests while facilitating research, laid the foundations for a relationship of trust between researchers and producers.

Over the years, numerous informal discussions took place, consolidating this relationship. These exchanges focused as much on scientific results as on agricultural practices, logistical challenges, local memory, and environmental issues. In 2019, floristic monitoring was initiated to inform the producers about the potential spreading of exotic and invasive species, which can, among other impacts, reduce crop productivity (Lavoie, 2019).

With preliminary results suggesting that the former floodplain maintained high residual lateral and vertical hydrological connectivity, a proposal was made to producers in 2021 to expand the study area. A second meander was included, and financial compensation was adjusted. The idea of a large-scale restoration project for the entire plain then emerged, provided that no significant impact on yields or agricultural operations was observed. The farmers perceived this project as a way to contribute to the ecological health improvement of the lake Saint-Pierre, an ecological treasure in their region.

In order to guide discussions with producers and rigorously define the area of intervention, a functional freedom space was delimited and presented to producers. This delimitation was based on historical aerial photographs of the former meanders, stratigraphic data collected in the field, and observations from monitoring surface and piezometric water levels. In this case, the freedom space corresponded to the extension of the floodplain alluvial deposits where lateral and vertical hydrological exchanges between the channel and its riparian environment remained partially active.

At the same time, a project proposal was presented to various regional stakeholders, including a producers' union (UPA), a watershed management organization (OBV), and habitat protection

organizations. Collaborations were initiated, particularly in the context of regional participatory consultation processes related to wetland and stream restoration, such as the Lac-Saint-Pierre Living Laboratories and the implementation of the Regional Wetland and Water Plans of the Pierre de Saurel Regional County Municipality (MRC). As a result of this collaboration, the MRC has agreed to conduct two annual drone flyovers, and several joint conferences with regional and national stakeholders have been held. These actions have helped rally key support, including from the Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs (MELCCFP), which in 2022 awarded funding for a three-year pilot project.

This pilot project, called *Un Méandre à la fois* (One Meander at a Time), is based on a passive approach to restoring the processes of a straightened agricultural stream and its riparian area. Two key interventions were to be implemented during phase 1 (2022-2025) (Figure 4.4): 1) the removal of crops from the stream's freedom space, allowing spontaneous revegetation in the former floodplain, and 2) the replacement of the undersized culvert.

The area actually withdrawn from cultivation has been slightly adjusted from the initial delimitation of the freedom space for two reasons: firstly, to accommodate the passage of agricultural machinery, and secondly, to include certain areas located outside the historical floodplain, in order to be able to compare the ecological responses inside and outside the freedom space as part of the monitoring system. This compromise made it possible to preserve the initial hydrological logic while ensuring the operational feasibility and scientific value of the project. An amount corresponding to the loss of income was paid to the producers of the Parentall Farm as rent for their land throughout phase 1. In the final year of phase 1 of the project, the producers decided on their own initiative to add a buffer zone of forage crops to the crop withdrawal zone, in order to simplify the passage of machinery as much as possible and to add an additional protection zone for streams.

The undersized circular culvert (1100 mm) was replaced by an arched culvert with a flow area four times greater than the previous one (2500 x 1800 mm). This scenario was chosen from among three others (ford, bridge, arched culvert) because it was recommended for clay soil, was practical and safe for producers, and represented a reasonable total cost.

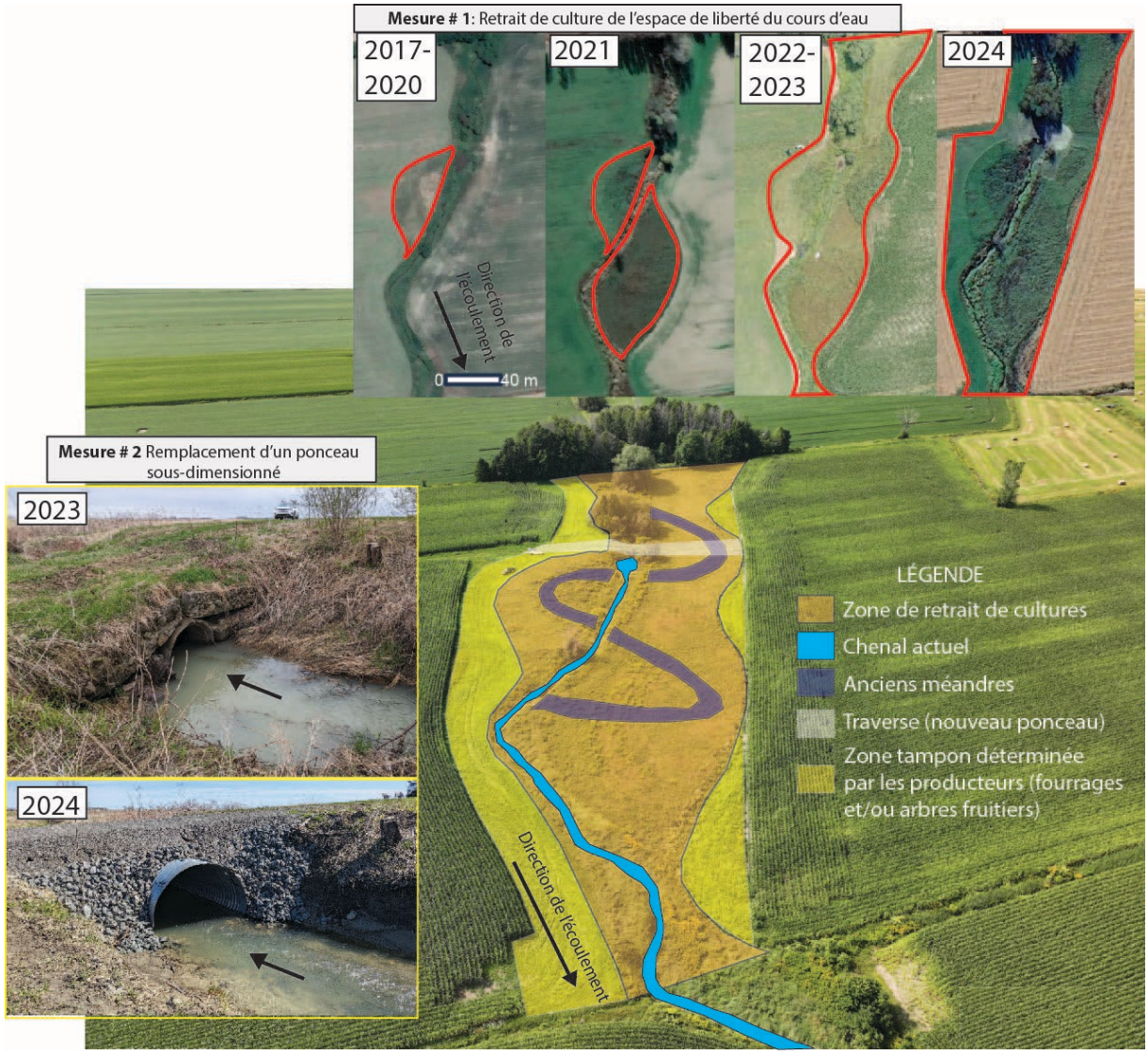


Figure 4.4. Restoration measures implemented as part of the Un Méandre à la fois project during phase 1(2022-2025), including (1) changes to the configuration of crop removal from the historic alluvial plain and the replacement of the undersized culvert (diameter: 1100 mm) with a wider arched culvert (2500 x 1800 mm).

The project was designed to allow for both ecological and social assessment, with a view to transferability. Monitoring was planned to document potential gains in biodiversity and stakeholder perceptions. The indicators chosen were intended to reflect both the quality of the habitat and the perceived value of the project by agricultural producers. The protocol, which has been implemented in 2022, is based on simple, comparative, and inexpensive methods inspired by the BACI (Before-After Control-Impact) design. It is presented in the following section.

4.3.4. Monitoring methodology

In order to document the ecological and social effects of the *Un Méandre à la fois* project, an ecological monitoring strategy (Figure 4.5) and a protocol for semi-directed interviews with producers were implemented from the first year of the intervention (2022). The indicators for ecological monitoring were selected for their relevance in an agricultural context, their relevance in the context of a passive restoration approach for a stream and its riparian environment, and their simplicity of implementation.

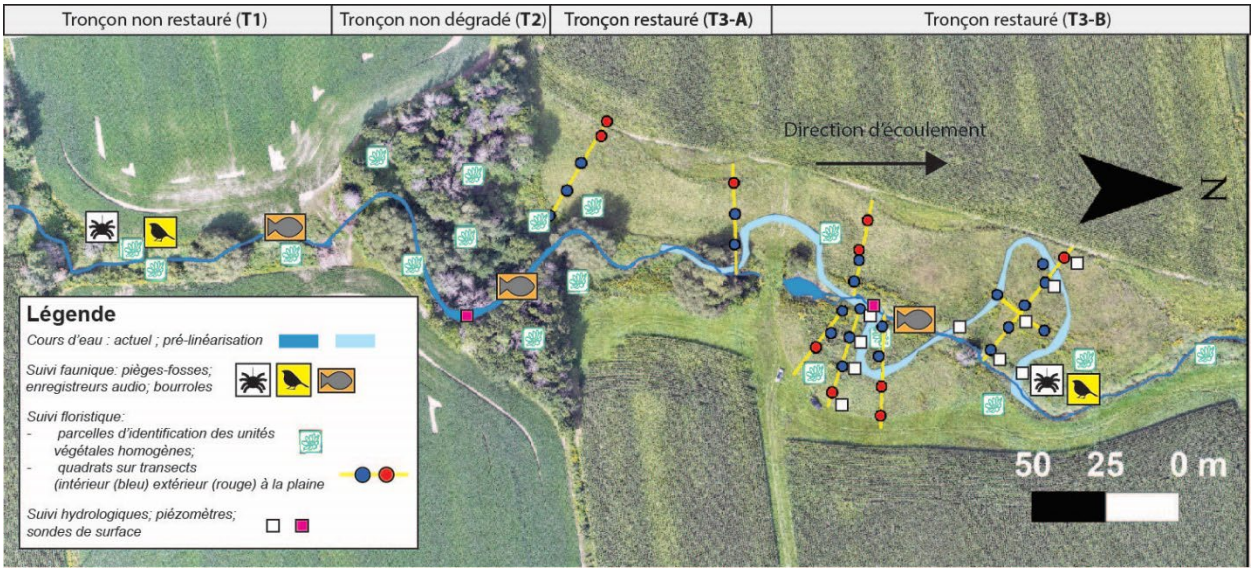


Figure 4.5 Location of the various flora, fauna, and hydrological monitoring devices at the study site

4.3.4.1 Vegetation monitoring

The dynamics of plant recolonization in the riparian environment were monitored by floristic inventory in homogeneous plant units and within sampling plots arranged on transects perpendicular to the stream (Figure 5). Surveys were conducted annually during the growing season (end of July). The floristic composition was analyzed based on species richness and the ratios of native, exotic, and invasive exotic species. Changes in the floristic composition of the riparian environment were compared between the restored straightened reach (T3) and control sites located upstream of the study site (unstraightened (T2) and unrestored (T1)).

4.3.4.2 Wildlife monitoring

Several wildlife groups were targeted for their sensitivity to changes in aquatic and riparian habitats and for their importance to agricultural producers.

- Spiders: Arachnid communities were sampled using *pitfall* traps installed for 10 days (early June) in the riparian zone of the restored straightened reach (T3) and the unrestored control reach (T1). This indicator was chosen as a proxy for the terrestrial invertebrate food web, particularly pollinating insects. Species richness, abundance, and biomass were used to compare sites.

- Farmland birds: The songbird species present were detected using SM4 (Song Meter) recorders set up for 10 days during the nesting period (early June). Although field birds do not constitute a formal scientific category, they include various species associated with agricultural and semi-open environments, where they play an important ecological role, particularly in regulating insect pests (Mayne et al., 2023) and in ensuring pollination and seed dispersal (Wenny et al., 2011; Triplett et al., 2012). Species diversity and number of territories were the variables used to compare the restored straightened reach (T3) and the non-restored straightened reach (T1).

- Fish: Sampling campaigns for fish fauna were conducted using crayfish traps. These were set up in the stream for 24 hours, and the individuals caught were identified to species and then released. Three sampling campaigns were carried out each year (late April, early June, end of summer). Two traps were set up per site, one in the restored straightened reach (T3), one in the unrestored non degraded reach (T2), and one in the unrestored straightened reach (T1). Abundance, species richness, and the Shannon-Wiener diversity index were used to compare the sites.

4.3.4.3 Hydrogeomorphological monitoring

In addition to continuing to monitor surface water levels (with pressure probes) and groundwater (with a network of piezometers), the study site was also assessed using the Morphological Quality Index (MQI) adapted to small agricultural streams. The IQM assesses the level of anthropogenic disturbances that may affect the morphological condition of a river (Rinaldi et al., 2013, 2016; Lemay et al., 2021; Pouliot et al., 2024). It is based on the assessment of 28 indicators related to the level of integrity of hydrogeomorphological forms and processes in the channel and riparian environment, as well as the level of artificiality and the history of the stream.

In 2020, an initial survey covering the entire study site provided a baseline profile with an overall score of 0.55, corresponding to moderate morphological quality (Lemay et al., 2021). The main

weaknesses identified were the discontinuity of the floodplain, the widespread absence of functional vegetation (trees and shrubs), the uniformity of cross-sectional profiles, and the presence of a culvert limiting longitudinal connectivity. A more detailed reassessment was carried out in 2023, subdividing the studied reach according to the limits of the experimental protocol (restored, unrestored, straightened, unstraightened). This approach made it possible to better distinguish the states of degradation related to historical interventions and to position the restored reach on a morphological naturalness gradient.

4.3.4.4 Socio-economic perceptions

The agricultural producers at Ferme Parentall were consulted at various stages of the project, either through regular informal discussions or by means of a comprehensive questionnaire distributed once a year. These interactions made it possible to monitor the evolution of the project's acceptability, desired adjustments, and perceptions of benefits or constraints.

Although not a specific objective of the first phase of the project, the issue of sustainability, i.e., the implementation of a legal tool to ensure the sustainability of restoration measures, was also discussed with producers. A comprehensive review of existing legal conservation tools and funding programs in Quebec was conducted to facilitate their consideration.

At the same time, a multiple-choice questionnaire was distributed to more than 30 agricultural producers outside the project to try to document the technical, human, financial, and regulatory conditions that would promote participation in a restoration project such as the Parentall Farm project. A specific analysis of the sustainability tools and questionnaire responses can be found in the Marchand and Biron report (2025, see Appendix D).

4.4 Results of the *Un Méandre à la fois* project (phase 1 2022-2025)

4.4.1. Evolution of riparian vegetation

Three years after the removal of crops from the former floodplain, observations reveal gradual plant recolonization, dominated by exotic herbaceous species, with the occasional appearance of wetland plant communities. Between 2019 and 2022, approximately 2,000 m² of the 13,000 m² of riparian area available for plant recolonization had a composition specific to wetlands, including a modest extension (100 m²) beyond the pre-existing regulatory riparian strip (3 m) in the restored section (T3, see Figure 4.5 for section boundaries).

Between 2022 and 2024, homogeneous plant units showed inter-annual substitution dynamics. Some meadow land was thus replaced by different plant communities (Figure 4.6), without any major disruption to the overall structure. In the vegetation recolonization zone, the percentage of coverage by *Bromus inermis* prairie (*friche*) decreased from 55% in 2022 to 51% in 2024. The *Lactuca serriola* meadow disappeared completely between 2022 and 2024, while *Phleum pratense* meadow appeared. The percentage of *Phalaris arundinacea* marsh areas decreased from 25% coverage in 2022 to 14% in 2024, being replaced by *Solidago canadensis* marshes. Finally, a *Solidago canadensis* meadow area appeared within the *Bromus inermis* meadow increasing its percentage of coverage from 8% to 11%. The proportion of wet plant associations remained stable (2022: 25%, 2024: 26%), indicating a slow transition of wet soil conditions favorable to hygrophilous species in the crop retreat zone.

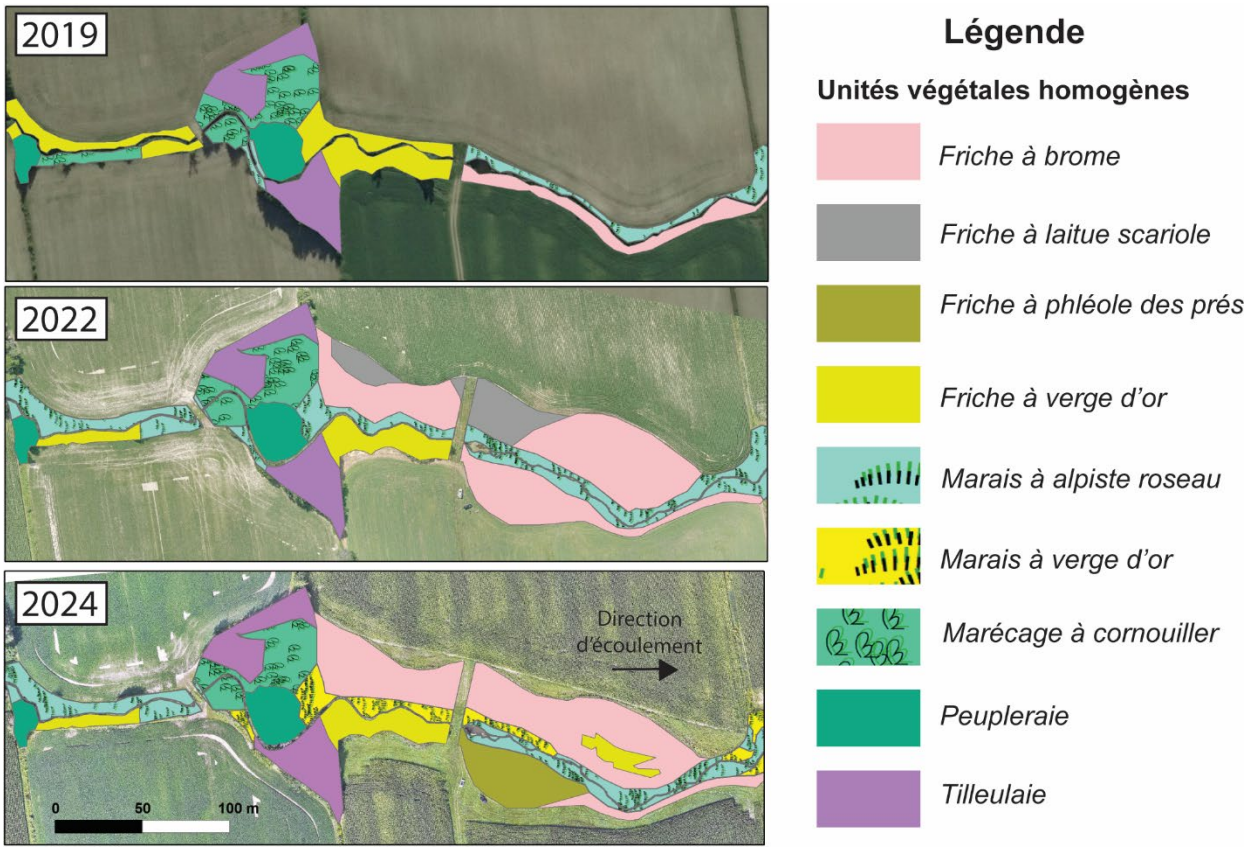


Figure 4.6. Evolution of homogeneous vegetation units (HVUs) on the study site between 2019 and 2024

Floral inventories per plot reveal a persistent dominance of exotic species, representing between 54% and 84% of the cover depending on the inventory plots, while native species cover only 2% to 12% on average (Table 4.1). However, a significant downward trend in the coverage of invasive

alien plant species (EFEE) was observed between 2022 and 2024, particularly in plots located within the former floodplain. Of the nine EFEE species recorded, most saw their abundance decline, with the exception of Reed Canary Grass (*Phalaris arundinacea)*, whose coverage increased between 2022 and 2023, before declining slightly in 2024.

Interesting differences emerge between transects located inside and outside the historical floodplain. Notably, after a period of three years, the percentage of coverage by native species and total species richness are generally higher within the floodplain than outside it, suggesting that ecological conditions in the former floodplain potentially favor more diverse plant recolonization and stronger competition for the growth of exotic and invasive species (Table 4.1). However, in 2024, a statistically significant difference (T-test) was only observed for exotic species cover between transects located inside and outside the former alluvial plain.

Table 4.1. Summary of floristic species inventories (per plot) conducted in the crop withdrawal area. Coverage is expressed in percentage while richness represents the average number of unique species per plot for each category.

	Variable	2022		2023		2024		
		Intérieur	Extérieur	Intérieur	Extérieur	Intérieur	Extérieur	Tendance 2022-2024
TOTAL	% recouvrement EFEE	34.0	22.3	31.0	18.7	22.2	13.4	Diminution
	% recouvrement E	54.4	75.3	59.9	79.8	66.9	84.4	Hausse
	% recouvrement I	11.6	2.4	9.1	1.5	11.0	2.2	Stable
	richesse	6.1	7.0	5.6	4.7	5.2	4.4	Légère baisse
	richesse des exotiques	4.8	6.5	4.7	4.4	4.4	4.1	Légère baisse
	richesse des indigènes	1.3	0.5	0.9	0.3	0.8	0.4	Légère baisse
	richesse des EFEE	1.5	1.8	2.0	1.7	1.2	1.3	Légère baisse

Overall, these preliminary results suggest that the cessation of agricultural activities, combined with spontaneous revegetation, allows for the gradual restoration of more diverse and potentially more functional plant communities, although significant biological pressures persist, notably the omnipresence of exotic species. Longer-term monitoring is needed to assess the ecological success of the approach.

4.4.2. Responses of wildlife communities

Wildlife diversity was assessed using three bioindicator groups sensitive to changes in riparian habitats: grassland birds, spiders, and fish. These groups provide a complementary readout of the ecological effects of the project.

4.4.2.1 Spiders

The density, biomass, and species diversity of spiders captured in pitfall traps at the restored site (T3) shows higher values than at the unrestored site (T1), but these results are preliminary considering the small samples (Table 4.2). Between 2023 and 2024, the two traps at T3 captured 45 and 36 individuals (11 species), respectively, compared to 6 and 20 individuals (7 species) at T1. The average weight of the specimens was also higher at the restored site. Mowing surveys conducted in 2024 confirmed this trend: although abundance was comparable (16 individuals at T1, 17 at T3), diversity (Shannon index) was higher at T3 (2.2 vs. 1.6). This increased diversity could reflect a more complex local food web. Several species characteristic of open wetlands were recorded at T3, including Lycosidae, which are considered good bioindicators (Marusik & Koponen, 2002). These results suggest that the removal of crops from the open space has promoted an increase in the diversity and biomass of arachnid communities, reflecting a more complex trophic structure and greater prey availability.

Table 4.2: Compilation of spider inventory results obtained using pitfall traps at the Parentall Farm restoration site between June 9 and 22, 2023, and between August 16 and 25, 2024.

	2023		**2024**	
Site non-restauré (T1)	**Piège #1**	**Piège #2**	**Piège #1**	**Piège #2**
Densité / piège	0	6	10	10
Diversité (nb d'espèces) / piège	0	3	4	5
Poids / piège (g)	0	0.01	0.138	0.167
Poids moyen / site (g) ± 0.0005	0.005		0.152	
Quantité d'individus moyenne (Nb / site)	3		10	
Diversité moyenne (Nb d'espèces /site)	1.5		4.5	
Indice de diversité de Shannon	1.01		1.61	
Site restauré (T3)	**Piège #1**	**Piège #2**	**Piège #1**	**Piège #2**
Densité / piège	26	19	16	20
Diversité (nb d'espèces) / piège	4	4	8	7
Poids / piège (g)	0.862	0,483	0.342	0.503
Poids moyen / site (g) ± 0.0005	0.673		0.423	
Quantité d'individus moyenne (Nb / site)	22.5		18	
Diversité moyenne (Nb d'espèces /site)	4		7.5	
Indice de diversité de Shannon	1.28		1.94	

4.4.2.2 Farmland birds

Among birds, data from SM4 recorders indicate higher species richness and territory occupancy on the restored site (Table 4.3). On average, there were 14.8 ± 4.3 territories and 12.3 ± 4.0 species

per recording, compared with 12.8 ± 4.1 territories and 10.6 ± 3.8 species on the unrestored site. Although the total number of species detected was similar between the two sites (36 at T3, 35 at T1), these higher averages at T3 suggest higher bird density and better territory occupancy. The restored section attracts more species from open habitats, such as the Meadow Bunting and the Bobolink, the latter only being detected on T3. Conversely, T1 is home to slightly more species from bushes environment, influenced by the adjacent small woodland. Three species of conservation concern were recorded, two of which (the Eastern Pioui and the Bobolink) appear to be benefiting from the conditions created by the restoration project.

These results support the hypothesis that the removal of crops and conversion to grassland improves habitat quality for birdlife. Unfortunately, the bird survey was only carried out in the summer of 2023, as a configuration problem affected the quality of the recordings made in 2024. Although based on a limited sample, these results provide an encouraging first indication of the avian response to restoration.

Table 4.3: Summary of average territories and bird species diversity per recording for each site inventoried (T1 and T3) between June 6 and 16, 2023

	Moyenne de territoires par enregistrement	**Moyenne d'espèces par enregistrement**
Site non restauré (T1)	12.8 ± 4.1	10.6 ± 3.8
Site restauré (T3)	14.8 ± 4.3	12.3 ± 4.0
Différence significative	**Oui** (t = 4.53, df = 29, p-value < 0.001)	**Oui** (t = 3.82, df = 29, p-value < 0.001)

4.4.2.3 Fish

The results for the fish community are more mixed (Table 4.4). In 2022, nine species were recorded, all of which were native cyprinids. In 2024, this number fell to five species, but overall abundance increased sharply (from 65 to 518 individuals), mainly due to a peak in Five-spined Sticklebacks. The restored site maintained a more stable species richness (i.e. number of unique species) between the two years (six then five species) compared to the control sites, but the differences were not significant. The Shannon index (based on species richness and evenness), lowest at T3 (restored section) in 2022, becomes the highest in 2024, without a clear link to restoration measures being established. The persistent dominance of tolerant omnivorous species across all sites reflects the still modest habitat quality. Comparisons with historical inventories in

the Pot-au-Beurre watershed (1970–2016) (Couture et al., 2024) suggest relatively low diversity at the study site compared to other inventory sites further downstream in the watershed.

Table 4.4: Summary of fish inventories conducted at the study site in 2022 and 2024

		Site non restauré (T1)		Site forestier (T2)		Site restauré (T3)	
Nom commun	***Nom latin***	2022	2024	2022	2024	2022	2024
Crapet soleil	*Lepomis gibbosus*	0	0	0	0	1	0
Épinoche à cinq épines	*Culaea inconstans*	10	120	3	296	16	90
Fondule barré	*Fundulus diaphanus*	0	0	0	0	0	1
Mené à nageoires rouges	*Luxilus cornutus*	0	1	1	1	0	2
Méné jaune	*Notemigonus crysoleucas*	1	0	0	0	1	0
Mulet à cornes	*Semotilus atromaculatus*	5	1	2	1	5	4
Tête-de-boule	*Pimephales promelas*	6	0	2	0	6	0
Umbre de vase	*Umbra limi*	0	0	0	0	0	1
Ventre-Pourri	*Pimephales notatus*	2	0	1	0	3	0
	Abondance	**24**	**122**	**9**	**298**	**32**	**98**
	Richesse	**5**	**3**	**5**	**3**	**6**	**5**
	Indice Shannon	**1.59**	**0.24**	**1.68**	**0.42**	**1.25**	**1.07**

4.4.3. Hydrogeomorphological monitoring of the restored section

The IQM scores obtained in the various sub-reaches of the study site range from 0.58 to 0.94, reflecting moderate to very good morphological quality (Appendix C). The unrestored reach in wooded areas (T2), located upstream of the restored section and having undergone little historical disturbance, has the highest score (0.94, very good quality). This segment is characterized by a sinuous channel, an unaltered wooded floodplain, and good morphological diversity in the channel and outside (including an abandoned meander pond). Section T3A (score: 0.85, good quality), although included in the restored area, is distinguished by its relative morphological integrity: the channel has not been straightened, no structures impede hydrosedimentary processes, but the riparian strip remains narrow and the floodplain morphology have been partially altered by backfilling. Section T3B (score 0.58: moderate quality), on the other hand, corresponds to the historically straightened portion, with high bed homogeneity and a virtual absence of woody vegetation. This is also where the undersized culvert was located, which was replaced in the fall of 2024. These results make it possible to identify the reaches with the greatest morphological potential, which can guide the prioritization of restoration or monitoring efforts in a subsequent phase of the project.

The low representation of trees and shrubs throughout the site, particularly on segment T3B, limits the improvement of the overall score despite the herbaceous colonization observed since 2022. It should be noted that the IQM gives greater weight to woody vegetation because of its role in bank stabilization and river process dynamics.

The immediate impacts of replacing the culvert on hydrogeomorphological dynamics could not be documented as the culvert was replaced late in the project (fall 2024). It is already clear that the new culvert will have no impact on the IQM score, as it would have had to be completely dismantled to affect this index. In the coming years, comprehensive topographic and bathymetric monitoring will nevertheless make it possible to document the potential development of new intra-channel flow facies in connection with the restoration of sediment and wood transport between the upstream and downstream sections of the new culvert.

4.4.4. Evolution of producer involvement

The *Un Méandre à la fois* project is based on close collaboration with Ferme Parentall, which began in 2017. Although the producers expressed from the outset that they wished to remain involved to a limited extent due to their many responsibilities, their commitment has grown steadily over the years. Their participation initially took a pragmatic form: providing storage space for monitoring equipment, validating financial transfers related to compensation for lost income, and brief discussions during field visits. However, this contribution, although limited in terms of time, gradually evolved into a genuine ownership of the project.

Informal exchanges and semi-directed interviews conducted between 2022 and 2024 reveal a marked change in their perceptions. Initially perceived as an external environmental initiative, the project has become, in the eyes of the producers, a valuable endeavor to which they actively contribute. Their growing interest in ecological processes, particularly the role of riparian environments in hydrological regulation, was evident in recurring questions and growing enthusiasm during discussions. They also recognized the project's contribution to increasing the resilience of their businesses to climate change. Indeed, during the summer flood associated with Storm Debby in August 2024, producers emphasized that without a large restored riparian area, they would have suffered economic losses due to the flooding of their crops (see the extent of this flooding in Figure 4.3 (C)). Although not formally assessed, this hydrological event highlighted the perceived value of the restored area as an ecosystem service contributing to climate change adaptation.

This growing ownership of the project has resulted in several concrete actions: publication of photos of the site on social media, participation in television and written reports, and acceptance of additional monitoring and a subsequent restoration phase. The autonomous addition of a forage

crop area at the edge of the crop withdrawal area at the end of phase 1 is interpreted as a clear sign of ownership of the project by the producers involved.

4.4.5 Conditions for sustainability

Beyond the ecological and social results achieved during the first phase of the pilot project, the issue of the sustainability of restoration measures, particularly the withdrawal of crops from the freedom space, quickly emerged as a central challenge. Interviews conducted between 2022 and 2024 with producers reveal their nuanced position on this issue. At first glance, the producers at Ferme Parentall recognize the relevance of a legal tool to ensure the sustainability of the project beyond the partnership with the research team. However, they have repeatedly expressed their desire to retain ownership of the land and to preserve a certain degree of autonomy over the agricultural uses that will be possible in the freedom space (e.g., traffic in the area via the new culvert, maintenance of drains, maintenance of a forage strip, etc.).

In addition, financial assistance and/or land exchange mechanisms to offset their long-term loss of crop income (more than one hectare) appear to be an essential part of the sustainability mechanism, not only for the producers but also for the project promoters (i.e. research team). It is important to recognize that the specific contribution of a private landowner to the ecological health of an ecosystem such as a stream benefits the entire watershed community. Producers ultimately expressed the need to take the time to explore the modalities, potential partners (e.g., conservation organizations), and long-term implications, particularly in the event of a transfer of the business, for the various sustainability strategies proposed.

4.5. Discussion

In just three years, the *Un Méandre à la fois* project has demonstrated that passive, process-based restoration can generate measurable ecological gains in a restored reach of degraded agricultural stream. Despite the simplicity of the interventions, the project has led to a significant improvement in biodiversity, particularly among spiders and farmland birds. These results confirm the hypothesis that hydrological connectivity gradients influence plant diversity, with cascading effects on wildlife food chains. They also highlight some concrete benefits for producers, such as an increase in the number of pollinators and greater resilience to climate hazards (e.g., storm Debby). These positive signals contrast with the more mixed results of several European studies,

where river restoration has not always translated into short- or medium-term ecological benefits (Kristensen et al., 2012; Lorenz & Feld, 2013; Kristensen et al., 2014; Brettschneider et al., 2023).

With regard to fish populations, it is premature to associate an improvement in fish quality with restoration, especially since the replacement of the undersized culvert, which was identified as a major limiting factor, was not completed until the end of the project period (September 2024). Studies suggest that the positive effects of punctual restoration measures on fish populations are likely to be small or diluted over time, given the accumulation of constraints at the watershed scale (Roni et al., 2008; Gates & Smiley, 2024; Roni et al., 2025) .

With regard to riparian vegetation, the data show gradual substitutions between types of meadows, with no rapid transformation of the overall structure (meadows versus wetlands). This slow but noticeable dynamic suggests that abiotic factors, such as limited hydrological connectivity, compacted soil, low-contrast topography, or low availability of native propagules, may inhibit the establishment of more hygrophilous or more diverse plant communities (Baattrup-Pedersen et al., 2000; Clilverd et al., 2022; Greet et al., 2022; Morra et al., 2023). In highly anthropized environments, the rate of ecological transition can be significantly reduced when relying solely on natural colonization processes (Forget et al., 2013; Aleeje et al., 2025). This case study thus highlights the importance of taking these ecological constraints into account when assessing passive restoration trajectories.

This next section provides a cross-sectional analysis of the main levers that have made this approach possible, while highlighting the tensions that still limit its expansion. Based on field results, feedback from partners, and recommendations from the literature, four key dimensions have been identified to ensure the success of this type of passive restoration: 1) the use of cross-analysis of hydrological connectivity, 2) the enhancement of the floodplain as a functional and mediating space, 3) the building of a lasting trust relationship with producers, and 4) the anchoring of the project in intersectoral and participatory governance. These dimensions, detailed in section 4.5.1, closely mirror the success factors identified by Gariépy-Girouard et al. (2025), in particular the ability to mobilize a diversity of actors around common objectives, to anchor the project in local realities, and to maintain constant dialogue between partners. The following sections (4.5.2 and 4.5.3) address the challenges related to the sustainability of the project and open the discussion on the conditions for replicating this approach in other agricultural basins.

4.5.1 Dimensions of successful passive restoration

4.5.1.1 Cross-referencing analyses to better understand hydrological connectivity

The combination of hydraulic, hydrogeomorphological, and hydrogeological approaches was decisive at three stages of the project: initial diagnosis, planning of measures, and monitoring of impacts (Table 4.5).

Table 4.5. Types of hydrological connectivity analyses carried out at the Parentall farm site.

Composante analysée	Méthode utilisée	Échelle d'analyse	Rôle dans le diagnostic ou la planification	Lien avec la connectivité hydrologique
Morphologie du cours d'eau	*Relevés LiDAR, photo-interprétation, sondages stratigraphiques*	*Tronçon et plaine alluviale*	*Délimitation de l'ancienne plaine alluviale et des zones de remblai*	*Identification des discontinuités latérales et longitudinales*
Dynamique hydraulique	*Modélisation HEC-RAS, relevés de hauteurs d'eau (sondes à pression)*	*Tronçon et ponceau*	*Détection des effets de seuils et de refoulement liés au ponceau sous-dimensionné et aux différents scénarios de nouveau ponceau*	*Mise en évidence de ruptures de connectivité de surface*
Fluctuations piézométriques	*Suivi piézométrique haute fréquence*	*Points fixes (piézomètres)*	*Repérage de zones à forte réactivité de la nappe*	*Confirmation de la connectivité verticale et latérale résiduelle*
Flux souterrains	*Modélisation MODFLOW*	*Tronçon, plaine alluviale et versant*	*Simulation des échanges entre les unités géomorphologiques*	*Quantification des flux verticaux et latéraux entre unités hydrogéologiques*
Observations écologiques (végétation, faune)	*Relevés terrain et indicateurs fauniques*	*Zone restaurée vs témoin*	*Détection d'effets en cascade des conditions hydriques sur la biodiversité*	*Validation écologique des gradients de connectivité*

During the diagnostic phase, water level monitoring and HEC-RAS 1D modeling revealed a longitudinal discontinuity in hydrological connectivity linked to the culvert acting as a partial dam during flood events. This culvert hindered sediment transport and the movement of dead wood, which are key elements for natural re-meandering (Lorenz et al., 2009), in addition to hindering fish movement during low-flow periods. LiDAR surveys, photo interpretation, and stratigraphic surveys confirmed the presence of alluvium in the footprint of the former meandering channel. Piezometric monitoring and the MODFLOW model (Marchand, 2025, chapter 2) revealed an almost synchronous response between the shallow water table within the alluvium and the channel, despite the embankments, suggesting residual subsurface hydrological connectivity (Marchand et al., 2022).

The connectivity diagnostics guided the planning of the culvert resizing. The new configuration aims to reduce the backwater effect and restore sufficient flow velocities for sediment transport in the upstream section, as well as mitigate the pressurized flow observed at the culvert outlet. It also aims to maintain adequate water depth in the culvert to ensure free fish passage in all seasons. Studies suggest that measures to restore hydrological connectivity (dam removal, culvert replacement, restoration of lateral connection with the plain) should precede measures to create fish habitat within the channel, such as the addition of dead wood (Roni et al., 2008; Gates & Smiley, 2024) .

The data collected also identified areas with high piezometric dynamics, conducive to the establishment of wetland plant communities. These benchmarks are useful for anticipating vegetation growth trajectories in the restored floodplain (Bätz et al., 2016). These cross-analyses have thus identified certain areas of interest for targeted planting of native wetland species, the detailed planning of which is one of the objectives for a subsequent phase of the project.

Hydrogeomorphological, piezometric, and hydraulic monitoring has been set up to document the effects of the new culvert on water levels and flow velocities. The IQM, observation of hydro-sedimentary processes, and precise mapping of flow facies will be used in the future to detect the first signs of natural re-meandering. The piezometers, which are still in place, will also make it possible to monitor changes in the hydrogeological regime in the riparian environment in relation to changes in flow conditions and the growth of riparian vegetation. These instruments will also facilitate future groundwater quality monitoring.

Understanding the multiple dimensions of hydrological connectivity is essential to any coherent restoration approach (Harvey et al., 2019; Wohl, 2017a; Mason et al., 2025), but this cross-disciplinary approach is still rarely used in small agricultural streams (Gariépy-Girouard et al., 2025). Through a rigorous methodological effort to characterize hydrological and geomorphological dynamics, it has promoted transparency, interdisciplinary dialogue, and trust among producers and partners. This interdisciplinary approach thus responds to recent calls to strengthen the integration of scientific, technical, and social knowledge in restoration projects in order to improve their effectiveness and acceptability (Flávio et al., 2017; Alp et al., 2024).

4.5.1.2 The floodplain as a narrative, spatial, and functional lever

The enhancement of the floodplain of the river targeted by the restoration project played a central role in the appropriation of the project by the producers involved. As a space shaped by floods and hydrogeomorphological processes, the floodplain embodies both the historical memory of the river and a tangible object for understanding the natural processes still at work. For the producers involved, this floodplain has made it possible to move away from a linear and simplistic view of the river and adopt a spatialized representation of river functioning, consistent with the site's historical and geomorphological context. It embodies what Morizot and Husky (2024) summarize with the phrase: "a stream is not a blue line on a map" but rather a territory in its own right. In this context, the space for crops removal is no longer perceived as an arbitrary loss, but as a logical and spatially delimited restoration of a functional space within the river system.

The floodplain has also helped to structure a dialogue between natural dynamics and agricultural uses. In an agricultural context, it can be seen as a highly fertile area or an area with major constraints (flooding, erosion) for crops and infrastructure (e.g., agricultural drainage networks) (Ruiz et al., 2023). In addition to embodying the many ecological services provided by streams, alluvial plains therefore help to raise awareness among restoration project leaders of the concrete challenges faced by producers in such initiatives. This mediating function of the floodplain is in line with recent findings by Löfqvist et al. (2023), according to which shared spatial representations improve mutual understanding and the equitable implementation of restoration projects.

In short, the floodplain of a river that has been straightened in an agricultural area acts as a point of convergence between science, territory, and culture. It provides a foundation for restoration objectives by anchoring them in a spatial, historical, and perceptible reality, thereby strengthening their acceptability to the agricultural community. It also helps to bridge the gap between scientific understanding of hydrological connectivity and the management decisions made by local stakeholders, primarily the producers at Ferme Parentall.

4.5.1.3 Trust as a lever for change

The producers' commitment is based on a relationship of trust built up over time, addressing the technical, logistical, and economic aspects of a restoration project without taboos. This relationship goes beyond simple negotiation: it is also nourished by emotional ties and mutual recognition.

Through regular visits, informal exchanges, and joint decision-making, a climate of respect, even friendship, has developed, strengthening trust between the parties. A few minutes spent in the field are sometimes enough, while once or twice a year, in-depth discussions around the kitchen table help to maintain the producers' commitment. This relational approach is in line with the approach advocated by Mould et al. (2018), which calls for a socio-geomorphology (Ashmore, 2015) that is attentive to emotional ties, dialogue, and the co-construction of knowledge. River management cannot be separated from the social, emotional, and epistemic relationships that emerge locally (Gariépy-Girouard et al., 2025). This is also in line with the findings of Dumont et al. (2025), according to which adequate emotional and cognitive support can be a decisive factor in the sustainable adoption of new agro-environmental practices.

Maintaining commitment also requires identifying and, above all, accepting the uncertainties associated with the project. For example, it is impossible to guarantee that passive revegetation will not lead to the emergence of harmful exotic species or alter the drainage efficiency of adjacent agricultural land, nor is it possible to specify at this stage the legal and financial arrangements for long-term sustainability. Informed of the potential uncertainties, producers are likely to be more willing to continue their commitment if certain issues arise. This approach is in line with the findings of some studies, which suggest that the adoption of conservation or restoration practices is based on gradual learning, which reduces perceived uncertainty (Pannell, 2003; Dumont et al., 2025) .

With Ferme Parentall, this approach based on trust and transparency has transformed a research project into a co-constructed and adaptable pilot restoration project. It has fostered growing commitment among producers, leading to the gradual expansion of the withdrawal zone to cover the entire freedom space. It has also made it possible to better integrate their knowledge and concerns into the project's design, particularly in defining the selection criteria for the new crossing (i.e. culvert), choosing relevant ecological monitoring indicators (e.g., invasive exotic species), and deciding on the type and amount of financial compensation.

A relationship of trust was also established with MELCCFP professionals, who agreed to subsidize a passive restoration pilot project based on natural processes without extensive technical intervention. This choice involves some uncertainty about the duration and intensity of future

changes, which contrasts with the more prescriptive approaches often required by subsidy programs in Quebec.

Finally, this dialogue-based approach has broadened discussions with representatives of the agricultural community. Although unions defend arable land, constructive exchanges have led to recognition that restoring extensive riparian areas can also help preserve agricultural functions in a context of growing economic and climate disruption.

4.5.1.4 Integrated, multi-level governance

The success of the *Un Méandre à la fois* project depends largely on the involvement of stakeholders from various levels of governance. From the very beginning, partners such as OBVs, the UPA, the MRC, research centers (UQTR, UQAM, Laval University, Environment and Climate Change Canada) and several government departments (MELCCFP, MAPAQ) were involved. This integration helped strengthen the project's legitimacy and tailor actions to the specific realities of each stakeholder. For example, the UPA's sensitivity to the loss of farmland led to a preference for a leasing formula rather than rushing to adopt a conservation mechanism. Similarly, the shared recognition of the deterioration of Lake Saint-Pierre as a regional problem reinforced the relevance of the project by linking it to a concern broader than the restored section alone.

This collaborative approach was reinforced by a deliberate multidisciplinary approach, both in the analysis and implementation. The removal of crops, although appearing to be a simple technical gesture, raises a multitude of interrelated issues: loss of income, changes in land value, impacts on farming practices, including agricultural drainage, but also potential effects on biodiversity, river dynamics, and pollination. Added to this are important heritage and symbolic dimensions. In this sense, the project leader cannot act alone. They must surround themselves with partners with complementary skills and experience: agricultural engineers, biologists, hydrogeomorphologists, human geographers, lawyers, tax specialists, consultation and conservation professionals, etc. This network of knowledge and expertise is essential for navigating between regulatory frameworks, agricultural practices, and ecological restoration objectives (Wohl et al., 2015; Bieroza et al., 2024; Gariépy-Girouard et al., 2025) .

This experience also highlights the value of structured intersectoral approaches: living laboratories, centers of expertise, regional forums, consultations related to PRMHH, and environmental conferences (ROBVQ, AGRCQ, ABQ). These ad hoc co-construction spaces make

it possible to mobilize diverse knowledge, better understand the needs of stakeholders, particularly farmers (Ruiz, 2023), identify socially acceptable compromises (Flávio et al., 2017), and consolidate financing or regulatory change strategies. The resulting assessments serve as benchmarks to guide action, and the resource persons involved often become key allies for implementation and sustainability. Far from being secondary, these regional and national approaches form an essential foundation for any restoration project rooted in agricultural realities (Palmer et al., 2022; Campeau et al., 2023; Tourinho et al., 2023).

4.5.2 Challenges and opportunities for the sustainability of the project

In the context of the *Un Méandre à la fois* project, personal conservation easements appear to be the most appropriate tool for ensuring sustainability. A conservation easement is a voluntary, legally binding agreement by which a landowner commits, via notarial act to restrict certain uses of his property to protect its ecological or natural-heritage values, while retaining ownership of the land. A personal easement is tied to a person or conservation organization incorporated as a legal entity while a real easement is tied to a property (which was not available in that case). Although other sustainability mechanisms exist, such as private nature reserves, social trust, or designation by ministerial plan, their application to the Parentall Farm project presents major constraints, whether administrative, legal, fiscal, or related to eligibility criteria (area, naturalness, presence of a dominant property, transfer of ownership). These constraints, combined with the producers' desire to retain ownership and certain agricultural uses, make personal conservation easements the most realistic and appropriate option in the current context. Their flexibility allows specific agreements to be reached between a landowner and a conservation organization without fragmenting the property or unduly restricting land use. At Ferme Parentall, this means maintaining certain agricultural activities (e.g., forage cultivation in the buffer zone, drain maintenance) while ensuring the long-term protection of the restored area. This tool can also be linked to mechanisms such as the Ecological Donation Program (Government of Canada, 2021), thereby increasing the possibilities for financial incentives.

However, concrete examples of personal conservation easements in the context of stream and riparian area restoration remain rare in Quebec. On the one hand, few funding programs allow for compensation for agricultural losses. On the other hand, recent court rulings (e.g.*, Fondation SÉTHY and Ville de Granby v. UPA,* 2021 QCTAQ 0655) show that the Commission de Protection

du Territoire Agricole du Québec (CPTAQ) sometimes rejects sustainability measures associated with restoration or conservation projects because of the permanent loss of agricultural land they might entail.

This perspective is consistent with the findings of several recent initiatives in Quebec, including those led by Racicot (2022), which recommend reforming the legislative framework to facilitate the adoption of flexible and adaptable conservation tools on private agricultural land. Drawing inspiration from conservation easements used in other Canadian jurisdictions, or OREs (Obligation Réelle Environnementale) used in France, these proposals call for greater recognition of the ecological value of riparian areas in agricultural settings, while taking into account the economic and land tenure realities specific to these environments.

The *Un Méandre à la fois* project illustrates that the success of a restoration project's sustainability depends not only on the choice of legal tools, but also on the quality of the relationship established between the parties, the degree of local ownership of the project, and the ability of institutions to demonstrate flexibility. In this sense, the establishment of a sustainability mechanism (e.g., personal conservation easement) cannot be considered independently of the social and relational trajectories that made the project possible.

4.5.3 Towards iterative, rooted, and replicable restoration of degraded small agricultural streams

Once it has been established that the *Un Méandre à la fois* project is a relative success on the scale of a small reach, the question becomes: how can the momentum be sustained and new initiatives developed in the basin and beyond? Each reach of agricultural stream has its own unique characteristics (location in the basin, development history) with constraints (land, cultural, economic) and expectations that differ depending on the landowners. The restoration of agricultural streams at the watershed scale must therefore contend with both the complexity of biophysical processes and changing socio-economic dynamics, in a rapidly changing climate context (Flávio et al., 2017; Groll, 2017; Iftekhar et al., 2017). In this manner, the literature converges in recommending iterative approaches based on adaptive management and sustained monitoring strategies, supported by pilot projects or well-documented case studies (Wohl et al., 2015a; Flávio et al., 2017; Alp et al., 2024). Because each project is contextual (environment, economy, governance), these cases serve to identify the levers and barriers to the implementation

of new projects. They also demonstrate the benefits, which facilitates buy-in and replication, as exemplified by New Zealand's riparian corridor restoration programs, which have significant net benefits (Daigneault et al., 2017).

With this in mind, restoration strategies must be flexible and go beyond punctual interventions in time and space (Alp et al., 2024; Reyes-Aldana, 2024). Approaches based on a "pristine" reference state ignore rapid climate change and the needs of producers and, for these reasons, are often unrealistic (Dufour & Piégay, 2009; Wohl et al., 2015a; Reyes-Aldana, 2024). In contrast, the *Un Méandre à la fois* project proposes that in agricultural settings, the goal is not to achieve ecologically ideal restorations, but to design projects that are rooted in the needs of producers and can be replicated elsewhere. By focusing on co-construction, flexibility, and mutual respect, such projects can become exemplary, and committed producers, such as those at Ferme Parentall, can become ambassadors for integrated, realistic, and sustainable restoration.

Regular monitoring allows for the identification of unwanted effects and timely adjustments (Gariépy-Girouard et al., 2025). Learning from experience, including failures that are not widely reported, is a prerequisite for improving restoration approaches restauration (Kondolf, 2006; Morandi et al., 2017; Lenhart et al., 2018; Alp et al., 2024). Monitoring should begin before the intervention to establish a baseline and remain aligned with the objectives (Alp et al., 2024). Success indicators should also be prioritized over time. Some responses (fish, water quality) require long time scales, meaning that assessments over 1-2 years may miss improvements (Kristensen et al., 2013; Wiberg-Larsen et al., 2025), while others (flora, insects, farmland birds) respond more quickly, as shown in this project. Long-term monitoring also helps to distinguish the effects of restoration from natural variations (Vaudor et al., 2015). The study by Roni et al. (2008) suggests that the variance observed in success indicators is largely due to site contexts, monitoring duration, and the variables chosen. However, it is important to remember that funding for monitoring remains a weak link in general (Wohl et al., 2015) and in Quebec in particular (Gariépy-Girouard et al., 2025) .

Finally, the success of a restoration strategy in agricultural areas ultimately depends on a watershed strategy and participatory governance (Daigneault et al., 2017; Flávio et al., 2017; Lenhart et al., 2018; Bieroza et al., 2024; Mason et al., 2025). These strategies must be supported by transferable tools (e.g., stream typologies, decision trees, accessible monitoring protocols) and by promoting

learning (e.g., field visits, "before/after" fact sheets) (Wohl et al., 2015; Alp et al., 2024; Bieroza et al., 2024; Dumont et al., 2025) .

In this context, *Un Méandre à la fois* can act as a catalyst for a continuous approach across the Pot-au-Beurre river basin: planning new sites while supporting existing projects, drawing on various ecological and socio-economic monitoring to improve practices, documenting and sharing results, and adjusting the trajectory to the changing needs of society. This is the condition for truly iterative, rooted, and reproducible restoration.

4.6 Conclusion

To our knowledge, the *Un Méandre à la fois* project is the first process-based stream restoration project in Quebec. It incorporates the concepts of freedom space by targeting the most obvious case of physical degradation, namely straightened streams in agricultural areas. This project demonstrates the capacity of research initiatives, supported by local, regional, and government stakeholders, to develop into concrete pilot projects and then become showcases for ecological restoration in agricultural settings. Born out of a desire to explore in detail the hydrological connectivity of a small, heavily modified agricultural stream, the project has evolved into the gradual implementation of process-based restoration actions in line with local issues and the expectations of a family of agricultural producers. It is now gaining recognition from conservation and restoration organizations in Quebec, as well as organizations that defend the interests of agricultural producers.

This project stands out for the importance it places on a detailed understanding of hydrological connectivity dynamics, both surface and underground, and for its clear commitment to aligning ecological objectives with local agricultural realities. Far from traditional approaches focused on mechanical interventions targeting only the channel, *Un Méandre à la fois* offers an alternative, more flexible and iterative approach based on passive restoration, building relationships of trust with producers, and a comprehensive strategy for monitoring ecological and socioeconomic impacts. This approach makes it possible to limit costs, adjust interventions over time, and anchor the measures in a dynamic of territoriality and dialogue.

In this sense, this study is part of a broader movement to challenge standardized approaches to river restoration in agricultural areas, in Quebec in particular. It supports recent calls to prioritize

approaches based on ecological processes and hydrological connectivity, integrating social, agricultural, and hydrological dimensions from the earliest stages of planning. This approach paves the way for more resilient projects that are better adapted to environmental and climate uncertainties and, above all, more likely to be replicated elsewhere thanks to the involvement of local communities.

Glossary:

AGRCQ: Association des gestionnaires régionaux de cours d'eau du Québec (Quebec Association of Regional Stream Managers).

ABQ: Association des biologistes du Québec (Quebec Association of Biologists).

CPTAQ: Commission de protection du territoire agricole du Québec (Quebec Agricultural Land Protection Commission).

MELCCFP: Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs (Quebec Ministry of the Environment, Climate Change, Wildlife and Parks).

MAPAQ: Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec (Quebec Ministry of Agriculture, Fisheries and Food).

MRC: Municipalité régionale de comté (Regional county municipality).

OBV / ROBVQ: Organisme de bassin-verant (Watershed organization) / Regroupement des organismes de bassin-versant du Québec (Quebec Association of Watershed Organizations).

PRMHH: Plan régional des milieux humides et hydriques (Regional wetland and water environment plan).

PRCMHH: Programme de restauration et de création de milieux humides et hydriques (Program for the restoration and creation of wetlands and water environments)

Chapter 5: Conclusion

This thesis aimed to document and understand hydrological connectivity in small straightened agricultural streams in the lower St. Lawrence River lowlands. It also explored how this understanding can guide process-based restoration approaches. It was based on an interdisciplinary approach, combining in-depth hydrogeological and hydrogeomorphological investigations with ecological and social science perspectives on agricultural stream restoration, including an analysis of compensation and funding mechanisms for farmers (see Appendix D). The range of skills and expertise required to support this research project, from fundamental to applied knowledge and from wide discussions on concepts to creative iterations for the commons, is therefore quite unique and, to my knowledge, this is the first time that process-based restoration has been implemented in Quebec.

5.1 Key findings

Chapter 1 showed that combining high-resolution piezometric monitoring with detailed hydrogeomorphological analysis allows for the accurate identification of surface and groundwater exchange patterns between small straightened lowland streams, their historical floodplain, and their hillslopes. The results highlighted the central role of certain geomorphological units, particularly coarse alluvium located in former meanders, as nodal areas of connectivity, as well as marked seasonal variations. These observations highlighted the importance of considering the vertical dimension (subsurface) of hydrological connectivity in degraded small agricultural streams where surface hydrological exchange processes may have been historically heavily altered. The detailed measurements taken at two different sites also revealed the challenge of generalization as marked contrasts were noted due to site-specific characteristics.

Chapter 2 supplemented this empirical approach with conceptual hydrogeological modelling using MODFLOW. This steady-state modelling reproduced the hydraulic gradients observed in the field at the Petit-Pot-au-Beurre site and quantified the relative distribution of groundwater flows between geomorphological units. It confirmed that the alluvial corridor comprising the straightened stream floodplain, despite morphological changes, acts as a “hot spot” for multidirectional exchanges and that its connectivity with other regional units strongly modulates the distribution of hydrogeological flows. While the model provided insights for strategic

restoration planning, its limitations, particularly those related to conceptual simplifications and the lack of fine calibration, highlight the need for further studies, to move from a mainly exploratory to a more predictive tool.

Chapter 3 applied this knowledge in the pilot project Un Méandre à la fois (One Meander at a Time), which aimed to restore a reach of straightened agricultural stream (Petite-Pot-au-Beurre) using a passive approach, i.e. process-based restoration where sufficient space is provided near the stream for fluvial processes (erosion and flooding) to operate. The monitoring results showed measurable ecological gains in the first few years (riparian vegetation, birdlife, spiders), while revealing that certain ecological indicators, such as fish fauna, are less likely to respond positively to restoration projects implemented only at the reach level. Above all, this project suggests that the historical floodplain of straightened reaches can play a relevant functional and educational role in stream restoration approaches in agricultural environments. It helps raise awareness among producers about ecosystem services resulting from stream–floodplain interactions (e.g. the concept of freedom space, Biron et al., 2014). It also highlights for project managers and government stakeholders the concrete socio-economic challenges faced by producers in such approaches. The relative success of the project is due to the use of cross-analysis of hydrological connectivity, the integration of producers' needs, intersectoral governance, and the flexibility of the approach, factors that closely match those identified by Gariépy-Girouard et al. (2025) for ensuring the success of stream restoration projects.

Taken together, these results advance both the science of hydrological connectivity, by combining fine-scale empirical monitoring with conceptual modelling, and the practice of process-based restoration, by demonstrating the value of interdisciplinary and relational approaches in agricultural lowland settings.

5.2 Future directions

From a scientific perspective, this research contributes to three major advances. First, it rehabilitates small degraded agricultural headwater streams as central geographical objects, highlighting their critically important role in hydrological connectivity dynamics and their often underestimated ecological functions (Gumiero et al., 2013; Van Stempvoort, 2021; 2022). Second, it proposes a conceptual and methodological integration of hydrological connectivity across vertical, lateral, longitudinal, and temporal dimensions, jointly mobilizing hydrogeology,

hydrogeomorphology, and biological monitoring. Finally, it demonstrates the relevance of a relational and territorial approach, where biophysical results are placed in dialogue with agricultural needs, institutional frameworks, and the building of trust relationships (Bieroza et al., 2024, Mason et al., 2025). Together, these three contributions constitute a coherent framework that links Earth science with restoration practice, and they open pathways for future interdisciplinary research in geography and allied fields.

This thesis also highlights certain methodological limitations that should be addressed in future scientific studies. Hydrogeological modelling in steady-state mode, combined with piezometric monitoring, did not allow an exact quantification of the absolute contributions of bank infiltration, precipitation inputs, and regional groundwater to surface–subsurface exchanges at either event or annual scales. Such quantification would clarify the dominant drivers of hydrological responses in lowland straightened streams and provide a stronger empirical basis for linking flow pathways with nutrient and pollutant dynamics as well as riparian revegetation trajectories. Addressing these gaps will require more comprehensive field instrumentation at the reach scale, such as the combined use of geochemical/isotopic tracers, on-site rainfall and soil-moisture monitoring, and denser piezometer networks extending into the regional environment, enabling more advanced statistical analyses such as PCA (Lewandowski et al., 2009). It would also call for the use of coupled surface–subsurface models under transient conditions, allowing the simulation of vadose zone processes and better capturing hydrological dynamics in response to floods and seasonal recharge.

Future research should also examine the long-term effects and scalability of process-based restoration approaches, such as crop withdrawal, culvert replacement, and low-tech interventions (e.g. addition of dead wood, Wheaton, 2019). Their effectiveness depends strongly on flood recurrence and on autogenic factors that regulate morphological change, but also on how interventions accumulate across space and time. It remains unclear at what level of cumulative implementation within a watershed measurable improvements in water quality, habitat condition, or flow regulation begin to emerge. Identifying threshold percentages of restored reaches that lead to detectable reductions in nutrient loads or habitat increases for example would provide valuable guidance for scaling interventions. Such analyses should be conducted across contrasting physiographic environments to identify context-specific responses. Promising avenues lie in the

integration of field-based methods (e.g. electrofishing, piezometer loggers, surface and subsurface water sampling) with advanced numerical modelling approaches, such as coupled hydrological–hydrogeological models (e.g. SWAT-MODFLOW), hydrodynamic models (e.g. HEC-RAS 2D), and morphodynamic models (e.g. TELEMAC).

Finally, to maintain a high level of relevance for agricultural stakeholders, future studies should aim to better link stream restoration measures with crop productivity and resilience under climate change. Understanding how interventions such as crop withdrawal from freedom space or wetland reconnection influence both ecological services and farming outcomes would strengthen the legitimacy of restoration efforts, enhance adoption by farmers, and support their integration into broader agro-environmental strategies.

From an operational perspective, this research highlights the learning and adaptive value of deploying pilot projects such as Un Méandre à la fois as living laboratories, where ecological and socioeconomic monitoring is used to continuously adjust practices. These pilots provide a safe space to explore thoroughly different scenarios, and refine practices, so that subsequent projects can be more readily implemented and socially acceptable. The concept of iterative restoration appears central (Wohl et al., 2015; Flávio et al., 2017; Alp et al., 2024): planning new projects while supporting those already underway, in a spirit of collective learning and adaptation to the changing needs of society.

In future restoration agricultural stream projects, the integration of tile drainage outlets must also be addressed directly by restoration planners and environmental and agricultural stakeholders, as it remains a major concern for agricultural producers in the context of stream restoration projects. Different designs of drainage outlets, such as reconstructed oxbow lakes (Schilling et al., 2018), herbaceous or shrub buffering corridors, or controlled drainage, need to be carefully planned and tested through pilot projects. These pilots should be accompanied by comprehensive monitoring programs to assess the effectiveness of nutrient retention and the impacts on farmers' logistics and productivity.

Looking ahead, the results suggest that nodal areas of connectivity, such as the historic alluvial plains of straightened streams, should be considered as priority targets for restoration and as criteria for prioritization at the watershed scale in agricultural settings. This is a particularly important finding to disseminate to the ministries and stakeholders involved in stream

management, as there are many cases where compensation is required following various interventions near stream, but that the chosen sites may not be optimal. For example, Fisheries and Oceans Canada (DFO) require offsetting measures to counterbalance the residual effects to fish and fish habitat that are caused by a project (https://www.dfo-mpo.gc.ca/pnw-ppe/reviews-revues/offsetting-plan-compensation-eng.html), for example by the Ministry of Transportation. Such measures include restoring degraded fish habitat to improve conditions for fish (which is DFO's preferred approach). The results from this thesis could be used to identify and prioritize areas where process-based restoration could be used as compensation through some kind of easement program with farmers, for example. With this in mind, the Un Méandre à la fois project could become the catalyst for a broader approach covering the entire Pot-au-Beurre river basin and beyond,provided that producer commitment is maintained, governance mechanisms are consolidated, and stable funding is secured. These conditions are essential for moving from promising local initiatives to a coordinated and sustainable restoration strategy rooted in the agricultural and hydrogeomorphological realities of the region.

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Appendix A : Supplemental figures (Chapter 2)

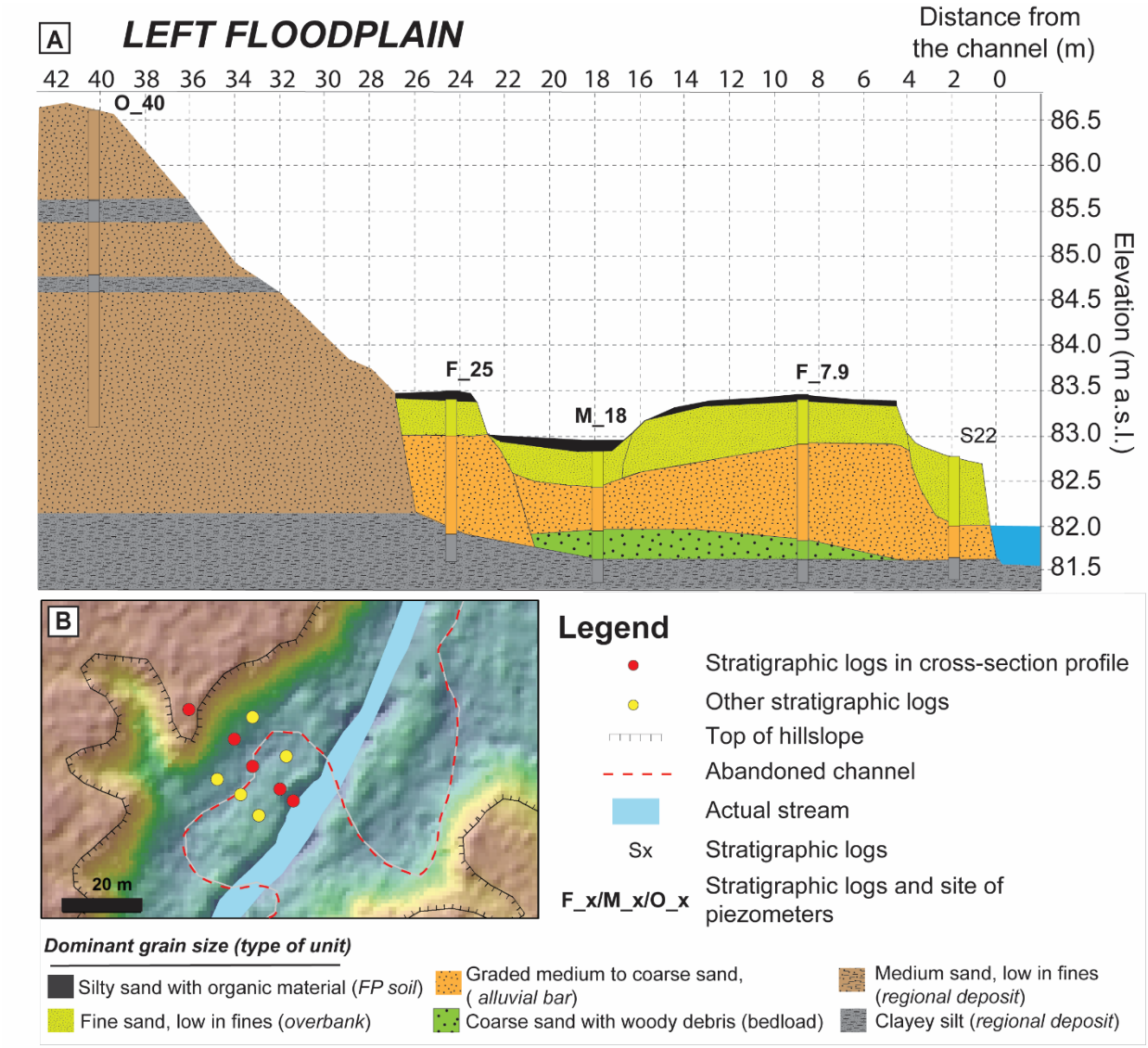


Figure A. (A) Stratigraphic cross-section profile at RM-MID site, representing the left floodplain (looking downstream). Borehole logs labelled with S (ex. S_22) were only used for the stratigraphic characterization. Borehole logs labelled with M (ex. M_18), F, and O were also used for the piezometer installation. Note a vertical exaggeration of 4×. (B) Digital elevation model of the RM site, with the position of the former and actual channel. Red dots indicate the stratigraphic logs that were used to build the cross-section profile.

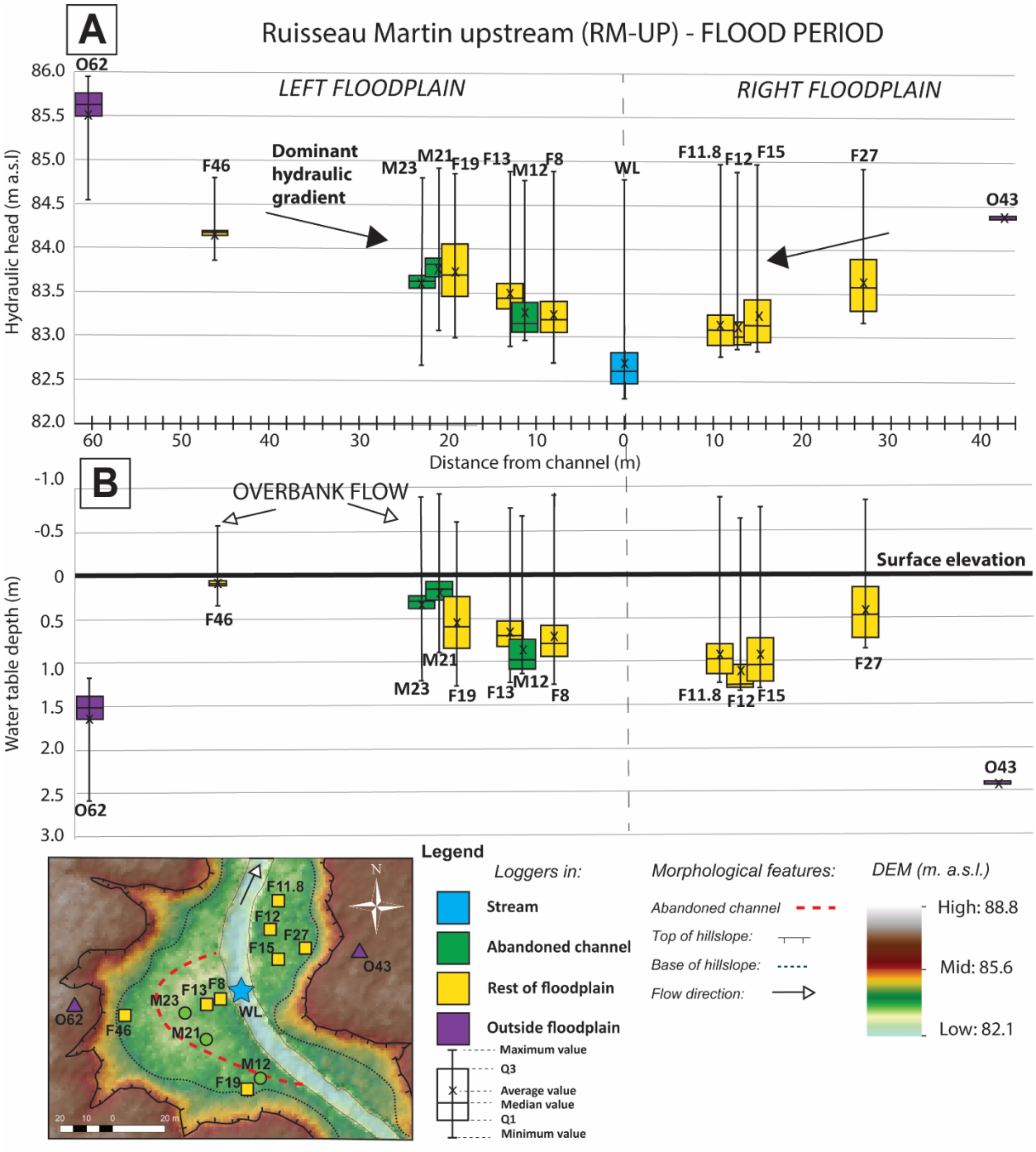


Figure B. Box plot graphs showing A) hydraulic head elevation and B) water depth of piezometers installed at the Ruisseau Martin upstream sites for the flood period (mid-March to mid-May and early October to late December). Negative water depth values indicate water level above the surface.

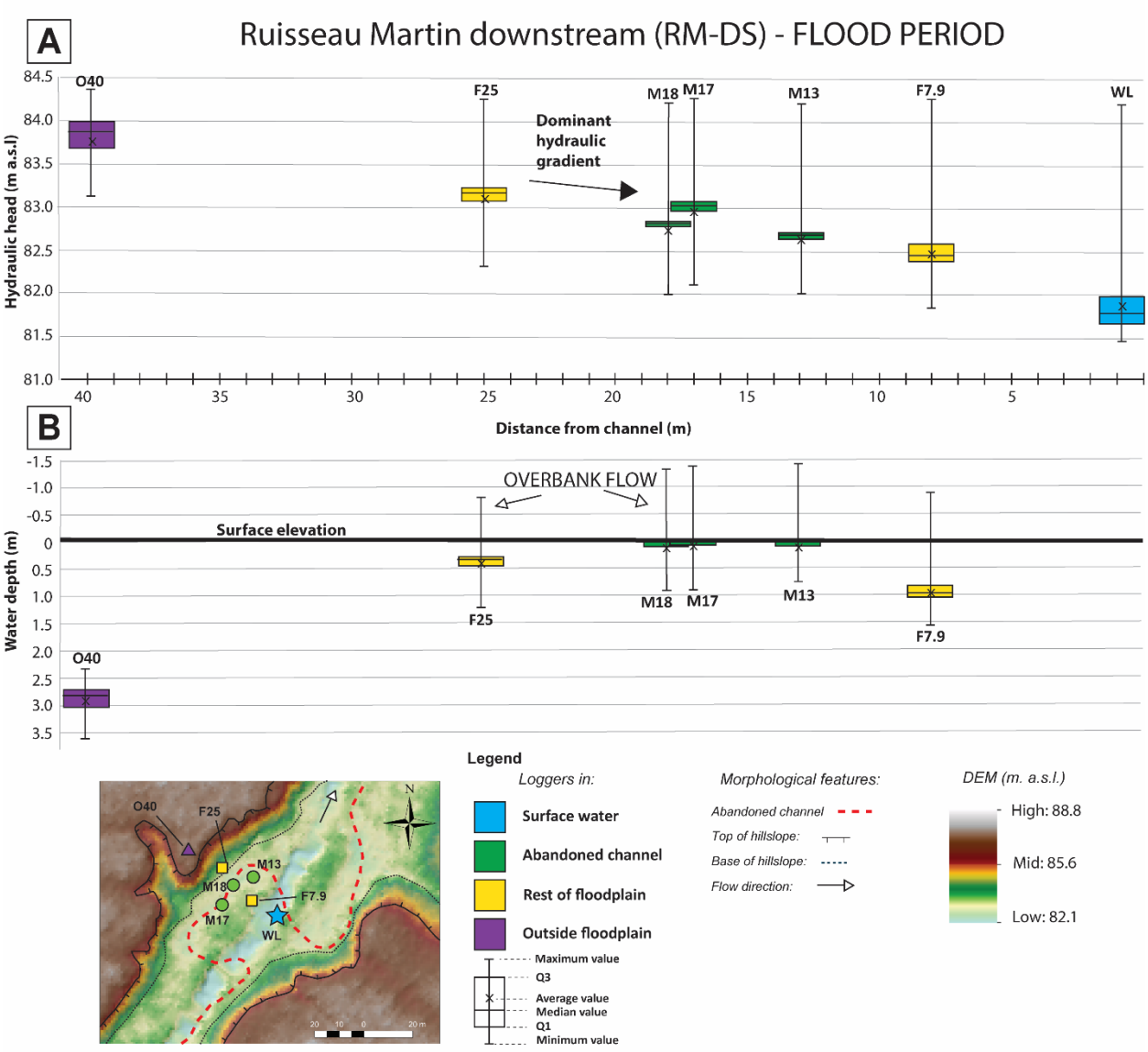


Figure C. Box plot graphs showing A) hydraulic head elevation and B) water depth of piezometers installed at the Ruisseau Martin downstream site for the flood period (mid-March to mid-May and early October to late December). Negative water depth values indicate water level above the surface.

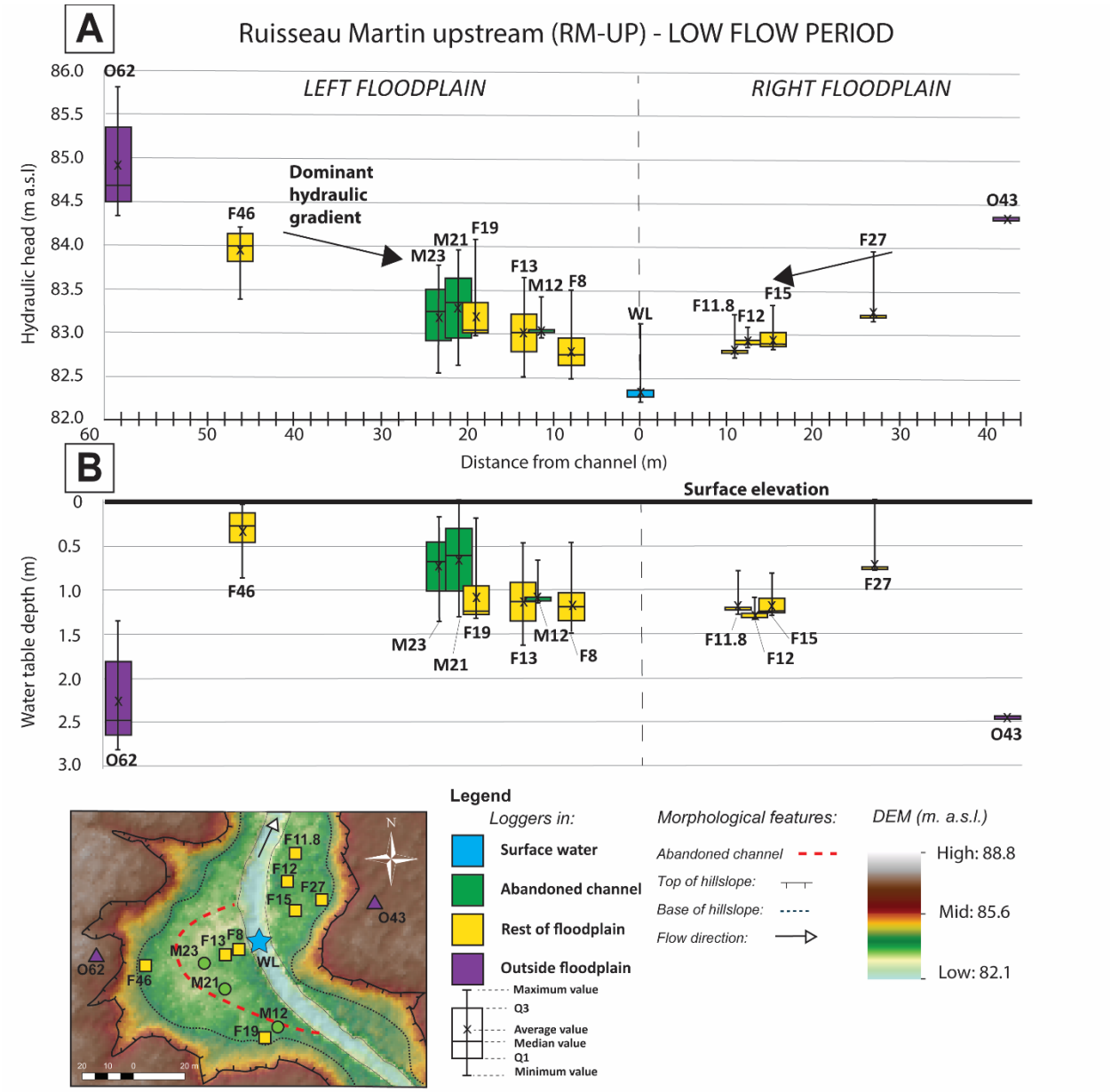


Figure D. Box plot graphs showing A) hydraulic head elevation and B) water depth of piezometers installed at the Ruisseau Martin upstream sites for the low flow period (mid-May to early October).

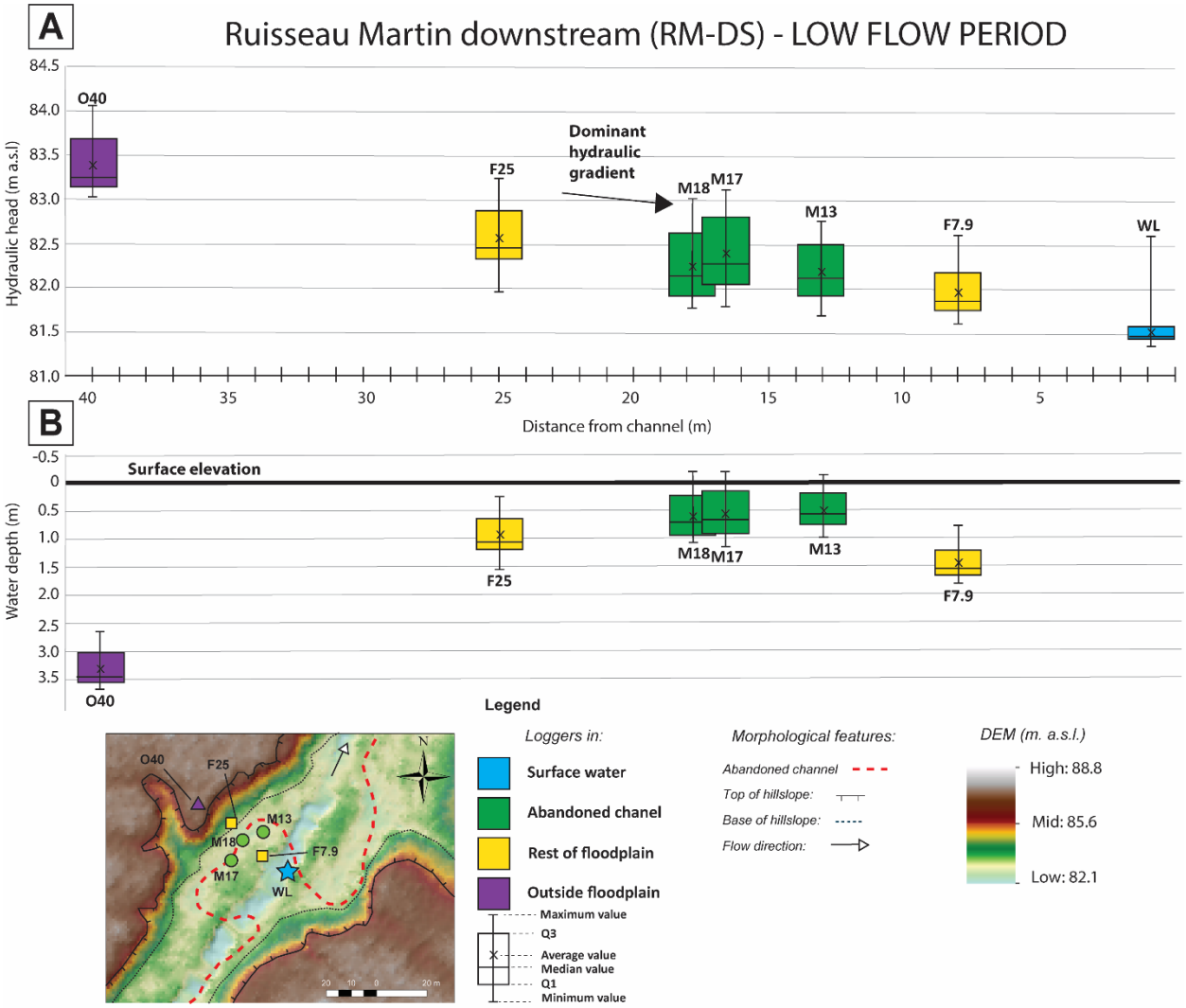


Figure E. Box plot graphs showing A) hydraulic head elevation and B) water depth of piezometers installed at the Ruisseau Martin downstream site for the low flow period (mid-May to early October). Negative water depth values indicate water level above the surface.

Appendix B: Raw results from MODFLOW simulations (Chapter 3)

Simulation parameters and results (steady-state conditions) for scenarios 1A, 1B, 2A and 2B

Simulation parameters

		Base scenario		Scenario 1A: increased alluvium K		Scenario 1B: lowered alluvium K		Scenario 2A: lowered fine alluvium K		Scenario 2B: increased coarse alluvium K	
	Hydraulic conductivity										
Unit	**Type of material**	**(m/day)**	**(m/sec)**	**(m/day)**	**(m/sec)**	**(m/day)**	**(m/sec)**	**(m/day)**	**(m/sec)**	**(m/day)**	**(m/sec)**
Coarse alluvium (1)	Medium to coarse sand	32.32	3.74E-04	32.32	3.74E-04	0.96	1.11E-05	32.32	3.74E-04	48.00	4.36E-04
Fine alluvium (2)	Fine sand with fines	0.96	1.11E-05	32.32	3.74E-04	0.96	1.11E-05	0.640	7.41E-06	0.96	3.02E-05
Actual stream bed (4)	Fine sand	1.84	2.13E-05	1.84	2.13E-05	1.84	2.13E-05	1.84	2.13E-05	1.84	1.07E-04
Backfill material (6)	Fine sand with fines	0.95	1.10E-05	0.95	1.10E-05	0.95	1.10E-05	0.95	1.10E-05	0.95	5.93E-06
Upper regional unit (3)	Silty sand	0.15	1.72E-06	0.15	1.72E-06	0.15	1.72E-06	0.15	1.72E-06	0.15	2.05E-06
Lower regional unit (5)	Silty clay	0.0020	2.31E-08	0.0020	2.31E-08	0.00	2.31E-08	0.0020	2.31E-08	0.0020	4.58E-08
	Recharge zone	**(m/day)**	**(mm/year)**	**(m/day)**	**(mm/year)**	**(m/day)**	**(mm/year)**	**(m/day)**	**(mm/year)**	**(m/day)**	**(mm/year)**
	Left regional	0.00015	54.75	0.00015	54.75	0.00015	54.75	0.00015	54.75	0.00015	54.75
	Right regional	0.00027	99.27	0.00027	99.27	0.00027	99.27	0.00027	99.27	0.00027	99.27
	Left alluvial plain	0.0009	328.5	0.0009	328.5	0.0009	328.5	0.0009	328.5	0.0009	328.5
	Right alluvial plain	0.0009	328.5	0.0009	328.5	0.0009	328.5	0.0009	328.5	0.0009	328.5
	Average residual error (m)	0.050									
	Diff. hydrological budget (%)	1.42		2.25		2.40		1.41		1.17	

FLOW BUDGET between all 6 material units

	Zone 1	**Test 801C**		**Scenario_1A**		**Scenario_1B**		**Scenario_2A**		**Scenario_2B**	
	Coarse alluvium	**Base scenario**		Increased alluvium K		Lowered alluvium K		Lowered fine alluvium K		Increased coarse alluvium K	
	FLUX IN	Abs	%	Abs	%	Abs	%	Abs	%	Abs	%
From fine alluvium	Zone 2 to zone 1	4.86	66.80	7.18	79.42	2.54	75.11	4.80	65.67	4.95	66.26
From upper regional unit	Zone 3 to zone 1	0.48	6.65	0.44	4.88	0.17	5.12	0.48	6.62	0.49	6.60
From actual stream bed	Zone 4 to zone 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
From lower regional unit	Zone 5 to zone 1	1.85	25.44	1.38	15.31	0.57	16.96	1.90	26.02	1.95	26.12
From backfill unit	Zone 6 to zone 1	0.08	1.11	0.03	0.38	0.09	2.80	0.12	1.69	0.08	1.02
	Total IN	7.27		9.04		3.38		7.32		7.47	
	FLUX OUT										
Toward fine alluvium	Zone 1 to zone 2	5.24	72.33	7.65	84.68	2.67	78.91	5.24	71.89	5.35	71.96
Toward upper regional unit	Zone 1 to zone 3	0.02	0.30	0.03	0.35	0.01	0.44	0.02	0.30	0.02	0.29
Toward actual stream bed	Zone 1 to zone 4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Toward lower regional unit	Zone 1 to zone 5	1.97	27.22	1.31	14.54	0.60	17.61	2.01	27.63	2.06	27.67
Toward backfill unit	Zone 1 to zone 6	0.01	0.16	0.04	0.43	0.10	3.04	0.01	0.18	0.01	0.08
	Total OUT	7.24		9.03		3.38		7.28		7.43	

	Zone 2	**Test 801C**		**Scenario_1A**		**Scenario_1B**		**Scenario_2A**		**Scenario_2B**	
	Fine alluvium	**Base scenario**		Increased alluvium K		Lowered alluvium K		Lowered fine alluvium K		Increased coarse alluvium K	
	FLUX IN	Abs	%	Abs	%	Abs	%	Abs	%	Abs	%
From coarse alluvium	Zone 1 to zone 2	5.24	26.50	7.65	27.74	2.67	15.87	5.24	27.70	5.35	26.82
From upper regional unit	Zone 3 to zone 2	5.33	26.97	8.67	31.43	4.85	28.86	4.60	24.32	5.41	27.12
From actual stream bed	Zone 4 to zone 2	0.00	0.00	0.07	0.25	0.00	0.00	0.00	0.00	0.00	0.00
From lower regional unit	Zone 5 to zone 2	1.27	6.43	2.89	10.48	1.27	7.59	1.13	5.98	1.25	6.26
From backfill unit	Zone 6 to zone 2	7.93	40.10	8.30	30.10	8.01	47.68	7.94	41.99	7.94	39.80
	Total IN	19.77		27.57		16.80		18.90		19.95	
	FLUX OUT										
Toward coarse alluvium	Zone 2 to zone 1	4.86	24.59	7.18	26.10	2.54	15.15	4.80	25.43	4.95	24.82
Toward upper regional unit	Zone 2 to zone 3	0.55	2.79	1.60	5.82	0.62	3.70	0.48	2.52	0.56	2.79
Toward actual stream bed	Zone 2 to zone 4	5.12	25.91	8.67	31.53	5.01	29.89	4.25	22.51	5.14	25.76
Toward lower regional unit	Zone 2 to zone 5	1.07	5.41	2.84	10.33	1.20	7.13	0.95	5.01	1.06	5.31
Toward backfill unit	Zone 2 to zone 6	8.16	41.30	7.21	26.22	7.41	44.14	8.41	44.53	8.24	41.31
	Total OUT	19.76		27.51		16.78		18.89		19.94	

	Zone 3	Test 801C		Scenario_1A		Scenario_1B		Scenario_2A		Scenario_2B	
	Regional silt	Base scenario		Increased alluvium K		Lowered alluvium K		Lowered fine alluvium K		Increased coarse alluvium K	
	FLUX IN	Abs	%	Abs	%	Abs	%	Abs	%	Abs	%
Recharge	RECHARGE	7.87	79.41	7.87	69.62	7.87	79.52	7.87	81.66	7.87	79.26
From coarse alluvium	Zone 1 to zone 3	0.02	1.05	0.03	0.92	0.01	0.73	0.02	1.24	0.02	1.05
From fine alluvium	Zone 2 to zone 3	0.55	27.05	1.60	46.64	0.62	30.64	0.48	26.90	0.56	27.06
From actual stream bed	Zone 4 to zone 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
From lower regional unit	Zone 5 to zone 3	0.16	7.96	0.20	5.89	0.16	8.02	0.15	8.64	0.16	7.90
From backfill unit	Zone 6 to zone 3	1.30	63.94	1.60	46.56	1.23	60.61	1.12	63.22	1.32	63.98
	Total IN	2.04	100.00	3.43	100.00	2.03	100.00	1.77	100.00	2.06	
	FLUX OUT										
Toward coarse alluvium	Zone 3 to zone 1	0.48	4.97	0.44	4.01	0.17	1.81	0.48	5.12	0.49	5.04
Toward fine alluvium	Zone 3 to zone 2	5.33	54.82	8.67	78.67	4.85	50.77	4.60	48.59	5.41	55.27
Toward actual stream bed	Zone 3 to zone 4	0.04	0.40	0.03	0.31	0.04	0.45	0.04	0.43	0.04	0.40
Toward lower regional unit	Zone 3 to zone 5	0.30	3.04	0.34	3.13	0.28	2.90	0.29	3.05	0.30	3.04
Toward backfill unit	Zone 3 to zone 6	3.58	36.77	1.53	13.89	4.21	44.07	4.05	42.81	3.55	36.25
	Total OUT	9.73		11.02		9.55		9.46		9.79	

	Zone 4	Test 801C		Scenario_1A		Scenario_1B		Scenario_2A		Scenario_2B	
	Actual stream bed	Base scenario		Increased alluvium K		Lowered alluvium K		Lowered fine alluvium K		Increased coarse alluvium K	
	FLUX IN	Abs	%	Abs	%	Abs	%	Abs	%	Abs	%
RIVER LEAKAGE		0.12	0.78	0.23	1.45	0.12	0.77	0.12	0.78	0.12	0.79
RECHARGE		0.00	0.02	0.00	0.02	0.00	0.02	0.00	0.02	0.00	0.02
From coarse alluvium	Zone 1 to zone 4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
From fine alluvium	Zone 2 to zone 4	5.12	32.66	8.67	54.86	5.01	32.38	4.25	27.15	5.14	32.68
From upper regional unit	Zone 3 to zone 4	0.04	0.25	0.03	0.21	0.04	0.28	0.04	0.26	0.04	0.25
From lower regional unit	Zone 5 to zone 4	0.05	0.31	0.02	0.12	0.05	0.32	0.06	0.36	0.05	0.31
From backfill unit	Zone 6 to zone 4	10.34	65.98	6.85	43.33	10.26	66.23	11.19	71.43	10.37	65.95
	Total IN	15.67		15.81		15.49		15.66		15.72	
	FLUX OUT										
Toward the river	River Leakage	15.62	99.68	15.54	98.28	15.43	99.60	15.62	99.76	15.67	99.68
Recharge		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Toward coarse alluvium	Zone 4 to zone 1	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00
Toward fine alluvium	Zone 4 to zone 2	0.00	0.00	0.07	0.43	0.00	0.00	0.00	0.00	0.00	0.00
Toward upper regional unit	Zone 4 to zone 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Toward lower regional unit	Zone 4 to zone 5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Toward backfill unit	Zone 4 to zone 6	0.05	0.32	0.20	1.29	0.06	0.40	0.04	0.24	0.05	0.32
	Total OUT	15.67		15.81		15.49		15.66		15.72	

	Zone 5	Test 801C		Scenario_1A		Scenario_1B		Scenario_2A		Scenario_2B	
	Lower regional unit	Base scenario		Increased alluvium K		Lowered alluvium K		Lowered fine alluvium K		Increased coarse alluvium K	
	FLUX IN	Abs	%	Abs	%	Abs	%	Abs	%	Abs	%
From coarse alluvium	Zone 1 to zone 5	1.97	59.12	1.31	29.18	0.60	28.79	2.01	61.95	2.06	60.25
From fine alluvium	Zone 2 to zone 5	1.07	32.03	2.84	63.16	1.20	57.84	0.95	29.15	1.06	31.03
From upper regional unit	Zone 3 to zone 5	0.30	8.85	0.34	7.66	0.28	13.38	0.29	8.90	0.30	8.72
From actual stream bed	Zone 4 to zone 5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
From backfill unit	Zone 6 to zone 5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total IN	3.34		4.50		2.07		3.25		3.41	
	FLUX OUT										
Toward coarse alluvium	Zone 5 to zone 1	1.85	55.52	1.38	30.80	0.57	27.85	1.90	58.70	1.95	57.19
Toward fine alluvium	Zone 5 to zone 2	1.27	38.15	2.89	64.27	1.27	61.82	1.13	34.87	1.25	36.61
Toward upper regional unit	Zone 5 to zone 3	0.16	4.87	0.20	4.50	0.16	7.89	0.15	4.71	0.16	4.77
Toward actual stream bed	Zone 5 to zone 4	0.05	1.46	0.02	0.43	0.05	2.44	0.06	1.72	0.05	1.42
Toward backfill unit	Zone 5 to zone 6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total OUT	3.33		4.50		2.06		3.24		3.41	

	Zone 6	Test 801C		Scenario_1A		Scenario_1B		Scenario_2A		Scenario_2B	
	Backfill material	Base scenario		Increased alluvium K		Lowered alluvium K		Lowered fine alluvium K		Increased coarse alluvium K	
	FLUX IN	Abs	%	Abs	%	Abs	%	Abs	%	Abs	%
Recharge		8.01	40.45	8.01	47.14	8.01	40.49	8.01	39.04	8.01	40.36
From coarse alluvium	Zone 1 to zone 6	0.01	0.10	0.04	0.43	0.10	0.87	0.01	0.11	0.01	0.05
From fine alluvium	Zone 2 to zone 6	8.16	69.16	7.21	80.28	7.41	62.88	8.41	67.23	8.24	69.56
From upper regional unit	Zone 3 to zone 6	3.58	30.31	1.53	17.03	4.21	35.73	4.05	32.36	3.55	29.96
From actual stream bed	Zone 4 to zone 6	0.05	0.43	0.20	2.26	0.06	0.52	0.04	0.30	0.05	0.42
From lower regional unit	Zone 5 to zone 6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total IN	11.80	100.00	8.99	100.00	11.78	100.00	12.52	100.00	11.84	100.00
	FLUX OUT										
Toward the river	River Leakage	0.16	0.80	0.21	1.26	0.19	0.97	0.16	0.78	0.15	0.78
Recharge	Recharge	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Toward coarse alluvium	Zone 6 to zone 1	0.08	0.41	0.03	0.20	0.09	0.48	0.12	0.60	0.08	0.38
Toward fine alluvium	Zone 6 to zone 2	7.93	40.01	8.30	48.83	8.01	40.49	7.94	38.67	7.94	39.98
Toward upper regional unit	Zone 6 to zone 3	1.30	6.59	1.60	9.40	1.23	6.21	1.12	5.44	1.32	6.64
Toward actual stream bed	Zone 6 to zone 4	10.34	52.20	6.85	40.31	10.26	51.85	11.19	54.51	10.37	52.22
Toward lower regional unit		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total OUT	19.81		17.00		19.78		20.53		19.85	

Simulation parameters and results (steady-state conditions) for scenarios 3A, 3B, 4A and 4B

Simulation parameters

	Conductivité hydraulique	Base scenario		Scenario 3A: increased K and RCH/regional unit		Scenario 3B: decreased K and RCH/regional unit		Scenario 3B: increased K and RCH/backfill unit		Scenario 4B: decreased K and RCH/ backfill unit	
Unit	**Type of material**	**(m/day)**	**(m/sec)**	**(m/day)**	**(m/sec)**	**(m/day)**	**(m/sec)**	**(m/day)**	**(m/sec)**	**(m/day)**	**(m/sec)**
Coarse alluvium (1)	Medium to coarse sand	32.32	3.74E-04	32.32	3.74E-04	32.32	3.74E-04	32.32	3.74E-04	32.32	4.36E-04
Fine alluvium (2)	Fine sand with fines	0.96	1.11E-05	0.96	1.11E-05	0.96	1.11E-05	0.96	1.11E-05	0.96	3.02E-05
Actual stream bed (4)	Fine sand	1.84	2.13E-05	1.84	2.13E-05	1.84	2.13E-05	1.84	2.13E-05	1.84	1.07E-04
Backfill material (6)	Fine sand with fines	0.95	1.10E-05	0.95	1.10E-05	0.95	1.10E-05	1.73	2.00E-05	0.15	5.93E-06
Upper regional unit (3)	Silty sand	0.15	1.72E-06	1.73	2.00E-05	0.009	1.04E-07	0.15	1.72E-06	0.15	2.05E-06
Lower regional unit (5)	Silty clay	0.0020	2.31E-08	1.7300	2.00E-05	0.0090	1.04E-07	0.0020	2.31E-08	0.0020	4.58E-08
	Recharge zone	**(m/day)**	**(mm/year)**	**(m/day)**	**(mm/year)**	**(m/day)**	**(mm/year)**	**(m/day)**	**(mm/year)**	**(m/day)**	**(mm/year)**
	Left regional	0.00015	54.75	0.00023	83.95	0.00005	18.25	0.00015	54.75	0.00015	54.75
	Right regional	0.000272	99.26792	0.00041	149.65	0.00005	18.25	0.000272	99.267922	0.000272	99.26792
	Left alluvial plain	0.0009	328.5	0.0009	328.5	0.0009	328.5	0.00135	492.75	0.0002	73
	Right alluvial plain	0.0009	328.5	0.0009	328.5	0.0009	328.5	0.00135	492.75	0.0002	73
	Average residual error (m)	0.050									
	Diff. hydrological budget (%)	1.42		1.87		2.70		1.42		1.86	

FLOW BUDGET between all 6 material units

	ZONE 1	**Test 801C**		**Scenario_3A**		**Scenario_3B**		**Scenario_4A**		**Scenario_4B**	
	Coarse alluvium	**Base scenario**		Increased K and RCH/regional unit		Decreased K and RCH/regional unit		Increased K and RCH/backfill unit		Decreased K and RCH/ backfill unit	
	FLUX IN	Abs	%	Abs	%	Abs	%	Abs	%	Abs	%
From fine alluvium	Zone 2 to zone 1	4.86	66.80	3.07	44.55	2.83	73.10	5.65	68.37	3.44	62.54
From upper regional unit	Zone 3 to zone 1	0.48	6.65	0.33	4.83	0.04	1.12	0.48	5.78	0.50	9.02
From actual stream bed	Zone 4 to zone 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
From lower regional unit	Zone 5 to zone 1	1.85	25.44	3.42	49.63	0.96	24.90	2.02	24.49	1.52	27.65
From backfill unit	Zone 6 to zone 1	0.08	1.11	0.07	0.99	0.03	0.89	0.11	1.36	0.04	0.79
	Total IN	7.27		6.89		3.87		8.26		5.51	
	FLUX OUT										
Toward fine alluvium	Zone 1 to zone 2	5.24	72.33	1.69	24.60	2.84	74.22	6.04	73.38	3.81	69.60
Toward upper regional unit	Zone 1 to zone 3	0.02	0.30	0.00	0.00	0.00	0.04	0.02	0.26	0.02	0.38
Toward actual stream bed	Zone 1 to zone 4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Toward lower regional unit	Zone 1 to zone 5	1.97	27.22	5.18	75.35	0.99	25.74	2.16	26.20	1.63	29.82
Toward backfill unit	Zone 1 to zone 6	0.01	0.16	0.00	0.04	0.00	0.00	0.01	0.16	0.01	0.21
	Total OUT	7.24		6.87		3.83		8.23		5.47	

	ZONE 2	**Test 801C**		**Scenario_3A**		**Scenario_3B**		**Scenario_4A**		**Scenario_4B**	
	Fine alluvium	**Base scenario**		Increased K and RCH/regional unit		Decreased K and RCH/regional unit		Increased K and RCH/backfill unit		Decreased K and RCH/ backfill unit	
	FLUX IN	Abs	%	Abs	%	Abs	%	Abs	%	Abs	%
From coarse alluvium	Zone 1 to zone 2	5.24	26.50	1.69	11.16	2.84	26.37	6.04	27.26	3.81	24.89
From upper regional unit	Zone 3 to zone 2	5.33	26.97	2.24	14.80	0.95	8.77	4.70	21.19	7.19	47.01
From actual stream bed	Zone 4 to zone 2	0.00	0.00	0.00	0.01	0.00	0.04	0.00	0.00	0.00	0.00
From lower regional unit	Zone 5 to zone 2	1.27	6.43	5.02	33.13	0.96	8.90	1.30	5.86	1.21	7.88
From backfill unit	Zone 6 to zone 2	7.93	40.10	6.20	40.90	6.03	55.92	10.13	45.69	3.09	20.22
	Total IN	19.77		15.15		10.78		22.16		15.30	
	FLUX OUT										
Toward coarse alluvium	Zone 2 to zone 1	4.86	24.59	3.07	20.25	2.83	26.23	5.65	25.51	3.44	22.53
Toward upper regional unit	Zone 2 to zone 3	0.55	2.79	0.32	2.09	0.21	1.94	0.55	2.47	0.52	3.37
Toward actual stream bed	Zone 2 to zone 4	5.12	25.91	2.05	13.56	2.91	27.05	4.75	21.45	7.06	46.16
Toward lower regional unit	Zone 2 to zone 5	1.07	5.41	5.65	37.32	0.64	5.95	1.10	4.95	0.98	6.38
Toward backfill unit	Zone 2 to zone 6	8.16	41.30	4.06	26.78	4.18	38.84	10.11	45.63	3.30	21.56
	Total OUT	19.76		15.15		10.77		22.15		15.29	

	Zone 3	Test 801C		Scenario_3A		Scenario_3B		Scenario_4A		Scenario_4B	
	Regional silt	Base scenario		Increased K and RCH/regional unit		Decreased K and RCH/regional unit		Increased K and RCH/backfill unit		Decreased K and RCH/ backfill unit	
	FLUX IN	Abs	%	Abs	%	Abs	%	Abs	%	Abs	%
Recharge	RECHARGE	7.87	79.41	11.95	86.20	1.94	60.25	7.87	79.99	7.87	77.32
From coarse alluvium	Zone 1 to zone 3	0.02	1.05	0.00	0.01	0.00	0.11	0.02	1.09	0.02	0.90
From fine alluvium	Zone 2 to zone 3	0.55	27.05	0.32	16.55	0.21	16.28	0.55	27.85	0.52	22.32
From actual stream bed	Zone 4 to zone 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
From lower regional unit	Zone 5 to zone 3	0.16	7.96	0.37	19.14	0.75	58.53	0.16	8.29	0.16	7.03
From backfill unit	Zone 6 to zone 3	1.30	63.94	1.23	64.30	0.32	25.09	1.24	62.77	1.61	69.75
	Total IN	2.04	100.00	1.91	100.00	1.28	100.00	1.97	100.00	2.31	100.00
	FLUX OUT										
Toward coarse alluvium	Zone 3 to zone 1	0.48	4.97	0.33	2.41	0.04	1.38	0.48	4.97	0.50	4.95
Toward fine alluvium	Zone 3 to zone 2	5.33	54.82	2.24	16.23	0.95	30.32	4.70	48.87	7.19	71.74
Toward actual stream bed	Zone 3 to zone 4	0.04	0.40	0.07	0.50	0.00	0.06	0.03	0.33	0.09	0.94
Toward lower regional unit	Zone 3 to zone 5	0.30	3.04	10.95	79.25	1.27	40.66	0.28	2.95	0.35	3.46
Toward backfill unit	Zone 3 to zone 6	3.58	36.77	0.22	1.60	0.86	27.58	4.12	42.89	1.90	18.90
	Total OUT	9.73		13.81		3.12		9.61		10.03	

	ZONE 4	Test 801C		Scenario_3A		Scenario_3B		Scenario_4A		Scenario_4B	
	Actual stream bed	Base scenario		Increased K and RCH/regional unit		Decreased K and RCH/regional unit		Increased K and RCH/backfill unit		Decreased K and RCH/ backfill unit	
	FLUX IN	Abs	%	Abs	%	Abs	%	Abs	%	Abs	%
RIVER LEAKAGE		0.12	0.78	0.04	0.22	0.22	2.43	0.11	0.58	0.15	1.46
RECHARGE		0.00	0.02	0.00	0.02	0.00	0.04	0.01	0.03	0.00	0.01
From coarse alluvium	Zone 1 to zone 4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
From fine alluvium	Zone 2 to zone 4	5.12	32.66	2.05	10.18	2.91	32.23	4.75	24.99	7.06	67.49
From upper regional unit	Zone 3 to zone 4	0.04	0.25	0.07	0.35	0.00	0.02	0.03	0.17	0.09	0.90
From lower regional unit	Zone 5 to zone 4	0.05	0.31	12.65	62.75	0.13	1.41	0.05	0.24	0.06	0.58
From backfill unit	Zone 6 to zone 4	10.34	65.98	5.34	26.49	5.77	63.88	14.07	74.00	3.09	29.55
	Total IN	15.67		20.17		9.04		19.01	19.01	19.01	
	FLUX OUT										
Toward the river	River Leakage	15.62	99.68	20.01	99.21	8.98	99.38	18.97	99.76	10.39	99.30
Recharge		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Toward coarse alluvium	Zone 4 to zone 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Toward fine alluvium	Zone 4 to zone 2	0.00	0.00	0.00	0.01	0.00	0.05	0.00	0.00	0.00	0.00
Toward upper regional unit	Zone 4 to zone 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Toward lower regional unit	Zone 4 to zone 5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Toward backfill unit	Zone 4 to zone 6	0.05	0.32	0.16	0.78	0.05	0.57	0.04	0.24	0.07	0.70
	Total OUT	15.67		20.17		9.04		19.01		10.46	

	Zone 5	Test 801C		Scenario_3A		Scenario_3B		Scenario_4A		Scenario_4B	
	Lower regional unit	Base scenario		Increased K and RCH/regional unit		Decreased K and RCH/regional unit		Increased K and RCH/backfill unit		Decreased K and RCH/ backfill unit	
	FLUX IN	Abs	%	Abs	%	Abs	%	Abs	%	Abs	%
From coarse alluvium	Zone 1 to zone 5	1.97	59.12	5.18	23.79	0.99	34.05	2.16	61.01	1.63	55.23
From fine alluvium	Zone 2 to zone 5	1.07	32.03	5.65	25.95	0.64	22.13	1.10	30.99	0.98	33.03
From upper regional unit	Zone 3 to zone 5	0.30	8.85	10.95	50.26	1.27	43.81	0.28	8.01	0.35	11.74
From actual stream bed	Zone 4 to zone 5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
From backfill unit	Zone 6 to zone 5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total IN	3.34		21.78		2.90		3.54		2.95	
	FLUX OUT										
Toward coarse alluvium	Zone 5 to zone 1	1.85	55.52	3.42	15.93	0.96	34.38	2.02	57.30	1.52	51.60
Toward fine alluvium	Zone 5 to zone 2	1.27	38.15	5.02	23.38	0.96	34.28	1.30	36.79	1.21	40.85
Toward upper regional unit	Zone 5 to zone 3	0.16	4.87	0.37	1.71	0.75	26.80	0.16	4.62	0.16	5.50
Toward actual stream bed	Zone 5 to zone 4	0.05	1.46	12.65	58.97	0.13	4.54	0.05	1.29	0.06	2.05
Toward backfill unit	Zone 5 to zone 6	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.01
	Total OUT	3.33		21.46		2.80		3.53		2.95	

	Zone 6	Test 801C		Scenario_3A		Scenario_3B		Scenario_4A		Scenario_4B	
	Backfill material	Base scenario		Increased K and RCH/regional unit		Decreased K and RCH/regional unit		Increased K and RCH/backfill unit		Decreased K and RCH/ backfill unit	
	FLUX IN	Abs	%	Abs	%	Abs	%	Abs	%	Abs	%
Recharge		8.01	40.45	8.59	65.91	7.19	58.51	11.47	44.53	2.64	33.34
From coarse alluvium	Zone 1 to zone 6	0.01	0.06	0.00	0.06	0.00	0.00	0.01	0.09	0.01	0.21
From fine alluvium	Zone 2 to zone 6	8.16	41.19	4.06	91.33	4.18	82.10	10.11	70.75	3.30	62.48
From upper regional unit	Zone 3 to zone 6	3.58	18.05	0.22	4.97	0.86	16.88	4.12	28.85	1.90	35.92
From actual stream bed	Zone 4 to zone 6	0.05	0.26	0.16	3.55	0.05	1.01	0.04	0.31	0.07	1.39
From lower regional unit	Zone 5 to zone 6	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00
	Total IN	19.81		4.44	100.00	5.10	100.00	14.29	100.00	5.28	100.00
	FLUX OUT										
Toward the river	River Leakage	0.16	0.80	0.19	1.48	0.12	0.96	0.21	0.82	0.08	0.98
Recharge	Recharge	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Toward coarse alluvium	Zone 6 to zone 1	0.08	0.41	0.07	0.52	0.03	0.28	0.11	0.44	0.04	0.55
Toward fine alluvium	Zone 6 to zone 2	7.93	40.01	6.20	47.56	6.03	49.11	10.13	39.32	3.09	39.08
Toward upper regional unit	Zone 6 to zone 3	1.30	6.59	1.23	9.44	0.32	2.62	1.24	4.80	1.61	20.33
Toward actual stream bed	Zone 6 to zone 4	10.34	52.20	5.34	41.00	5.77	47.03	14.07	54.63	3.09	39.05
Toward lower regional unit	Zone 6 to zone 5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total OUT	19.81		13.03		12.28		25.75		7.92	

Simulation parameters and results (steady-state conditions) for scenarios 5A, 5B, 6A and 6B

Simulation parameters

	Conductivité hydraulique	Base scenario		Scenario 5A: increased thickness of alluvial units		Scenario 5B: decreased thickness of alluvial units		Scenario 6A: increased thickness of coarse alluvium		Scenario 6B: decreased thickness of coarse alluvium	
Unit	**Type of material**	**(m/day)**	**(m/sec)**	**(m/day)**	**(m/sec)**	**(m/day)**	**(m/sec)**	**(m/day)**	**(m/sec)**	**(m/day)**	**(m/sec)**
Coarse alluvium (1)	Medium to coarse sand	32.32	3.74E-04	32.32	3.74E-04	32.32	3.74E-04	32.32	3.74E-04	32.32	4.36E-04
Fine alluvium (2)	Fine sand with fines	0.96	1.11E-05	0.96	1.11E-05	0.96	1.11E-05	0.96	1.11E-05	0.96	3.02E-05
Actual stream bed (4)	Fine sand	1.84	2.13E-05	1.84	2.13E-05	1.84	2.13E-05	1.84	2.13E-05	1.84	1.07E-04
Backfill material (6)	Fine sand with fines	0.95	1.10E-05	0.95	1.10E-05	0.95	1.10E-05	0.95	1.10E-05	0.95	5.93E-06
Upper regional unit (3)	Silty sand	0.15	1.72E-06	0.15	1.72E-06	0.15	1.72E-06	0.15	1.72E-06	0.15	2.05E-06
Lower regional unit (5)	Silty clay	0.0020	2.31E-08	0.0020	2.31E-08	0.0020	2.31E-08	0.0020	2.31E-08	0.0020	4.58E-08
	Recharge zone	**(m/day)**	**(mm/year)**	**(m/day)**	**(mm/year)**	**(m/day)**	**(mm/year)**	**(m/day)**	**(mm/year)**	**(m/day)**	**(mm/year)**
	Left regional	0.00015	54.75	0.00015	54.75	0.00015	54.75	0.00015	54.75	0.00015	54.75
	Right regional	0.00027	99.27	0.00027	99.27	0.00027	99.27	0.00027	99.27	0.00027	99.27
	Left alluvial plain	0.0009	328.5	0.0009	328.5	0.0009	328.5	0.0009	328.5	0.0009	328.5
	Right alluvial plain	0.0009	328.5	0.0009	328.5	0.0009	328.5	0.0009	328.5	0.0009	328.5
	Average residual error (m)	0.050									
	Diff. hydrological budget (%)	1.42		1.40		2.18		1.31		1.58	

FLOW BUDGET between all 6 material units

	ZONE 1	**Test 801C**		**Scenario_5A**		**Scenario_5B**		**Scenario_6A_**		**Scenario_6B**	
	Coarse alluvium	**Base scenario**		Increased thickness of alluvial units		Decreased thickness of alluvial units		Increased thickness of coarse alluvium		Decreased thickness of coarse alluvium	
	FLUX IN	Abs	%	Abs	%	Abs	%	Abs	%	Abs	%
From fine alluvium	Zone 2 to zone 1	4.86	66.80	5.41	86.17	3.87	72.70	5.36	85.48	4.88	70.73
From upper regional unit	Zone 3 to zone 1	0.48	6.65	0.54	8.58	0.43	8.12	0.56	8.86	0.50	7.20
From actual stream bed	Zone 4 to zone 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
From lower regional unit	Zone 5 to zone 1	1.85	25.44	0.27	4.25	0.07	1.28	0.28	4.50	1.44	20.89
From backfill unit	Zone 6 to zone 1	0.08	1.11	0.06	0.99	0.95	17.91	0.07	1.16	0.08	1.17
	Total IN	7.27		6.27		5.33		6.27		6.90	
	FLUX OUT										
Toward fine alluvium	Zone 1 to zone 2	5.24	72.33	3.91	62.77	5.28	99.38	3.71	59.62	5.23	76.08
Toward upper regional unit	Zone 1 to zone 3	0.02	0.30	0.04	0.57	0.00	0.00	0.04	0.57	0.01	0.21
Toward actual stream bed	Zone 1 to zone 4	0.00	0.00	2.06	33.14	0.00	0.00	2.21	35.56	0.00	0.00
Toward lower regional unit	Zone 1 to zone 5	1.97	27.22	0.22	3.51	0.02	0.38	0.26	4.24	1.62	23.54
Toward backfill unit	Zone 1 to zone 6	0.01	0.16	0.00	0.01	0.01	0.24	0.00	0.00	0.01	0.16
	Total OUT	7.24		6.23		5.31		6.23		6.87	

	ZONE 2	**Test 801C**		**Scenario_5A**		**Scenario_5B**		**Scenario_6A_**		**Scenario_6B**	
	Fine alluvium	**Base scenario**		Increased thickness of alluvial units		Decreased thickness of alluvial units		Increased thickness of coarse alluvium		Decreased thickness of coarse alluvium	
	FLUX IN	Abs	%	Abs	%	Abs	%	Abs	%	Abs	%
From coarse alluvium	Zone 1 to zone 2	5.24	26.50	3.91	21.81	5.28	33.24	3.71	21.30	5.23	26.50
From upper regional unit	Zone 3 to zone 2	5.33	26.97	6.17	34.38	0.06	0.37	5.64	32.35	5.33	27.01
From actual stream bed	Zone 4 to zone 2	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.04	0.00	0.00
From lower regional unit	Zone 5 to zone 2	1.27	6.43	0.19	1.05	0.10	0.62	0.10	0.57	1.27	6.43
From backfill unit	Zone 6 to zone 2	7.93	40.10	7.67	42.75	10.45	65.78	7.97	45.74	7.91	40.06
	Total IN	19.77		17.93		15.88		17.43		19.74	
	FLUX OUT										
Toward coarse alluvium	Zone 2 to zone 1	4.86	24.59	5.41	30.17	3.87	24.40	5.36	30.77	4.88	24.76
Toward upper regional unit	Zone 2 to zone 3	0.55	2.79	0.76	4.22	0.00	0.02	0.58	3.32	0.55	2.79
Toward actual stream bed	Zone 2 to zone 4	5.12	25.91	6.14	34.24	5.14	32.41	5.99	34.40	5.11	25.91
Toward lower regional unit	Zone 2 to zone 5	1.07	5.41	0.11	0.63	0.04	0.23	0.05	0.27	1.03	5.23
Toward backfill unit	Zone 2 to zone 6	8.16	41.30	5.51	30.75	6.82	42.95	5.44	31.24	8.15	41.30
	Total OUT	19.76		17.92		15.88		17.43		19.72	

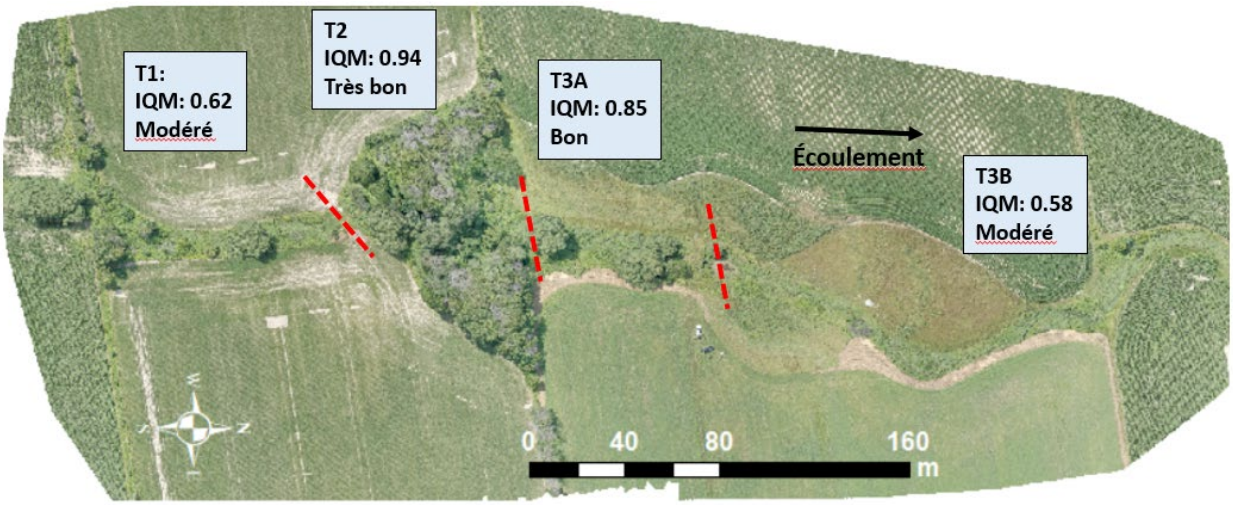
	Zone 3	Test 801C		Scenario_5A		Scenario_5B		Scenario_6A_		Scenario_6B	
	Regional silt	Base scenario		Increased thickness of alluvial units		Decreased thickness of alluvial units		Increased thickness of coarse alluvium		Decreased thickness of coarse alluvium	
	FLUX IN	Abs	%	Abs	%	Abs	%	Abs	%	Abs	%
Recharge	RECHARGE	7.87	79.41	7.83	77.27	7.83	88.49	7.83	78.93	7.87	79.36
From coarse alluvium	Zone 1 to zone 3	0.02	1.05	0.04	1.55	0.00	0.00	0.04	1.68	0.01	0.71
From fine alluvium	Zone 2 to zone 3	0.55	27.05	0.76	32.80	0.00	0.29	0.58	27.66	0.55	26.91
From actual stream bed	Zone 4 to zone 3	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00
From lower regional unit	Zone 5 to zone 3	0.16	7.96	0.11	4.69	0.14	13.36	0.13	6.13	0.16	8.04
From backfill unit	Zone 6 to zone 3	1.30	63.94	1.41	60.96	0.88	86.25	1.35	64.53	1.32	64.34
	Total IN	2.04	100.00	2.31	100.00	1.02	100.00	2.09	100.00	2.05	100.00
	FLUX OUT										
Toward coarse alluvium	Zone 3 to zone 1	0.48	4.97	0.54	5.40	0.43	5.06	0.56	5.69	0.50	5.12
Toward fine alluvium	Zone 3 to zone 2	5.33	54.82	6.17	61.80	0.06	0.68	5.64	57.69	5.33	54.88
Toward actual stream bed	Zone 3 to zone 4	0.04	0.40	0.06	0.59	0.05	0.55	0.06	0.62	0.04	0.42
Toward lower regional unit	Zone 3 to zone 5	0.30	3.04	0.26	2.64	0.50	5.83	0.23	2.37	0.28	2.87
Toward backfill unit	Zone 3 to zone 6	3.58	36.77	2.95	29.58	7.51	87.88	3.29	33.64	3.57	36.71
	Total OUT	9.73		9.98		8.54		9.78		9.71	

	ZONE 4	Test 801C		Scenario_5A		Scenario_5B		Scenario_6A_		Scenario_6B	
	Actual stream bed	Base scenario		Increased thickness of alluvial units		Decreased thickness of alluvial units		Increased thickness of coarse alluvium		Decreased thickness of coarse alluvium	
	FLUX IN	Abs	%	Abs	%	Abs	%	Abs	%	Abs	%
RIVER LEAKAGE		0.12	0.78	0.11	0.70	0.12	0.77	0.11	0.70	0.12	0.78
RECHARGE		0.00	0.02	0.00	0.02	0.00	0.02	0.00	0.02	0.00	0.02
From coarse alluvium	Zone 1 to zone 4	0.00	0.00	2.06	13.11	0.00	0.00	2.21	14.05	0.00	0.00
From fine alluvium	Zone 2 to zone 4	5.12	32.66	6.14	38.97	5.14	32.93	5.99	38.04	5.11	32.66
From upper regional unit	Zone 3 to zone 4	0.04	0.25	0.06	0.38	0.05	0.30	0.06	0.38	0.04	0.26
From lower regional unit	Zone 5 to zone 4	0.05	0.31	0.03	0.18	0.05	0.35	0.03	0.18	0.05	0.31
From backfill unit	Zone 6 to zone 4	10.34	65.98	7.34	46.63	10.25	65.63	7.35	46.62	10.32	65.96
	Total IN	15.67		15.75		15.63		15.76		15.65	
	FLUX OUT										
Toward the river	River Leakage	15.62	99.68	15.74	99.94	15.62	99.99	15.75	99.95	15.60	99.68
Recharge		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Toward coarse alluvium	Zone 4 to zone 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Toward fine alluvium	Zone 4 to zone 2	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.05	0.00	0.00
Toward upper regional unit	Zone 4 to zone 3	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Toward lower regional unit	Zone 4 to zone 5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Toward backfill unit	Zone 4 to zone 6	0.05	0.32	0.01	0.05	0.00	0.00	0.00	0.00	0.05	0.32
	Total OUT	15.67		15.75		15.63		15.76		15.65	

	Zone 5	Test 801C		Scenario_5A		Scenario_5B		Scenario_6A_		Scenario_6B	
	Lower regional unit	Base scenario		Increased thickness of alluvial units		Decreased thickness of alluvial units		Increased thickness of coarse alluvium		Decreased thickness of coarse alluvium	
	FLUX IN	Abs	%	Abs	%	Abs	%	Abs	%	Abs	%
From coarse alluvium	Zone 1 to zone 5	1.97	59.12	0.22	36.76	0.02	3.68	0.26	48.73	1.62	55.25
From fine alluvium	Zone 2 to zone 5	1.07	32.03	0.11	18.97	0.04	6.53	0.05	8.56	1.03	35.24
From upper regional unit	Zone 3 to zone 5	0.30	8.85	0.26	44.27	0.50	89.61	0.23	42.71	0.28	9.51
From actual stream bed	Zone 4 to zone 5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
From backfill unit	Zone 6 to zone 5	0.00	0.00	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.00
	Total IN	3.34		0.59		0.56		0.54		2.93	
	FLUX OUT										
Toward coarse alluvium	Zone 5 to zone 1	1.85	55.52	0.27	45.11	0.07	12.35	0.28	52.50	1.44	49.31
Toward fine alluvium	Zone 5 to zone 2	1.27	38.15	0.19	31.75	0.10	17.76	0.10	18.40	1.27	43.41
Toward upper regional unit	Zone 5 to zone 3	0.16	4.87	0.11	18.30	0.14	24.75	0.13	23.87	0.16	5.62
Toward actual stream bed	Zone 5 to zone 4	0.05	1.46	0.03	4.84	0.05	9.86	0.03	5.23	0.05	1.66
Toward backfill unit	Zone 5 to zone 6	0.00	0.00	0.00	0.00	0.19	35.28	0.00	0.00	0.00	0.00
	Total OUT	3.33		0.59		0.55		0.54		2.93	

	Zone 6	Test 801C		Scenario_5A		Scenario_5B		Scenario_6A_		Scenario_6B	
	Backfill material	Base scenario		Increased thickness of alluvial units		Decreased thickness of alluvial units		Increased thickness of coarse alluvium		Decreased thickness of coarse alluvium	
	FLUX IN	Abs	%	Abs	%	Abs	%	Abs	%	Abs	%
Recharge		8.01	40.45	8.01	48.60	8.01	35.53	8.01	47.84	8.01	40.50
From coarse alluvium	Zone 1 to zone 6	0.01	0.10	0.00	0.00	0.01	0.09	0.00	0.00	0.01	0.09
From fine alluvium	Zone 2 to zone 6	8.16	69.16	5.51	65.07	6.82	46.92	5.44	62.33	8.15	69.19
From upper regional unit	Zone 3 to zone 6	3.58	30.31	2.95	34.84	7.51	51.66	3.29	37.66	3.57	30.29
From actual stream bed	Zone 4 to zone 6	0.05	0.43	0.01	0.09	0.00	0.00	0.00	0.00	0.05	0.43
From lower regional unit	Zone 5 to zone 6	0.00	0.00	0.00	0.00	0.19	1.34	0.00	0.00	0.00	0.00
	Total IN	11.80	100.00	8.47	100.00	14.53	100.00	8.73	100.00	11.77	100.00
	FLUX OUT										
Toward the river	River Leakage	0.16	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.80
Recharge	Recharge	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Toward coarse alluvium	Zone 6 to zone 1	0.08	0.41	0.06	0.38	0.07	0.43	0.07	0.43	0.08	0.41
Toward fine alluvium	Zone 6 to zone 2	7.93	40.01	7.67	46.53	7.97	47.63	7.97	47.63	7.91	39.97
Toward upper regional unit	Zone 6 to zone 3	1.30	6.59	1.41	8.53	1.35	8.06	1.35	8.06	1.32	6.65
Toward actual stream bed	Zone 6 to zone 4	10.34	52.20	7.34	44.57	7.35	43.88	7.35	43.88	10.32	52.18
Toward lower regional unit	Zone 6 to zone 5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total OUT	19.81		16.48		16.74		16.74		19.79	

Appendix C : IQM results (Chapter 4)



Segmentation of homogeneous reach and IQM score results for 2022 and 2024 for the study site

Facteurs IQM	Description	Tronçon 1-Année 2022	Tronçon 1-Année 2024	Tronçon 2-Année 2022	Tronçon 2-Année 2024	Tronçon 3A-Année 2022	Tronçon 3A-Année 2024	Tronçon 3B-Année 2022	Tronçon 3B-Année 2024	Site d'étude complet
F1	Continuité longitudinale dans le transport de sédiments et de bois	3	3	3	3	0	0	3	3	3
F2	Présence d'une plaine alluviale moderne	2	2	0	0	2	2	2	2	3
F3	Connectivité entre le corridor fluvial et les versants									
F4	- Processus d'érosion des berges	3	3	0	0	0	0	2	2	0
F5	Présence d'un corridor d'érodabilité potentiel	0	0	0	0	0	0	0	0	3
F6	La configuration du lit (confiné)									
F7	Unités géomorphologiques dans le chenal	5	5	0	0	3	3	5	5	3
F8	Unités géomorphologiques dans la plaine alluviale moderne	3	3	0	0	2	2	3	3	2
F9	Variabilité de la section transversale	5	5	0	0	3	3	5	5	5
F10	La structure du substrat	2	2	0	0	0	0	0	0	5
F11	Présence de bois mort	3	3	2	2	2	2	3	3	3
F12	Largeur occupée par un couvert végétal naturel	3	3	0	0	2	2	3	3	3
F13	Étendue linéaire occupée par un couvert végétal naturel	3	3	0	0	3	3	5	5	5

A1	Altération des débits liquides (BV)	0	0	0	0	0	0	0	0		0
A2	Altération des débits solides (BV)	0	0	0	0	0	0	0	0		0
A3	Infrastructures altérant le régime hydrologique à l'échelle du tronçon	0	0	0	0	0	0	0	0		0
A4	Infrastructures altérant les flux solides à l'échelle du tronçon	0	0	0	0	0	0	0	0		0
A5	Présence de traverses de cours d'eau	3	3	3	3	0	0	3	3		3
A6	Présence de mesures de protection contre l'érosion des berges	0	0	0	0	0	0	0	0		0
A7	Présence de digues (levées artificielles)	0	0	0	0	0	0	0	0		0
A8	Rectification du tracé fluvial/dragage	6	6	0	0	0	0	12	12		2
A9	Autres infrastructures de stabilisation du lit	0	0	0	0	0	0	0	0		0
A10	Retrait des sédiments (dragage)	6	6	0	0	0	0	6	6		6
A11	Retrait du bois mort										
A12	Gestion de la bande riveraine et de la végétation aquatique	2	2	0	0	2	2	5	5		5
C1	Ajustement du style fluvial (indice de tressage ou de sinuosité*) depuis 1960	3	3	0	0	0	0	6	6		
C2	Ajustement de la largeur active depuis 1960	0	0	0	0	0	0	0	0		
C3	Ajustement du niveau du lit depuis 1960										
IQM final		**0.62**	**0.62**	**0.94**	**0.94**	**0.85**	**0.85**	**0.58**	**0.58**		**0.55**
		Modéré	**Modéré**	**Très bon**	**Très bon**	**Bon**	**Bon**	**Modéré**	**Modéré**		**Modéré**

Appendix D: « Un Méandre à la fois » final report

Mars 2025

PROJET UN MÉANDRE À LA FOIS

Analyse du potentiel de restauration de cours d'eau en milieu agricole

PHASE 1 (2022 - 2025)



PRÉSENTÉ PAR

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Laboratoire de gestion des rivières

Université Concordia

Analyse du potentiel de restauration de cours d'eau en milieu agricole (phase 1 : 2022-2025)

–

Rapport final

Pour le quatrième livrable du contrat no. DACMH22-001

Mars 2025

Pour
Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs

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Page couverture :

Site de restauration Un Méandre à la fois en juillet 2024 (Crédit photo : MRC Pierre de Saurel)

Note de non-engagement de responsabilité :

Le contenu de ce document, y compris les observations et recommandations fournies, n'engage que l'auteur et/ou l'Université dont il est issu. Ce rapport est destiné à des fins informatives et ne doit pas être interprété comme une validation officielle de toute organisation, entreprise ou entité tierce mentionnée. »»»«

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Résumé

Le projet "Un Méandre à la fois" vise à restaurer les processus hydrogéomorphologiques dans un tronçon de 280 mètres de cours d'eau agricole linéarisé en Montérégie. Les mesures clés de la première phase (2022-2025) comprenaient le retrait des cultures dans l'espace de liberté, basé sur la position historique des anciens méandres, pour améliorer les échanges hydrologiques entre le cours d'eau et son environnement riverain et favoriser la régénération naturelle des habitats. Le remplacement d'un ponceau sous-dimensionné a également été effectué pour renforcer la connectivité hydrologique longitudinale et soutenir les processus de mobilité latérale du tronçon linéarisé.

Le présent rapport relate les efforts et les résultats de la phase 1 (2022-2025), mais présente également un protocole pour une éventuelle phase 2 (2025-2028). De plus, certaines informations antérieures à 2022, issues de travaux menés dans le cadre d'un projet de recherche doctoral, sont présentées pour expliquer la genèse du projet.

Les résultats observés durant la phase 1 incluent une amélioration de la biodiversité, notamment une réponse positive des populations d'araignées et d'oiseaux, ainsi qu'un accroissement des milieux humides riverains. Un autre succès notable est la relation de confiance établie avec les producteurs agricoles, garantissant l'acceptabilité des interventions à long terme en tenant compte de leurs besoins économiques.

Le projet présente plusieurs éléments favorisant sa réplicabilité sur d'autres sites. Sa méthodologie flexible et graduelle a permis d'adapter les mesures de restauration aux spécificités agricoles locales, tout en préservant les processus naturels nécessaires à l'équilibre écologique. L'implication des parties prenantes locales, comme les producteurs, les groupes de conservation et les organismes régionaux (MRC, UPA, OBV), a renforcé la durabilité des actions. Le suivi écologique a utilisé des méthodes simples et économiques, facilement applicables à d'autres sites. Cette approche intégrée, combinant restauration des processus HGM et gestion économiquement équitable, offre un modèle réplicable pour des projets durables au Québec.

Néanmoins, plusieurs aspects nécessitent des études approfondies pour optimiser les stratégies de restauration en milieu agricole. L'impact à long terme des mesures de restauration passives, telles que le retrait des cultures de l'espace de liberté, doit être suivi de près pour évaluer la régénération des milieux humides et l'évolution de la biodiversité. De plus, un suivi continu de la biodiversité est essentiel pour ajuster les interventions en fonction des résultats. La pérennisation des efforts de restauration nécessite des mécanismes de financement solides et des stratégies flexibles pour les producteurs, tout en garantissant la durabilité des actions. Enfin, il est crucial de perfectionner les techniques de végétalisation pour contrôler les espèces exotiques envahissantes et intégrer les réseaux de drainage agricole.

En somme, "Un Méandre à la fois" a permis au final de restaurer une plaine alluviale de 280 m de long (environ 1 ha de surface) comprenant 3 méandres abandonnés. Ce projet novateur a montré l'efficacité des mesures de restauration basées sur les processus HGM dans un contexte agricole, tout en offrant un modèle applicable à d'autres régions. L'approche flexible et l'implication des acteurs locaux, soutenues par un suivi simple et reproductible, permettent de garantir la durabilité et de maximiser les gains écologiques à long terme.

1. Mise en contexte

1.1 Présentation sommaire des objectifs du projet

Le long des cours d'eau naturels, on retrouve un espace forgé par la migration du chenal et les inondations au fil de centaines, voire de milliers d'années. C'est ce qu'on appelle l'espace de liberté (Biron et coll. 2014). Les interactions entre les cours d'eau et cet espace de liberté résultent en une multitude de services écologiques (p. ex. atténuation des inondations et des étiages, amélioration de la qualité de l'eau, création d'habitats), de sorte que ces zones, malgré leur faible superficie, sont considérées comme des points chauds de la biodiversité sur la planète. En milieu agricole, au cours du 20e siècle, , de grands travaux ont été entrepris au Québec comme ailleurs afin de développer les infrastructures de drainage et simplifier la gestion de l'eau. Des décennies de travaux de redressement des cours d'eau, de remblaiement des plaines alluviales et d'installation de ponceaux ont permis une augmentation de la productivité agricole, mais ont, à l'inverse, sévèrement perturbé les services écologiques fournis par les milieux hydriques. Pour contrecarrer ces conséquences, il est primordial que le Québec innove en matière d'approches de restauration des petits cours d'eau de tête de bassin versant en milieu agricole qui ont été les plus affectés par ces interventions humaines.

Un projet de recherche élaboré par le Laboratoire de gestion des rivières de l'Université Concordia propose de mettre en place un protocole de restauration novateur d'un tronçon de 280 m d'un cours d'eau de tête redressé ainsi que de son espace de liberté (environ 1 ha) en milieu agricole. Un éventail de méthodes de restauration passive et active a été implanté sur la branche 13 de la rivière Petit-Pot-au-Beurre dans la municipalité de Saint-Robert, avec l'appui d'une famille de producteurs agricoles (Ferme Parentall), et ont été suivies par les chercheurs en hydrogéomorphologie de l'Université Concordia et leurs partenaires. Le projet a été retenu par la Direction des milieux humides du ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs (MELCCFP) pour une première phase de financement s'échelonnant sur la période 2022-2025. Les objectifs généraux du projet sont :

1. Analyser, identifier et implanter des mesures de restauration, qu'elles soient actives ou passives, adaptées spécifiquement au site d'étude.
2. Déterminer les indicateurs écologiques les plus pertinents pour mesurer les gains écologiques réalisés.
3. Analyser les différents outils et mécanismes de pérennisation et de financement des mesures de restauration pour assurer leur durabilité.
4. Établir les modalités nécessaires pour favoriser la réplicabilité et l'acceptabilité de ces projets parmi les producteurs agricoles.

Le présent document fait office de rapport final du projet, couvrant la période de septembre 2022 à janvier 2025. Il contient les sections suivantes :

- La description des travaux de restauration effectués entre 2022 et 2025
- Les principaux résultats des suivis de caractérisation écologique du site d'étude
- Un portrait de la collaboration mise en place avec les producteurs impliqués

- Un portrait de la perception et des besoins face au projet de restauration, pour les producteurs impliqués et en général
- Une description et analyse des mécanismes de pérennisation à mettre en place.
- Une description et analyse des mécanismes de financement pertinents
- Un portrait du potentiel écologique et socio-économique des projets de restauration basés sur les processus des cours d'eau de milieu agricole.
- Des recommandations de bonnes pratiques à mettre en place pour la conciliation des usages agricoles et des mesures de restauration
- Une description des travaux de restauration prévus pour une éventuelle phase 2.

1.2 Partenaires du projet

Un comité de suivi du projet a été mis sur pied pour suivre l'évolution du projet. Il est composé de représentants des organisations suivantes :

- Département de géographie, urbanisme et environnement de l'Université Concordia;
- Direction des milieux humides du ministère de l'Environnement et de la Lutte contre les changements climatiques, de la Faune et des Parcs (MELCCFP);
- Direction de l'agroenvironnement, MELCCFP;
- Direction de l'aménagement et du milieu hydrique, MELCCFP;
- Direction des territoires fauniques et des habitats, MELCCFP;
- Direction des habitats aquatiques et de la prévention des risques, MELLCFP;
- Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec (MAPAQ), Direction régionale de Montérégie;
- Ministère des Affaires municipales et de l'Habitation (MAMH), Direction régionale de Montérégie;
- Union des producteurs agricoles du Québec, fédération régionale de Montérégie;
- Municipalité régionale de comté de Pierre-De Saurel;
- Organisme de bassin versant Yamaska

Quatre rencontres ont eu lieu avec le comité de suivis : une rencontre de démarrage en début de projet, deux rencontres de suivi en mi-parcours et une rencontre à la fin du projet avec présentation des résultats.

En plus des personnes-ressources siégeant sur le comité de suivi, l'équipe de recherche du projet *Un Méandre à la fois* s'est entourée de professionnels experts dans des domaines spécifiques liés à la restauration écologique en milieu agricole (consultation des acteurs, suivis écologiques, travaux de restauration). La figure 1 présente la vaste majorité des partenaires ayant collaboré à ce projet pilote de recherche.

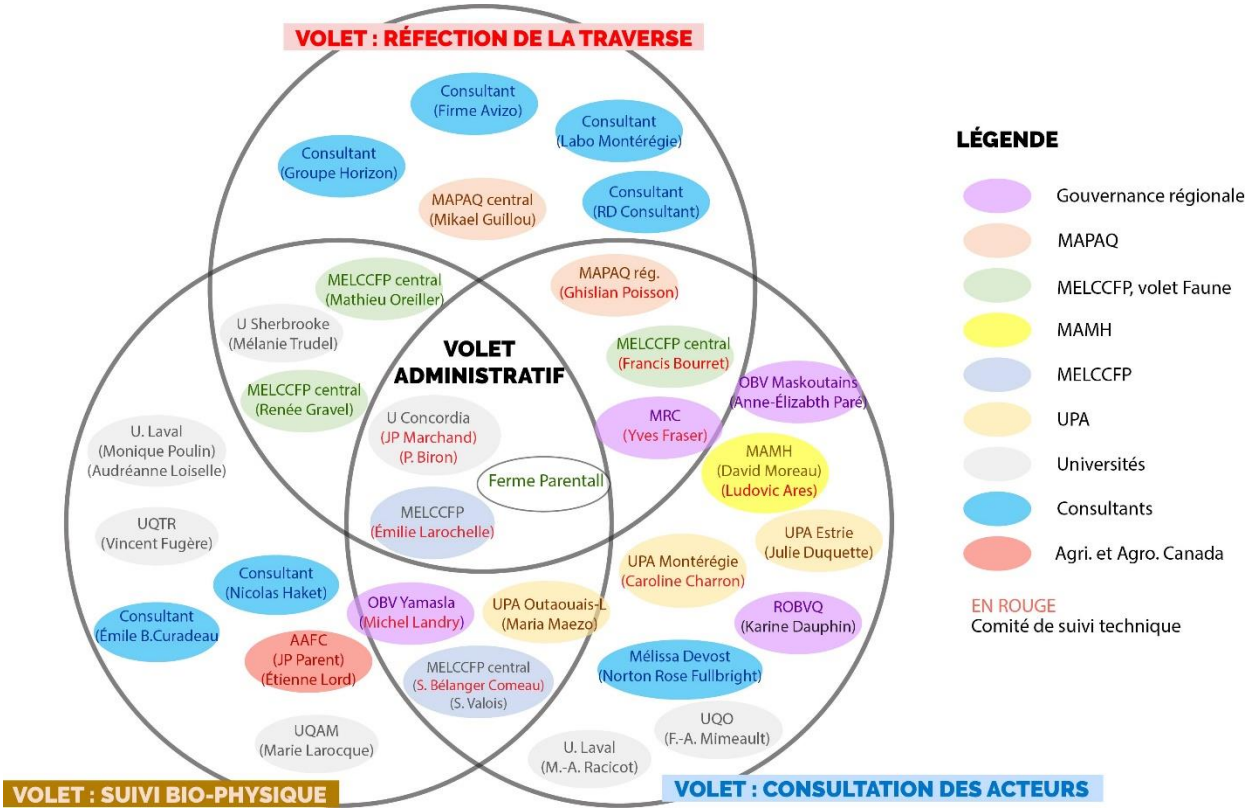


Figure 1. Principaux acteurs et collaborateurs impliqués dans le projet Un Méandre à la fois.

1.3 Site d'étude

Le site d'étude est un tronçon de 530 mètres de la branche 13 de la rivière Petite Pot-au-Beurre située dans la municipalité de Saint-Robert, en Montérégie. C'est un ruisseau de second ordre (Strahler) ayant une zone de drainage de 12.8 km^2 au site d'étude (figure 2). Le bassin versant de la branche 13 est principalement couvert (environ 90 %) par des champs cultivés (maïs, soya et plantes fourragères). Il fait partie du bassin versant de la rivière Pot-au-Beurre (208 km^2) qui est un tributaire de la rivière Yamaska.

La branche 13 présente une largeur et une profondeur du chenal au niveau plein-bord d'environ 4 et 1.5 m, respectivement. L'altitude du lit du cours d'eau dans le site d'étude varie entre 16.30 et 14.66 m au-dessus du niveau moyen des mers (n.m.m) tandis que sa pente avoisine 0.3%. L'indice de sinuosité du site d'étude est de 1.07. L'indice de sinuosité est le ratio de la longueur réelle d'un cours d'eau sur la distance directe (en ligne droite) entre ses points de départ et d'arrivée.

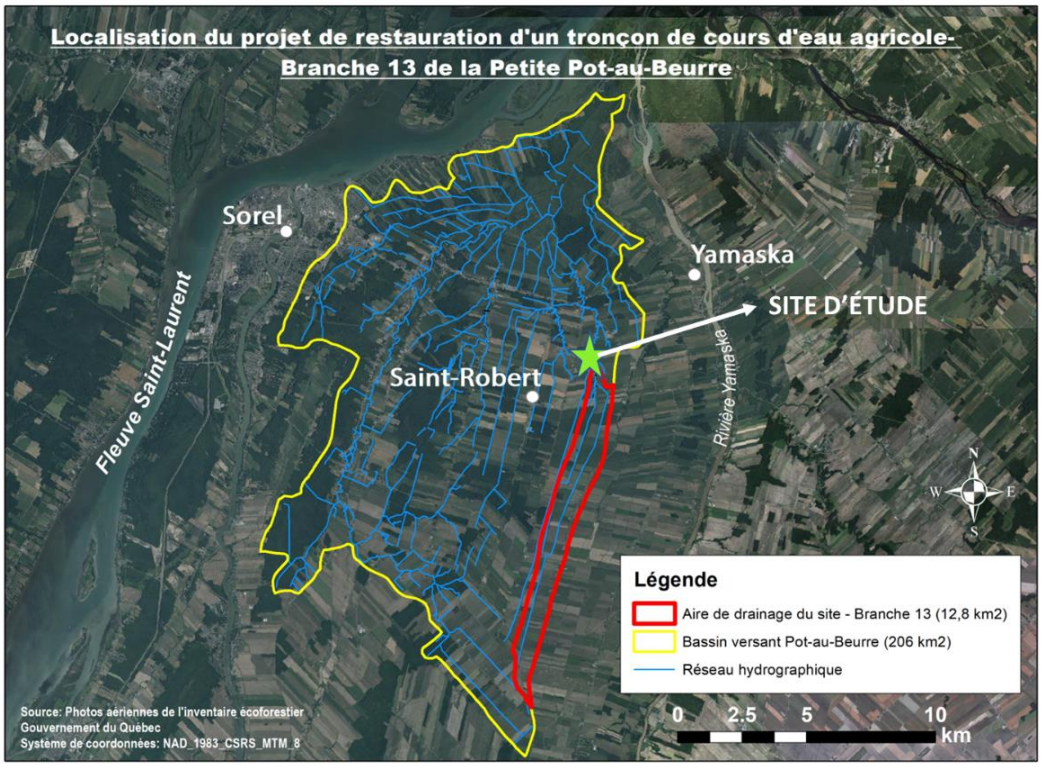


Figure 2 : Localisation du site d'étude dans le bassin versant de la Pot-au-Beurre

Le site d'étude se subdivise en trois tronçons d'étude : un tronçon amont agricole dégradé non restauré de 135 m (T1), un tronçon forestier non dégradé de 115 m (T2) et un tronçon aval agricole dégradé et visé par les travaux de restauration de 280 m (T3) (Figures 3 et 4). Le tronçon T3 est situé entièrement sur la propriété de l'entreprise agricole, la Ferme Parentall.

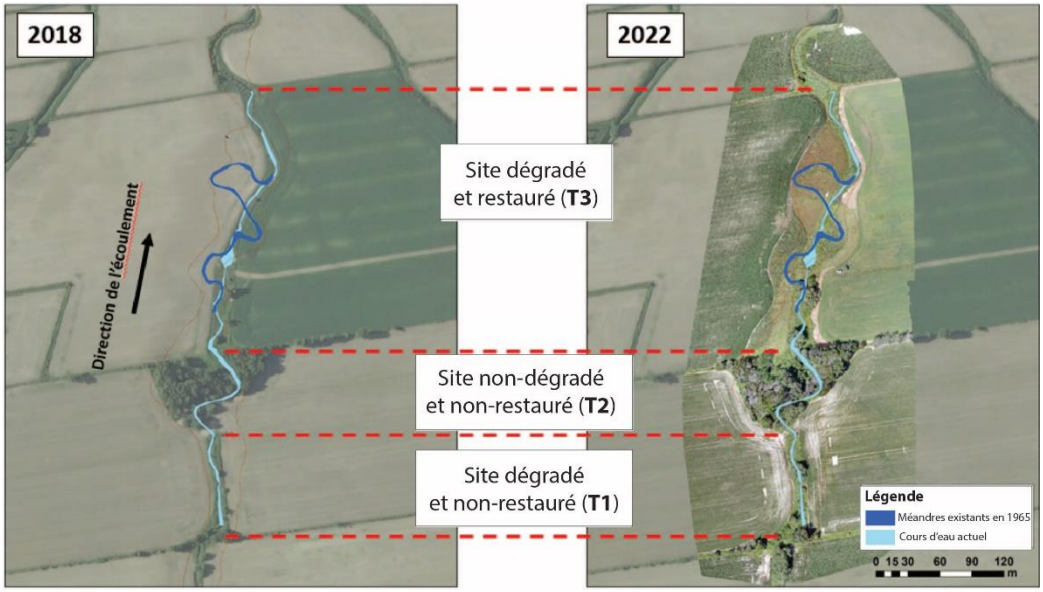


Figure 3 : Segmentation du tronçon étudié de la branche 13 de la rivière Petite Pot-au-Beurre utilisée comme protocole expérimental pour les suivis biophysiques

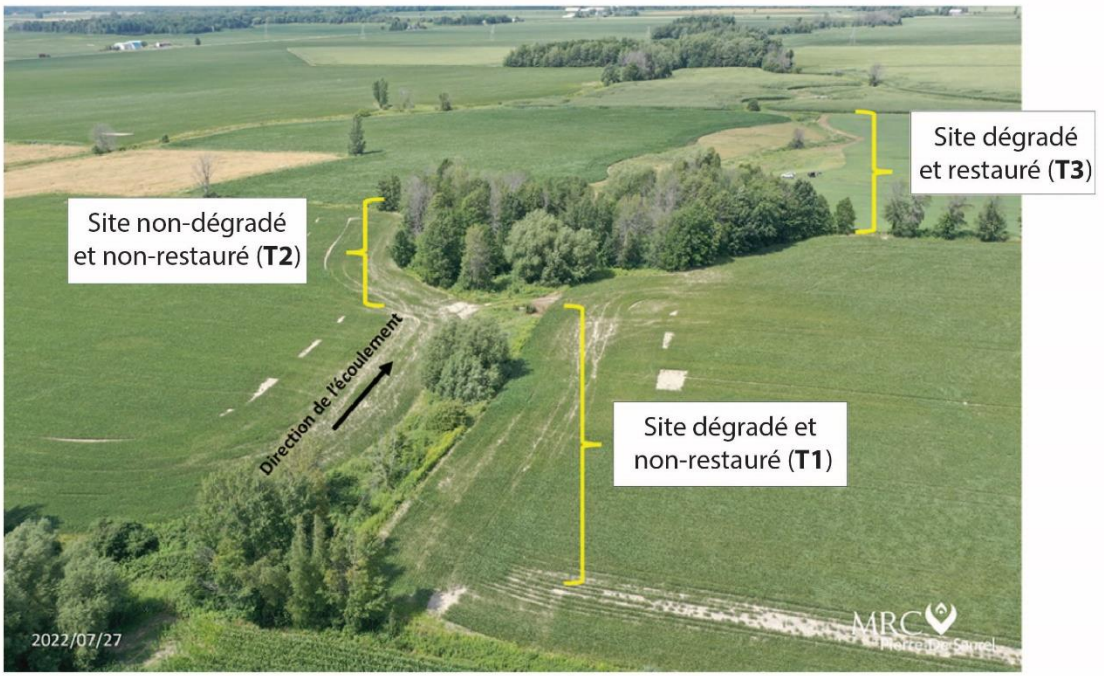


Figure 4. Vue par drone de la zone d'étude de la branche 13 de la Petite Pot-au-Beurre en juillet 2022 (Crédit photo : MRC Pierre de Saurel, 2022)

En 1965, le tronçon T3 (visé par le projet de restauration) comprenait une plaine alluviale aux abords d'un chenal sinueux, comme on peut toujours l'observer à la figure 5. L'indice de sinuosité du chenal était alors de 1,47. La plaine alluviale, d'une largeur variant entre 30 et 90 m et qui était délimitée par un talus d'environ 1,5 m, peut être observée sur les photos aériennes historiques (Figure 5). Le chenal au niveau du tronçon T3 a été redressé en 1983. Trois méandres ayant une ampleur entre 10 et 53 m ont été éliminés, totalisant une perte de 111 m linéaires de cours d'eau, et expliquant ainsi la baisse notable de l'indice de sinuosité. Un remblai de matériel local (silt argileux) a été placé sur les anciens méandres ainsi que sur la plaine alluviale du tronçon T3. Ce remblai masque aujourd'hui la plupart des caractéristiques topographiques de la plaine alluviale historique.

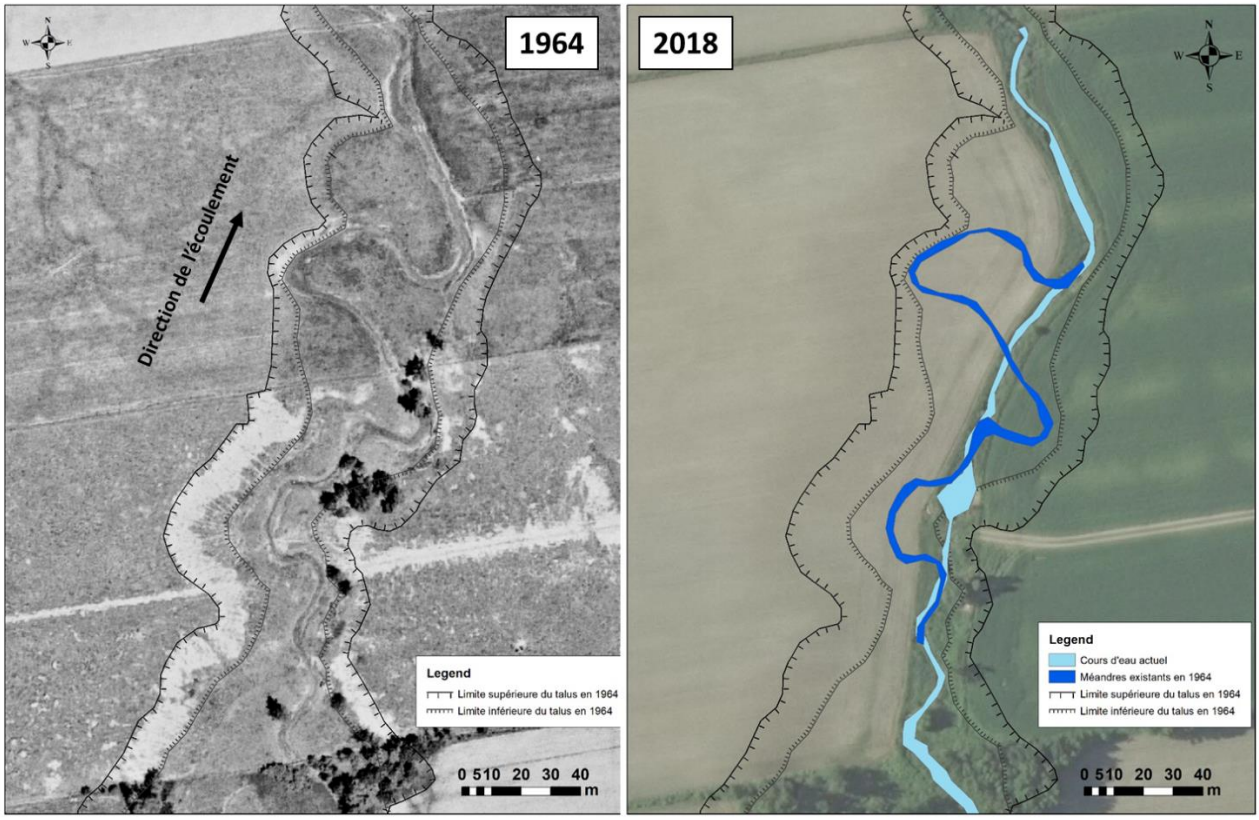


Figure 5. Tronçon T3 avant et après les travaux historiques de linéarisation et de remblaiement de la plaine alluviale (délimitée par les limites de talus).

Le modèle numérique de terrain bâti à partir du LiDAR (*Light Detection And Ranging*) permet toutefois d'identifier des dépressions semi-circulaires peu profondes qui sont des vestiges de la topographie de la plaine alluviale, antérieurs aux travaux de redressement (Figure 6). Dans le tronçon T2, la plaine alluviale n'a pas été remblayée historiquement. Fait intéressant, cette section comprend un bras mort (oxbow), localisé par l'étoile jaune à la Figure 6. Ce méandre abandonné résulte soit d'un processus naturel de recoupement de méandres ou d'un redressement artificiel antérieur à 1935 (année la plus ancienne des photos historiques disponibles). Il abrite aujourd'hui un milieu humide, soit celui de marécage à cornouiller stolonifère (Figure 7). Les détails sur les dépôts sédimentaires, les processus géomorphologiques actifs et l'hydrologie peuvent être consultés à l'annexe A.

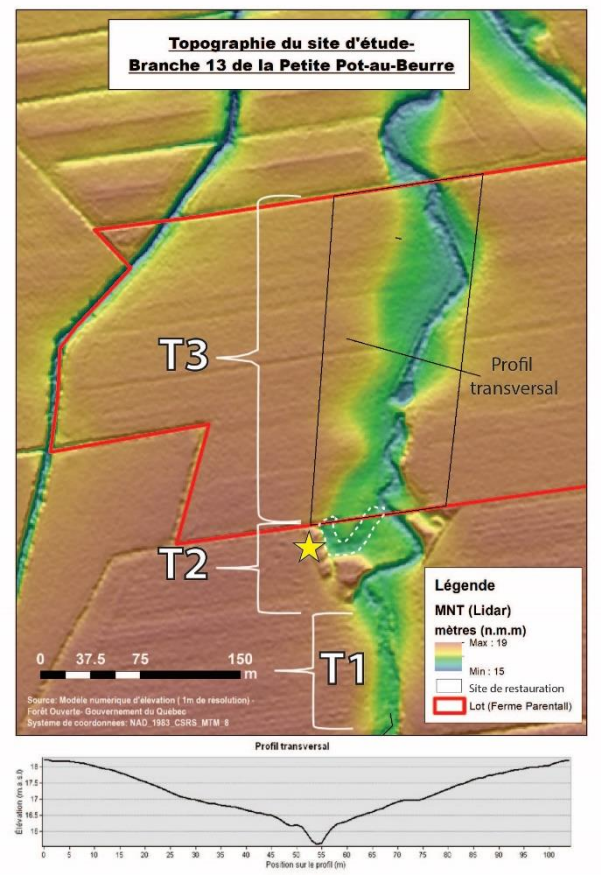


Figure 6: Modèle numérique d'élévation LiDAR de l'ensemble du site d'étude (T1-T2-T3). Les surfaces en vert indiquent la position approximative de la plaine alluviale historique. Le trait blanc pointillé avec l'étoile jaune indique la position d'un méandre abandonné.



Figure 7: Photographie prise le 2 décembre 2023 du méandre abandonné (étoile jaune dans la Figure 6) abritant un marais à cornouiller stolonifère dans le tronçon T2. (Source : Jean-Philippe Marchand)

2. Description des travaux de restauration effectués

Le choix des méthodes de restauration d'un cours d'eau nécessite d'abord une analyse des processus hydrogéomorphologiques et de la dynamique spatiale de ces processus dans le bassin versant. Cela inclut l'étude des interactions entre les processus hydrologiques, le transport sédimentaire et les flux biologiques et géochimiques, ainsi que l'évolution de ces interactions dans le temps et l'espace pour identifier l'état d'équilibre ou de réajustement d'un tronçon. L'objectif est de maintenir cet équilibre ou de favoriser un réajustement, tout en prenant en compte des cas spécifiques où un réajustement pourrait causer des dommages, tels qu'une incision verticale du lit ou une érosion latérale des berges exagérée. Ensuite, une analyse socio-économique des méthodes de restauration permet d' aligner les objectifs écologiques avec ceux des communautés locales, en particulier en milieu agricole. Il est crucial de considérer l'impact des mesures sur la rentabilité des entreprises agricoles et de justifier les investissements par des bénéfices environnementaux tangibles si l'on veut favoriser l'acceptabilité des projets de restauration au sein de la communauté agricole et soutenir l'engagement des participants volontaires.

La section qui suit présente les deux mesures de restauration de cours d'eau qui ont été implantées pour le site de la Ferme Parentall sur la branche 13 de la Petite Pot-au-Beurre (tronçon T3). Cette section présente les justifications qui sous-tendent ces mesures ainsi que des considérations techniques qui ont été mis à jour à partir des constats et des réflexions effectués durant la phase 1 du projet (2022-2025).

2.1 Retrait des cultures dans l'espace de liberté du cours d'eau

2.1.1 Explications du concept et de sa pertinence dans le cadre du projet

L'espace de liberté est un concept de gestion des cours d'eau et d'aménagement du territoire adapté au Québec par Biron et coll. (2013; 2014). Il reconnaît l'espace que doivent occuper les processus hydrogéomorphologiques, tels que l'érosion et les inondations. Les cours d'eau, ainsi façonnés, assurent une gamme de services écosystémiques et limitent les enjeux de sécurité publique. De manière générale, l'approche préconisée est de laisser en place un corridor érodable et inondable, qui inclut les milieux humides riverains, permettant un écoulement sans contrainte de l'eau ainsi qu'un transit des sédiments (incluant des phases de dépôt) dans un cours d'eau. Des concepts similaires ont été développés ailleurs dans le monde, par exemple en France (Malavoi et coll. 1998; 2007; Piégay et coll., 2005), en Espagne (Ollero, 2010), le long du fleuve Danube (Hein et coll., 2016) et au Vermont (Kline et Cahoon, 2010).

Biron et coll. (2013; 2014) distinguent l'espace de mobilité, associé à la dynamique latérale du chenal, et l'espace d'inondabilité plutôt associé au débordement d'eau hors du chenal, dans la plaine alluviale, et inclut aussi les milieux humides riverains. Les deux espaces combinés forment l'espace de liberté minimal (mobilité à court terme, inondabilité fréquente et milieux humides riverains), fonctionnel (mobilité à long terme, inondabilité moyenne) et rare (absence de mobilité et inondabilité exceptionnelle) (Figure 8). L'espace de mobilité assure un corridor fonctionnel pour que les processus hydrogéomorphologiques opèrent, tels que l'érosion des berges et le recrutement de bois mort. L'espace d'inondabilité assure la connectivité avec la nappe phréatique et les milieux humides riverains. L'espace de liberté offre une

meilleure qualité des habitats aquatiques et augmente la capacité de résilience du cours d'eau dans un contexte de changements climatiques.

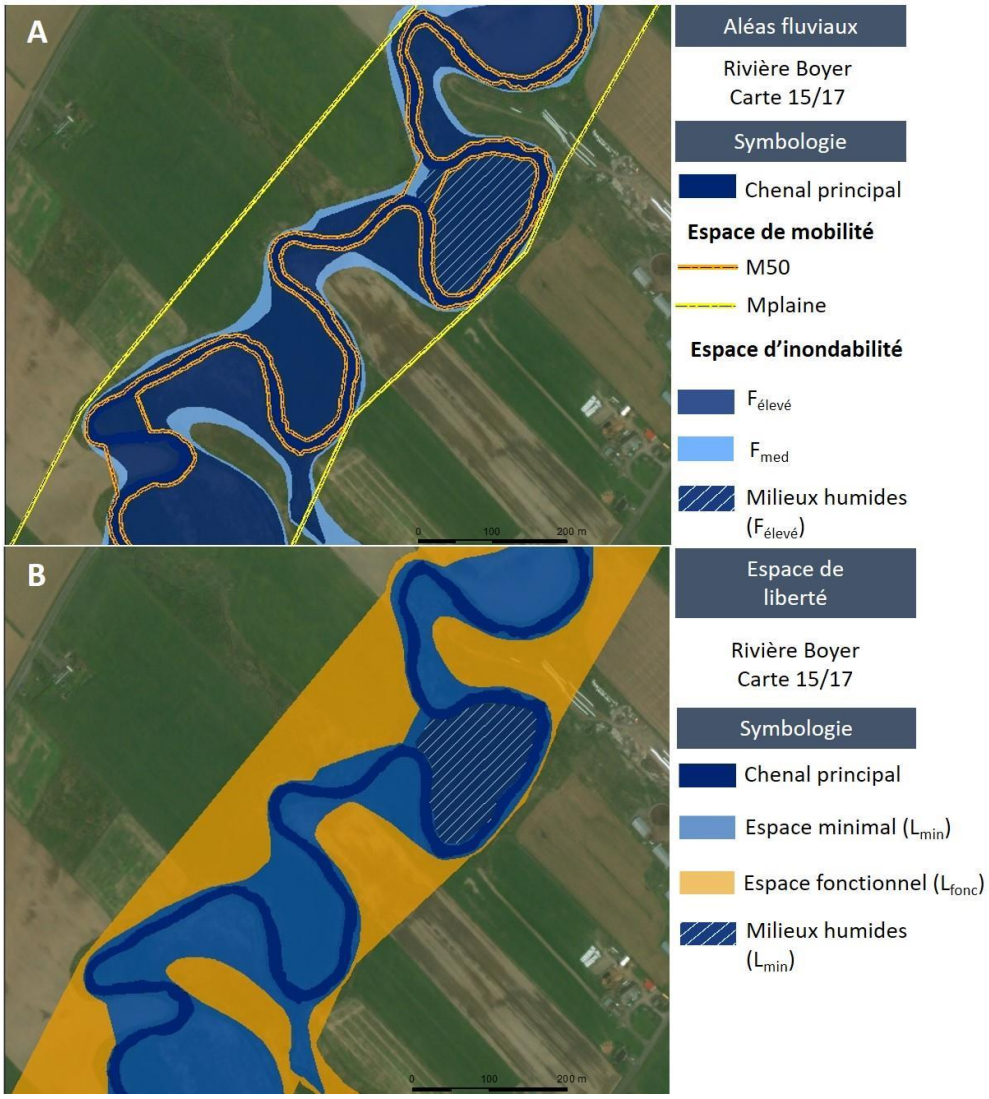


Figure 8: Exemple de cartographie d'un espace de liberté, sur la rivière Boyer. A) la cartographie des aléas fluviaux (deux espaces de mobilité (M50 et Mplaine), deux espaces d'inondabilité et les milieux humides riverains et B) l'espace de liberté minimal en bleu et fonctionnel en orange (Crédit : Biron et coll., 2020).

Le retrait des cultures de l'espace de liberté minimal constitue une étape préalable essentielle à la réussite du projet de restauration "Un Méandre à la fois", et ce pour deux raisons principales. Premièrement, il offre un cadre où les producteurs acceptent de consacrer une portion de leurs terres cultivables à la restauration du cours d'eau, tout en permettant aux porteurs du projet de définir des stratégies pour minimiser les impacts négatifs potentiels sur la viabilité économique des exploitations agricoles. Bien que le retrait des cultures de l'espace de liberté puisse avoir des impacts potentiellement négatifs sur des

pratiques agricoles, notamment en termes d'accès et d'efficacité des réseaux de drainage, cette mesure offre un espace suffisant pour mettre en place des solutions visant à réduire ces effets négatifs. Par exemple, en retirant les cultures, on libère de l'espace pour prévenir des effets non prévus, tels que l'érosion localement plus active en lien avec le reméandrage du cours d'eau, ou pour aménager des ouvrages hydroagricoles permettant de maintenir l'efficacité des réseaux de drainage (voir section 10). Le fait que ce soit la dynamique du cours d'eau qui détermine l'espace de liberté (plutôt qu'une largeur fixe de bande riveraine) engendre de nombreuses discussions afin de définir les paramètres du retrait de cultures, ce qui renforce la relation de confiance entre les producteurs et les différents intervenants, un élément essentiel pour garantir la pérennité du projet.

Deuxièmement, le retrait des cultures permet de diminuer considérablement les pressions anthropiques dans un espace de forte connectivité hydrologique du cours d'eau, soit sa plaine alluviale historique. La connectivité hydrologique désigne les nombreux échanges de masses et d'énergie entre le cours d'eau et son environnement, générés par des processus hydriques (Bracken et coll., 2010). À l'échelle du tronçon, plusieurs processus hydrogéomorphologiques et biogéochimiques dépendent de ces échanges. Par exemple, lors d'un évènement de crue, l'écoulement transporte des sédiments fins et des nutriments hors du chenal, dont une portion est captée et déposée dans la plaine, favorisant ainsi la création de nouveaux habitats riverains et améliorant la qualité de l'eau.

2.1.2 Délimitation de l'espace de liberté sur le site de la Ferme Parentall

La méthode employée pour délimiter l'espace de liberté dans le cadre de cette étude combine à la fois l'interprétation des photographies aériennes historiques, l'analyse de sondages stratigraphiques (soit l'analyse des couches de sédiments par forage manuel) ainsi que le suivi des niveaux d'eau de surface et souterrain. L'annexe B fournit plus de détails sur la méthode employée pour délimiter l'espace de liberté et pour son implantation sur le terrain. Les analyses de niveaux d'eau révèlent que, bien que le cours d'eau de la branche 13 ait été redressé et la plaine remblayée, les interactions par des processus hydrologiques sont toujours actives et donc le niveau de connectivité hydrologique est tout de même élevé. Les cours d'eau redressés devraient donc être priorisés dans les projets de restauration puisqu'on ne repart pas de zéro, avec une connectivité hydrologique souterraine qui s'est maintenue malgré les perturbations majeures à la surface. Il s'agit là d'une conclusion clé de l'article de Marchand et collaborateurs publié en 2022 dans la revue *River Research and Applications*. On peut notamment observer plusieurs épisodes d'inondations par année. Seulement au cours de l'été 2023, 4 épisodes d'inondations de surface ont eu lieu (Figure 9). Au cours du mois d'aout 2024, lors de la tempête Debby, l'entièreté de l'espace de liberté fut inondée pendant plus de 72 heures (voir section 8.5). Également, on peut observer que même en absence d'inondation de surface, la nappe d'eau souterraine dans la plaine réagit fortement aux fluctuations dans le chenal. La nappe se remplit lors des épisodes de pluie et se décharge lentement par la suite. Parce que les alluvions de la plaine sont de texture relativement grossière, ils peuvent accumuler de petites nappes d'eau souterraines tout au long du chenal, qui sont autant connectées aux eaux de précipitations qu'aux eaux en provenance du milieu régional, soit les plaines argileuses bordant la plaine alluviale. Plus de détails sur l'analyse du niveau de connectivité hydrologique au sein du site de la Ferme Parentall sont disponibles dans l'étude de Marchand et coll. (2022) (disponible sur *Wiley Online Library*).

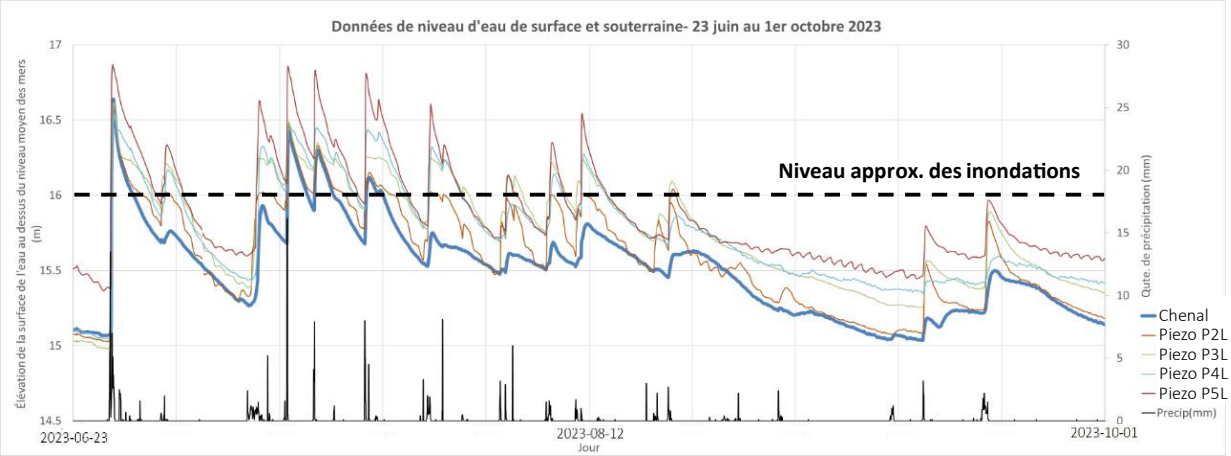


Figure 9. Hydrogramme des niveaux d'eau de surface et souterrain au site T3 en 2023, du 23 juin au 1er octobre 2023. La ligne bleue épaisse indique le niveau d'eau dans le chenal, alors que les autres indiquent les fluctuations dans différents piézomètres installés dans la plaine alluviale historique.

2.1.3 Implantation progressive d'un retrait de cultures de l'espace de liberté sur le site de la Ferme Parentall

Le retrait progressif des cultures sur le site de la Ferme Parentall remonte à 2017, lorsque Jean-Philippe Marchand, dans le cadre de son doctorat à l'U. Concordia, a lancé un protocole expérimental pour suivre les fluctuations de la nappe phréatique dans un méandre abandonné de la branche 13 de la Petite-Pot-au-Beurre. Ce site avait été identifié comme pertinent pour l'étude. Un premier retrait de cultures, d'environ 0,25 hectare, a été convenu avec les propriétaires, Denis Parent et Judith Allard, qui ont reçu un paiement annuel pour compenser la perte de revenus sous forme d'un montant équivalent à la location du fond de terre. La relation entre Jean-Philippe Marchand et les producteurs s'est renforcée au fil du temps, et en 2020, ces derniers ont accepté d'étendre la zone de retrait pour inclure un second méandre (figure 10). Le montant attribué pour la location a été ajusté en conséquence. En 2022, une entente de recherche avec le MELCCFP a permis d'augmenter à nouveau la superficie du projet et d'englober une portion importante de la plaine historique du cours d'eau, portant la superficie totale de la zone de retrait de cultures à 0,88 hectare, ce qui exclut les bandes riveraines réglementaires qui étaient déjà en place.

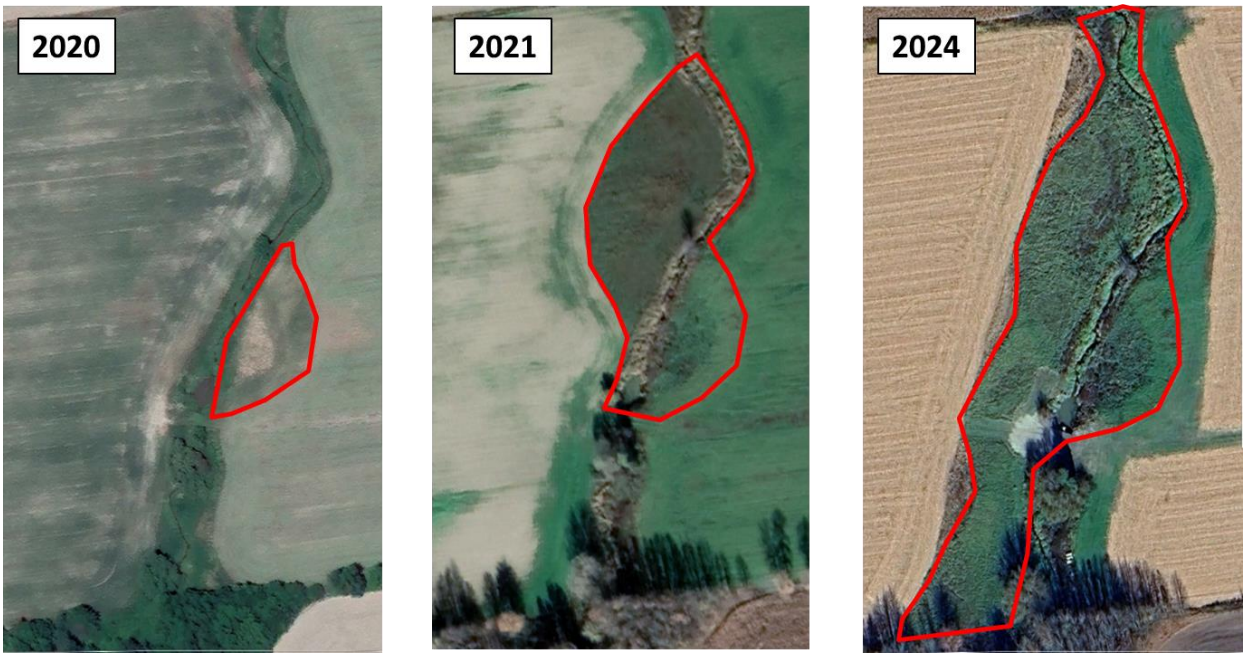


Figure 10. Retrait progressif des cultures dans l'espace de liberté de la branche 13, sur le site de la Ferme Parentall

2.1.4 Modalités et autres considérations

Le retrait des cultures d'un espace de liberté le long d'un cours d'eau a des implications importantes sur la logistique et la productivité des producteurs. Les producteurs de la Ferme Parentall ont souligné plusieurs considérations techniques, notamment la configuration des limites extérieures, les zones de passage et d'accès au réseau de drainage. D'abord, étant donné la taille croissante des machines agricoles, les limites des zones de retrait doivent être relativement régulières pour ne pas compliquer les opérations agricoles. Les corridors de passage doivent être suffisamment larges pour accueillir tous types de machines, y compris celles des soumissionnaires qui interviennent dans certaines étapes de la production. De plus, il est essentiel de délimiter clairement les zones de retrait, car les soumissionnaires ne connaissent pas toujours ces limites.

Dans le projet de la Ferme Parentall, les limites extérieures de la zone ont été ajustées pour faciliter la circulation des machines agricoles, avec des bornes de signalisation installées pour délimiter la zone. Cette configuration a été maintenue jusqu'en 2024, où les producteurs ont modifié la configuration de l'espace de retrait de cultures, préférant une forme linéaire en ajoutant une zone tampon à l'extérieur de l'espace de liberté (Figure 11). Cette zone tampon, d'une superficie de 0,48 hectare, a été partiellement (rive droite seulement) cultivée en plantes fourragères au cours de l'été 2024. Cela a permis du même coup de rajouter un espace de protection pour le cours d'eau en éloignant davantage les cultures de maïs et de soya.

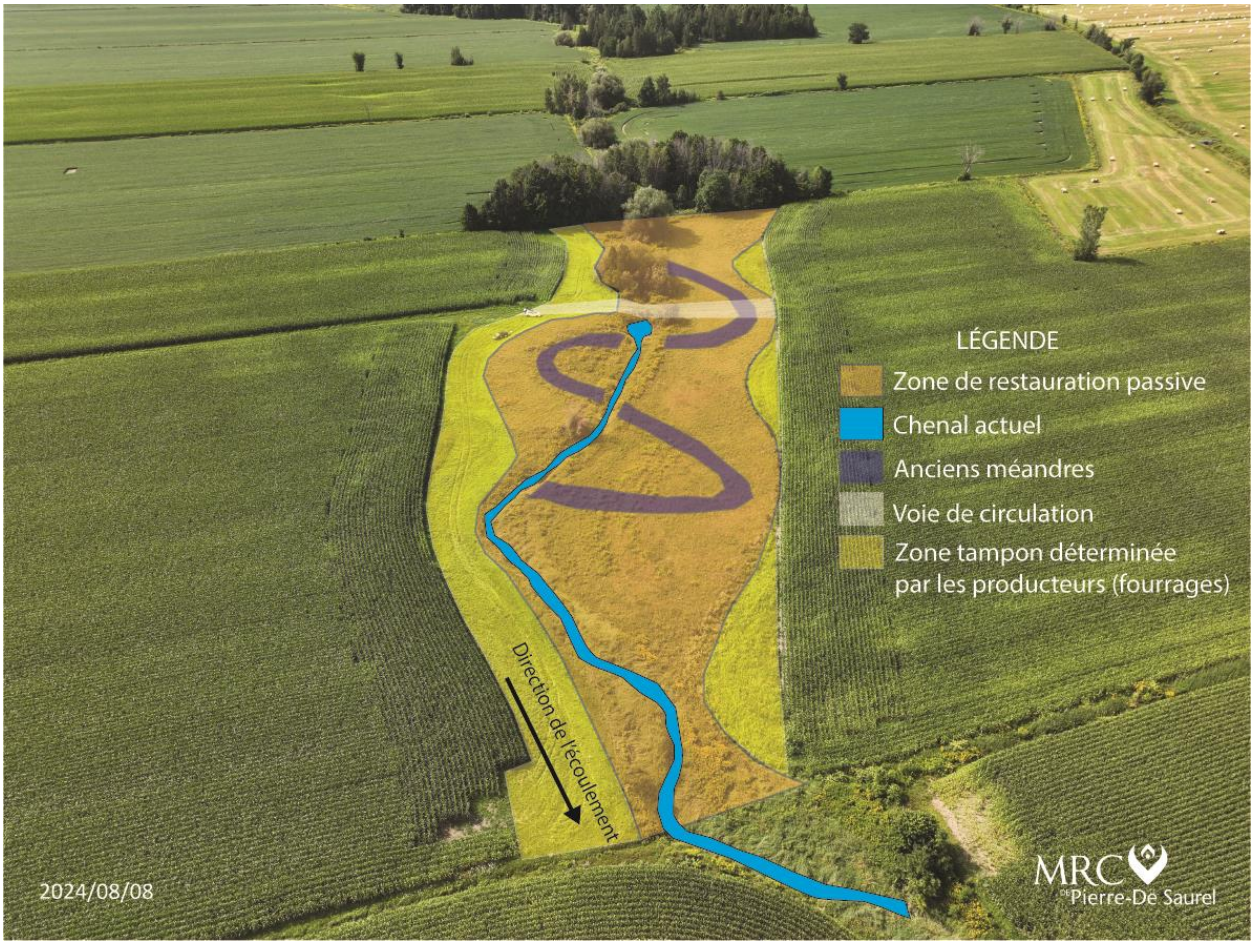


Figure 11. Configuration de l'espace de restauration du site de la Ferme Parentall, en aout 2024 (Crédit photo : MRC Pierre de Saurel)

Évidemment, les considérations financières associées au retrait des cultures sont névralgiques, puisque les revenus des producteurs sont directement diminués. D'un commun accord entre l'équipe de Concordia et la Ferme Parentall, un montant locatif de 2021$ par année (plus taxes) a été versé aux producteurs pendant toute la période de la phase 1 du projet. Ce montant a été négocié au départ du projet par les producteurs en fonction de l'estimation de leurs revenus perdus. Pour les deux premières années, ce montant correspondait donc à un tarif de location annuelle exacte 2386$(+taxes)/hectare, soit 2021$ + taxes pour 0.88 hectare. Pour la troisième année du projet, les producteurs ont ajouté la zone tampon (0.48 hectare) sans exiger de correction du montant de location. Le tarif de location annuel appliqué à l'année 2024 a donc été de 1486$+taxes/hectare, soit 2021C$+taxes pour 1,36 hectare.

Le retrait des cultures pose aussi des enjeux au niveau de la protection du territoire agricole et donc du respect du cadre légal et réglementaire québécois. Tous ces enjeux financiers et réglementaires seront approfondis dans les sections 6 et 7 du présent rapport concernant la pérennisation et le financement des mesures de restauration en milieu agricole.

2.2 Remplacement d'une traverse agricole sous-dimensionnée

La présence d'un ouvrage de traverse sous-dimensionné peut constituer une entrave aux flux hydrologiques, sédimentaires et biologiques dans un cours d'eau. Évidemment, le type et la configuration de l'ouvrage feront en sorte que les flux seront plus ou moins affectés. En milieu agricole, il n'est pas rare de trouver des ouvrages de traverse sous-dimensionnés et désuets, tels que des ponceaux surmontés d'un remblai. Ces infrastructures causent une rupture dans le niveau de connectivité longitudinale entre les portions amont et aval, soit en accélérant les flux ou en les bloquant considérablement. La réfection de ces ouvrages afin de rétablir ou d'améliorer les flux hydrologiques, sédimentaires et biologiques, est une mesure de restauration pertinente et souhaitable en milieu agricole.

La première question à se poser est la suivante : est-ce que l'ouvrage de traverse est toujours pertinent? En d'autres mots, est-ce que le retrait complet de l'ouvrage peut être envisagé au lieu de sa réfection ? Cela implique donc qu'un chemin alternatif ou une traverse située en amont ou en aval puisse être utilisé par les agriculteurs pour accéder à l'autre côté du cours d'eau. Il peut même être suggéré d'établir des ententes de location avec d'autres producteurs (situés sur l'autre rive) afin d'utiliser une traverse commune et ainsi démanteler des traverses superflues. Dans le cas du présent projet, cette option a été envisagée, mais n'a pas été retenue. Certaines considérations doivent être prises en compte dans le cadre de ces réflexions, comme la qualité de la relation avec les voisins, la capacité et l'état des chemins alternatifs et la distance à parcourir pour y accéder.

La traverse existante au début du projet était composée d'un ponceau circulaire sous-dimensionné (1100 mm) qui a causé une grande fosse d'érosion à l'aval (voir annexe A pour plus de détails). Le tablier artisanal du ponceau était en mauvais état avec un débordement fréquent sur la rive gauche qui entraînait de l'érosion et mettait à risque la pérennité de l'ouvrage. L'affouillement à la base du ponceau en amont induisait une déconnexion complète de l'écoulement avec le ponceau en période d'étiage, affectant potentiellement la libre circulation du poisson entre le secteur boisé et le tronçon en aval.

La réfection de la traverse était une des mesures planifiées et financées dans le cadre de la phase 1 du projet de restauration avec un budget pour élaborer différents scénarios de réfection, et un processus de consultation prévue avec la Ferme Parentall pour le choix final. Ce mandat a été donné à la firme Avizo, experts-conseils en ingénierie civile et en hydrogéomorphologie. La section qui suit présente le cheminement décisionnel sous-jacent au choix du modèle de nouvelle traverse ainsi que les plans et devis produits par la firme Avizo.

2.2.1 Processus décisionnel pour le choix de la nouvelle traverse

Au cours des deux premières années (2022-2023) du projet, la firme Avizo a analysé cinq types d'ouvrages de traverse pour le remplacement du ponceau sur le site de restauration: le ponceau à refoulement circulaire, le ponceau à refoulement arqué, le ponceau à arche voutée, le pont et la traverse à gué aménagée. L'analyse a porté sur les effets de ces différents types d'ouvrages sur des aspects hydrauliques de l'écoulement (niveau d'eau et vitesse en amont et aval de l'ouvrage) ainsi que sur la dynamique hydrogéomorphologique (profondeur/largeur, puissance spécifique, contrainte de cisaillement de l'écoulement au débit plein bord). La nouvelle traverse devait répondre aux objectifs suivants : limiter le refoulement d'eau en amont ainsi que l'écoulement en charge (sous pression) en aval lors des débits morphogènes (débit plein bord et plus). En effet, le refoulement de l'écoulement causé par le ponceau

sous-dimensionné réduit significativement les vitesses d'écoulement et inhibe toute la dynamique hydrosédimentaire en amont de la traverse. À l'inverse, l'écoulement en charge amplifie les vitesses d'écoulement et l'érosion en aval de la traverse. De plus, le nouvel ouvrage devait répondre aux critères suivants : passage facile et sécuritaire de la machinerie agricole, présence d'eau dans la traverse lors de l'étiage pour favoriser le passage du poisson, coûts et niveau de complexité de mise en place raisonnable et un entretien faible ou nul.

Le rapport complet de la firme Avizo est disponible à l'annexe C. Il présente le cheminement méthodologique, les résultats et le processus décisionnel ayant mené au choix du type et des dimensions de la nouvelle traverse. La figure 12 résume les principaux arguments en faveur ou en défaveur des différents ouvrages.

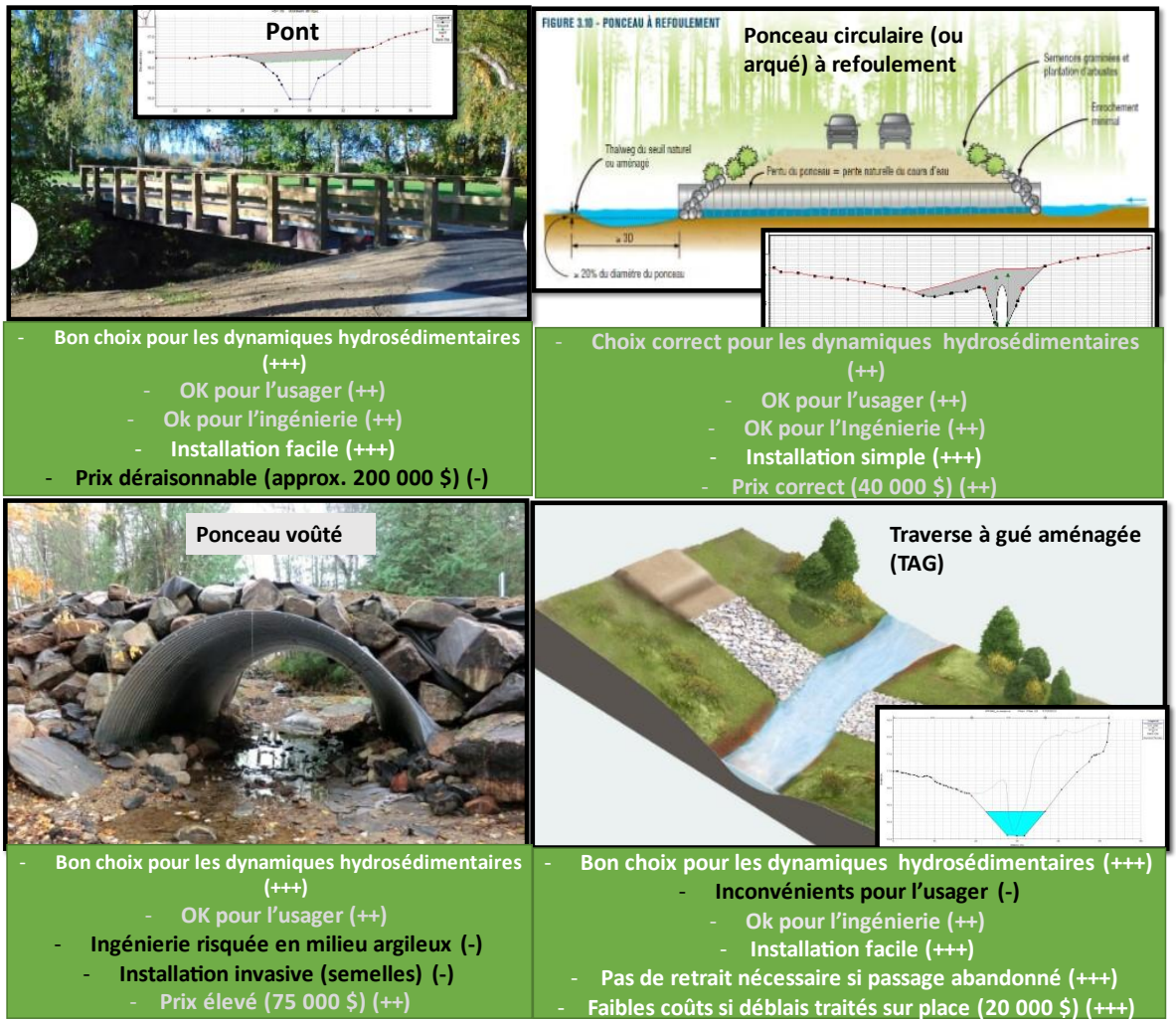


Figure 12: Principaux arguments en faveur et défaveur des différents ouvrages de traverses analysées dans la cadre du projet de restauration (Avizo, 2023 à l'annexe C). Les symboles de (+) désignent le niveau de satisfaction vis-vis des différents critères de sélection : (+++) : très satisfaisant, (++) satisfaisant, (-) pas satisfaisant, à exclure.

Pour la construction d'un pont, le prix estimé des travaux était de plus de 200 000$, ce qui est trop coûteux et ne permettait pas de reproduire ce scénario ailleurs. De plus, les propriétaires de la Ferme Parentall avaient des réticences face à ce type d'ouvrage, notamment parce que le tablier du pont aurait été construit en bois, un matériel qui se dégrade rapidement. Selon la firme Avizo, le ponceau à arche voutée n'est pas recommandé sur des sols argileux et présenterait des risques de stabilité à moyen et long terme. De plus, les travaux requis pour stabiliser au maximum les semelles de la structure auraient été fortement invasifs et coûteux. Par ailleurs, la traverse à gué demande un entretien récurrent pour retirer les dépôts fins qui s'accumulent chaque année lors des crues. Il est intéressant de noter toutefois sa simplicité d'installation, son faible coût et son effet minimal sur le cours d'eau à long terme si la traverse était abandonnée. Il peut toutefois être compliqué pour des machines agricoles lourdes d'utiliser une traverse à gué aménagée.

Pour creuser la question, un agriculteur de la municipalité de Saint-Dominique a été rencontré à l'été 2023 concernant l'usage d'une traverse à gué construite sur son terrain par le MAPAQ dans les années 1990 (Figure 13). Ce dernier affirme avoir utilisé cette traverse à gué pendant de nombreuses années avant de devoir l'abandonner puisque les nouvelles machines agricoles de grandes dimensions ne réussissaient plus à la franchir efficacement. L'accumulation de dépôts fins à chaque année, quoique facile à retirer, contribue à moyen terme à colmater la surface pavée de la traverse à gué et ainsi à limiter l'adhérence des roues des machines agricoles.



Figure 13. Traverse à gué en milieu agricole, dans la municipalité de Saint-Dominique : (A) en 1990 lors de la construction (Crédit : Ghislain Poisson, MAPAQ), (B) en 2017 alors que la végétation riveraine a colonisé le substrat rocheux (Crédit : Ghislain Poisson, MAPAQ) et (C) à la fin de l'hiver 2023 (Crédit : Jean-Philippe Marchand)

Au final, le ponceau à refoulement (circulaire ou arqué) répondait à tous les critères, à condition qu'il soit dimensionné adéquatement, alors que les autres types d'ouvrages présentaient tous un inconvénient majeur (Figure 12). Entre le ponceau circulaire à refoulement et le ponceau arqué, le ponceau arqué a été jugé plus pertinent puisqu'il permet de limiter la hauteur du remblai nécessaire et limite la création d'un écoulement en charge (sous pression) pour les débits morphogènes les plus récurrents étant donné sa forme évasée.

Le choix de la crue de conception pour le ponceau à refoulement s'est appuyé sur une logique de faibles risques de dommages aux infrastructures locales et de dégradation de l'environnement, en cas de dépassement de sa capacité ou de défaillance de l'ouvrage. La période de retour de 25 ans prescrite par le MAPAQ (2010) pour des ponceaux agricoles ne paraissait pas adaptée à un site de traverse situé sur une propriété privée, à l'usage exclusif du propriétaire, pour lequel les conséquences éventuelles d'un sous-dimensionnement étaient jugées faibles. Une période de retour de la crue de 2 ans a donc été initialement

utilisée pour la conception, considérant qu'en contexte agricole, il est souvent avantageux de tolérer un débordement qui contourne l'ouvrage lors des crues. Sur le plan hydrogéomorphologique, il est souhaitable que le ponceau permette à ce qu'une crue de 2 ans ne s'écoule pas en charge avec des vitesses de sorties élevées, puisque cette fréquence de crue représente les débits morphogènes les plus fréquents.

L'étude d'Avizo (annexe C) a conclu qu'avec un ponceau arqué à refoulement de 2130 x 1400 mm (équivalent à un ponceau circulaire de 1800 mm), les objectifs en termes de conditions hydrauliques (crue de retour 2 ans) et de dynamique HGM seraient atteints. Cependant, il a été noté après la remise du rapport d'Avizo que la MRC Pierre-de-Saurel prescrit une période de retour de 10 ans pour la réfection ou l'installation de nouvelles traverses en milieu agricole. Au final, c'est donc un ponceau arqué de 2500 mm X 1800 mm (figure 14) qui a été choisi pour respecter les normes de la MRC Pierre-de-Saurel. Ce dimensionnement permet de minimiser encore plus les effets de charge engendrés par le ponceau sur l'écoulement, sans dépasser la hauteur de remblai qu'aurait impliqué le recours à un ponceau circulaire. Rehausser le tablier du ponceau aurait représenté un potentiel inconvénient pour la circulation de la machinerie, selon les producteurs.



Figure 14. Ponceau arqué en acier galvanisé (2500 mm X 1800 mm) de la marque ArmTech installé au site de la Ferme Parentall.

2.2.2 Plans et devis

Dans la troisième année du projet de restauration (2024), un nouveau mandat a été donné à la firme Avizo pour la production d'une estimation pour les coûts de travaux et la production de plan et devis pour le choix d'ouvrages retenus (ponceau arqué). L'annexe D présente les descriptions et les estimations de prix pour les différentes étapes de réalisation du projet. Il est important de noter que ce sont des estimations de classe C qui visent à établir un estimé conservateur du coût de réalisation (i.e un coût maximal pour les travaux). Les critères de construction associés à chacune des étapes de réalisation ont été établis à partir des normes standardisées du ministère des Transports et de la Mobilité Durable du Québec (MTMD) pour les nouvelles traverses autoroutières.

En 2024, Avizo a évalué la réduction des coûts du projet en limitant l'envergure des enrochements et en ajustant les dépenses liées à l'ensemencement post-travaux, en tenant compte de la faible utilisation du

ponceau et de l'approche de restauration semi-passive du cours d'eau. Le plan final ainsi que le devis de construction de la nouvelle traverse produit par la firme Avizo sont disponibles à l'annexe E. La firme Avizo n'a pas été impliquée dans la réalisation des travaux puisqu'elle ne fait pas ce genre de travaux.

2.3.3 Descriptions des travaux effectués

Pour des raisons administratives, la Ferme Parentall a été désignée comme demandeur officiel des travaux plutôt que l'Université Concordia. L'équipe de Concordia a toutefois géré l'appel d'offres, la sélection des soumissionnaires, la rédaction des contrats et la supervision des travaux afin d'alléger la charge des producteurs. Une fois les travaux complétés, la Ferme Parentall a reçu et redistribué les paiements aux exécutants de services, une procédure simple nécessitant seulement 2 à 3 heures de travail de leur part.

En ordre chronologique, voici la description des travaux exécutés :

- **Juillet 2024** : appel d'offres - trois soumissionnaires contactés

- **Début aout 2024** : un seul répondant pour l'appel d'offres (Groupe Horizon), les deux autres n'ayant pas la main d'œuvre disponible pour faire les travaux au cours de l'été.

- **Fin aout 2024** : Signature de contrat avec la firme Groupe Horizon (45 000$ plus taxes). Le bordereau de soumission (caviardé) du Groupe Horizon est disponible à l'Annexe F.

- **Début septembre 2024** : mise en œuvre des travaux. Initialement, une surveillance de chantier en bonne et due forme était planifiée avec la firme Avizo. Une rencontre de démarrage fut organisée le 4 septembre 2024. Finalement, le contrat administratif rédigé par l'équipe de recherche de Concordia et signé entre la Ferme Parentall et le Groupe Horizon ne contenait pas tous les éléments d'un devis administratif standard qui aurait permis à la firme Avizo de produire une attestation de conformité et de conclure à une acceptation des travaux comme c'est normalement le cas sur les chantiers autoroutiers exécutés par le MTMD. La firme Avizo s'est donc retirée de la démarche de surveillance de chantier. Totefois, les travaux sur des ponceaux en terres privées n'exigent pas légalement ce niveau de surveillance, qui aurait représenté de surcroit un coût additionnel important.

  Afin de tout de même assurer une surveillance lors des travaux, un autre consultant privé, RD Consultant, fut embauché le 9 septembre 2024. La surveillance de chantier proposée était de type informel : aucun document d'attestation officielle n'en découlait. Par contre, la firme responsable de la surveillance s'engageait à visiter le site à deux reprises chaque jour de travail. Une première rencontre fut organisée la veille des travaux pour présenter le surveillant à l'équipe de Groupe Horizon. Le surveillant s'engageait aussi à rapporter si les travaux exécutés respectaient les indications du plan et du devis technique. En supplément, une firme privée en géotechnique (Labo Montérégie) fut engagée pour faire un test *in situ* de compaction pour l'assise du ponceau ainsi que pour le remblai ceinturant l'ouvrage. Avec le recul, le recours à une surveillance de chantier de type informel s'est avéré un choix judicieux, car il a permis d'assurer à l'équipe de projet ainsi qu'aux producteurs de la Ferme Parentall que les travaux avaient été fait selon les normes, mais à un coût raisonnable.

- 18-19 septembre : les travaux ont été exécutés en seulement deux jours. La première journée, l'ouvrage existant fut retiré, la déviation du cours d'eau (par pompage) fut installée, et les travaux d'excavation pour préparer l'assise du ponceau furent exécutés. Le deuxième jour, le ponceau, le remblai et les enrochements aux droits du ponceau furent installés.

Les travaux n'ont pas engendré d'entrave pour les activités agricoles de la Ferme Parentall, alors que les travaux de récolte ne commençaient que deux semaines plus tard. Le coût total des travaux par le Groupe Horizon a été de 52 141$ (incluant taxes) alors que la surveillance de chantier et les tests *in situ* de compaction ont respectivement coûté 1062$ et 1408$ (incluant les taxes).

2.2.4 Considérations des partenaires

Au cours des trois années du projet, les différents partenaires de ce projet (UPA, MELCCFP, MAPAQ, MRC Pierre-de-Saurel, OBV Yamaska) ont partagé leur perspective et recommandations concernant les travaux de modification de la traverse sur le site de restauration de la Ferme Parentall, ce qui est un atout précieux pour prendre des décisions bien informées. Les principales considérations émises du point de vue réglementaire, pour l'habitat du poisson, pour les impacts morphologiques chez le producteur agricole voisin ainsi que du point de vue des considérations financières sont présentées à l'annexe G.

3. Description du milieu initial, des suivis effectués et de l'état du milieu à la suite des suivis;

Cette section du rapport décrit les résultats obtenus à partir des inventaires écologiques effectués au cours de la période 2022 à 2025. Dans le cadre de ce projet de restauration, quatre catégories de suivi ont été effectuées : faunique, floristique, qualité des habitats aquatiques et qualité des processus hydrogéomorphologiques. Les détails sur les méthodologies employées ainsi que certains résultats bruts pour les différents inventaires se trouvent à l'annexe H. Une synthèse des résultats issus des différents suivis écologiques est également disponible à la fin de cette section.

3.1 Suivi faunique

Les discussions avec les partenaires du projet au cours de la première année ont permis de déterminer que la meilleure approche pour le suivi faunique était de sélectionner des espèces animales adaptées au contexte de milieu agricole et pouvant aussi fournir des services environnementaux aux agriculteurs. À la suite de ces recommandations, l'équipe de recherche a pris contact avec des spécialistes en biologie et en agronomie pour déterminer les types de suivi faunique les mieux adaptés au contexte de notre étude. Le protocole expérimental initialement prévu a été modifié en remplaçant l'inventaire de la macrofaune et des oiseaux migrateurs par des inventaires d'oiseaux champêtres, d'araignées et de poissons. Les oiseaux champêtres utilisent les milieux agricoles comme zone de reproduction et de nidification alors que les araignées sont considérées comme des bio-indicateurs de la qualité des insectes présents sur un site, notamment les insectes pollinisateurs. Les poissons peuvent être des indicateurs de la qualité de l'eau et des habitats aquatiques. L'édification de nos protocoles expérimentaux a bénéficié de l'aide de Jean-Philippe Parent, chercheur en entomologie chez Agriculture Agroalimentaire Canada, du chercheur

doctoral en biologie à l'Université McGill, Émile Brisson Curadeau, du professeur-chercheur en biologie et ornithologue Jacques Iberzabal, de l'Université du Québec à Chicoutimi, de Nicolas Haket, technicien en bioécologie et spécialiste des araignées, de Vincent Fugère, professeur-chercheur en écologie aquatique à l'Université du Québec à Trois-Rivières et de Renée Gravel, biologiste d'expérience au MELCCFP.

3.1.2 Bilan de l'inventaire d'araignées

La densité, la biomasse et la biodiversité des araignées ont été utilisées en tant que bio-indicateur de la qualité écologique des sites. Les araignées sont couramment utilisées pour évaluer la santé des écosystèmes d'eau douce (Mealfait et Hendrick, 1998; Marc et coll., 1999; Pearce et Venier, 2006; De et coll., 2021).

Au cours des deux années de suivi, les deux pièges fosses installés dans le tronçon T1 (tronçon dégradé), ont piégé de façon combinée 6 et 20 individus, appartenant à 7 espèces différentes (tableau 1). En 2023, le poids moyen des individus piégés dans l'un des deux pièges a été de 0,002 g, alors qu'en 2024, le poids moyen calculé pour les spécimens capturés dans les deux pièges était de 0,015 g. Dans le tronçon T3 (tronçon dégradé visé par les mesures de restauration), entre 2023 et 2024, les deux pièges combinés ont capturé respectivement 45 et 36 individus, appartenant à 11 espèces différentes. Le poids moyen des individus capturés dans les deux pièges en 2023 et 2024 était respectivement de 0,67g et 0,42 g (tableau 1).

Tableau 1 : Compilation des résultats d'inventaires d'araignées effectués avec les pièges fosses au site de restauration de la Ferme Parentall effectué entre le 9 et le 22 juin 2023 et entre le 16 et le 25 aout 2024.

	2023		2024	
Site non-restauré	**T1: Piège #1**	**T1: Piège #2**	**T1: Piège #1**	**T1: Piège #2**
Densité / piège	0	6	10	10
Diversité (nb d'espèces) / piège	0	3	4	5
Poids / piège (g)	0	0.01	0.138	0.167
Poids moyen / site (g) ± 0.0005	0.005		0.152	
Quantité d'individus moyenne (Nb / site)	3		10	
Diversité moyenne (Nb d'espèces /site)	1.5		4.5	
Indice de diversité de Shannon	1.01		1.61	
Site restauré	**T3: Piège #1**	**T3: Piège #2**	**T3: Piège #1**	**T3: Piège #2**
Densité / piège	26	19	16	20
Diversité (nb d'espèces) / piège	4	4	8	7
Poids / piège (g)	0.862	0,483	0.342	0.503
Poids moyen / site (g) ± 0.0005	0,673		0.423	
Quantité d'individus moyenne (Nb / site)	22,5		18	
Diversité moyenne (Nb d'espèces /site)	4		7.5	
Indice de diversité de Shannon	1.28		1.94	

Les inventaires d'araignées effectués par fauchage au cours de l'été 2024 indiquent que 16 individus appartenant à 6 espèces ont en tout été capturés sur le site non restauré (tableau 2). Pour le site restauré, 17 individus appartenant à 10 espèces ont été identifiés dans les deux pièges. Le poids moyen des individus est sensiblement le même entre le site non restauré (T1) et restauré (T3).

Tableau 2 : Compilation des résultats d'inventaire d'araignées effectués par fauchage au site de restauration de la Ferme Parentall effectué entre le 16 et le 25 aout 2024.

	2024	
Site non-restauré	**T1: Piège #1**	**T1: Piège #2**
Densité / piège	8	8
Diversité (nb d'espèces) / piège	4	5
Poids / piège (g)	0.204	0.198
Poids moyen / site (g) ± 0.0005	0.201	
Quantité d'individus moyenne (Nb / site)	8	
Diversité moyenne (Nb d'espèces /site)	5	
Indice de diversité de Shannon	1.6	
Site restauré	**T3: Piège #1**	**T3: Piège #2**
Densité / piège	7	10
Diversité (nb d'espèces) / piège	4	7
Poids / piège (g)	0.188	0.223
Poids moyen / site (g) ± 0.0005	0.206	
Quantité d'individus moyenne (Nb / site)	8.5	
Diversité moyenne (Nb d'espèces /site)	5.5	
Indice de diversité de Shannon	2.2	

Les valeurs d'abondance, de diversité d'espèces et de biomasse par piège fosse sont plus élevés sur le site restauré que non restauré. Cependant, il n'a pas été possible de tester la significativité statistique de ces différences d'abondance et de diversité puisque la taille des échantillons est trop petite. La diversité d'espèces (indice de Shannon, tableau 2) est aussi plus élevée au site restauré qu'au site non restauré pour les deux années d'inventaire avec les pièges fosses et pour une année de fauchage. Les résultats de capture par fauchage pour l'année 2024 ne permettent pas non plus de déterminer de différence significative dans l'abondance de chaque espèce entre le site restauré et non restauré même si l'indice de diversité de Shannon demeure plus élevé (2.2) pour le site restauré que non-restauré (1.6). Les résultats du fauchage pour l'année 2024 ne permettent pas de tester de différence significative dans l'abondance de chaque espèce entre le site restauré et non restauré. Tout de même, l'indice de diversité de Shannon demeure plus élevé (2.2) pour le site restauré que non restauré (1.6).

Les espèces retrouvées dans les pièges fosses (Annexe H) sont très souvent associées à des milieux humides ouverts, particulièrement *Grammonota gigas* (Banks 1896) et *Trochosa sp*. (Koch, 1847). Les Lycosidae possèdent un excellent potentiel bio-indicateur à cause de leur abondance, leur facilité à être récoltées dans les pièges-fosses et leur sensibilité aux différentes conditions environnementales (Marusik et Kopnen, 2002). Les Micaria (Koch, 1835) se trouvent souvent au sol dans divers habitats […] au Québec,

mais seul *Micaria pulicaria* (Sundevall, 1831) est généralement récolté dans les inventaires. Cette dernière espèce est commune dans plusieurs habitats, mais ses facteurs de sélection ne sont pas entièrement clairs (Dupérré et Paquin 2003).

Les espèces capturées au fauchage sont souvent associées aux milieux ouverts, particulièrement les Araneidae de grande taille comme *Araneus trifolium* (Hentz, 1847), *Araneus marmoreus* (Clerck, 1758), *Araneus nordmanni* (Thorell, 1870), *Neoscona arabesca* (Walckenaer, 1841) et le genre Argiope (C.L. Koch, 1838). *Araneus diadematus* (Clerck, 1758) est une araignée très commune au Québec qui est retrouvée dans plusieurs milieux différents, mais particulièrement les jardins (Dupérré et Paquin, 2003). Considérant que les sites de récolte se trouvent à proximité d'un très grand champ agricole, la présence de ces espèces est peu surprenante. D'autres espèces associées à la haute végétation, mais pas nécessairement aux milieux ouverts, comme *Clubiona pygmaea* (Dondale et Redner, 1982) et *Hypselistes florens* (O. Pickard-Cambridge, 1875) (Dupérré et Paquin, 2003), ont sans surprise été capturées.

Malgré l'absence de différences significatives généralisées dans les valeurs d'abondance entre le site restauré et non restauré, les résultats d'inventaires suggèrent que le rétablissement d'une grande prairie herbacée découlant du retrait des cultures de l'espace de liberté du cours d'eau a favorisé une plus grande abondance, diversité et biomasse des araignées occupant la zone riveraine. Cette plus grande densité d'araignées suggère qu'il y a une plus grande quantité de proies disponibles pour elles et pour les organismes qui se nourrissent d'araignées, ainsi qu'une biomasse par superficie plus élevée dans cet environnement. L'augmentation de biodiversité au niveau des araignées indique généralement une augmentation de la biodiversité sur toute la chaîne trophique puisque différentes espèces occupent des niches écologiques différentes et requièrent des ressources variées. Ces résultats indiquent qu'après seulement trois ans dans la mise en œuvre d'un projet de restauration passive d'un espace de liberté en milieu agricole, des gains pour la biodiversité peuvent être obtenus.

Mis à part les araignées, les pièges et le filet faucheur contenaient une multitude d'autres organismes qui n'ont pas été examinés. Ce rapport couvre uniquement la présence d'araignées, mais une analyse des autres invertébrés pourrait offrir un meilleur portrait de la santé du site avec l'utilisation d'autres espèces bio-indicatrices.

3.1.3 Bilan de l'inventaire des oiseaux champêtres

Les oiseaux champêtres désignent des oiseaux habitant dans des zones agricoles, des prairies, des champs, des zones de broussailles et des lisières de forêts. Ils sont souvent associés à des environnements ouverts ou semi-ouverts. Bien qu'il ne s'agisse pas d'une classification scientifique formelle, le terme d'oiseaux champêtres peut représenter un large éventail d'espèces, des passereaux jusqu'aux oiseaux de proie, qui occupent les terres agricoles et contribuent à leur fonctionnement écologique. En effet, les oiseaux champêtres peuvent contribuer au contrôle des insectes et des ravageurs (Mayne et coll., 2023), ainsi qu'à la pollinisation et à la dispersion des graines (Wenny et coll. 2011 ; Triplett et coll., 2012). Ils sont donc à la fois bénéfiques pour le maintien de la biodiversité, mais aussi pour la santé et la durabilité des environnements agricoles. La présence et la santé des populations d'oiseaux champêtres peuvent servir d'indicateurs de la qualité de l'environnement (Michelat et coll.,2012). Des populations d'oiseaux saines et diversifiées suggèrent généralement un écosystème bien équilibré, tandis que leur déclin peut signaler des problèmes écologiques (Environnement Canada, 2019).

Des inventaires réalisés dans le contexte de projet de restauration de cours d'eau en milieu agricole ont déjà démontré des effets positifs significatifs sur les populations d'oiseaux, notamment en contribuant à l'augmentation de la diversité d'habitats spécifiques et donc de la diversité d'espèces (Van Turnhout et coll., 2012). Le projet de la rivière Drugeon en France, qui incluait le reméandrage d'un tronçon de cours d'eau redressé ainsi que la désaffection de conduite de drainage, a notamment engendré une hausse des espèces d'oiseaux associés aux milieux humides riverains (Michelat et coll., 2012).

Les résultats de l'inventaire d'oiseau en 2023 sont présentés en détail à l'Annexe H et résumés ici. Des différences notables en termes de biodiversité aviaire ont été notées (tableau 3). En moyenne, le site restauré T3 a enregistré un nombre statistiquement plus élevé de territoires et d'espèces comparativement au site non restauré T1, indiquant une biodiversité aviaire plus élevée dans le site restauré.

Tableau 3 : Résumé des nombres de territoires et de l'abondance pour chaque site

Site	Moyenne du nombre de territoires par enregistrement	Moyenne du nombre d'espèces par enregistrement
Site restauré T3 (SM4)	***14,8 ± 4,3***	***12,3 ± 4,0***
Site non restauré T1 (SM4)	***12,8 ± 4,1***	***10,6 ± 3,8***

Le site T3 (restauré) semble donc présenter une diversité légèrement plus grande que celle du site T1 (non restauré), bien que le nombre total d'espèces territoriales soit semblable entre les deux sites (22 et 23 au site non restauré et restauré, respectivement), avec le même nombre d'espèces confirmées (versus les espèces probables) (annexe H). Il n'est pas impossible que cette tendance soit en partie due au fait que les enregistrements du site restauré soient moins exposés au vent, ce qui a pu favoriser la détection de chants plus distants aux enregistreurs. Toutefois, même lorsque la météo était clémente et que la qualité des enregistrements semblait similaire entre les deux sites (ex. : le 10 juin 2023), le site restauré est toujours en moyenne plus diversifié. Incluant toutes les espèces (même celles en vol), il y a eu 36 espèces de détectées au site restauré et 35 au site non restauré, pour un grand total de 40 espèces.

Globalement, la communauté des deux sites est dominée par des espèces de milieux ouverts et semi-ouverts, comme le bruant chanteur, le carouge à épaulettes, la paruline jaune et la paruline masquée, les quatre espèces les plus abondantes à travers les enregistrements. La communauté du site non restauré semble un peu plus porter vers les espèces de bosquets, avec un oriole de Baltimore mâle bien présent dans les enregistrements, un pioui de l'Est chantant parfois d'assez près, ainsi qu'une plus grande présence d'espèces comme la tourterelle et la mésange. Il est fort probable que les espèces entendues soient influencées par la proximité du petit boisé séparant les deux sites (par exemple : le pioui de l'Est, une espèce forestière, niche très probablement dans ce bosquet).

À l'inverse, il est évident que la communauté du site restauré (tronçon T3) est plus influencée par les espèces de milieux très ouverts. On y note notamment une plus grande présence de bruant des prés, une espèce qui niche exclusivement dans les champs et grandes clairières, et de deux goglus des prés nicheurs, également une espèce de milieux ouverts. Il est donc possible que la friche du site restauré attire ces

espèces, comme le goglu qui chantait souvent très près du micro et donc utilisait vraisemblablement cet habitat du site.

Trois oiseaux détectés dans les enregistrements possèdent un statut de conservation particulier, soit l'Hirondelle rustique, le pioui de l'Est et le goglu des prés. L'hirondelle rustique n'est pas considérée comme utilisant réellement l'un ou l'autre des sites, car elle a presque uniquement été détectée en vol et seulement à quelques reprises. Le pioui de l'est une espèce en péril selon le programme SOS-POP et préoccupant selon la Liste des Espèces en Péril du Gouvernement du Canada (SOS-POP 2009 ; Branch 2023). L'espèce utilise très probablement le boisé situé entre les deux sites, plutôt que l'un des deux sites en tant que tels. Le Goglu des prés est également une espèce en péril selon les différentes listes et programmes. Cette espèce utilise de manière prononcée le site restauré (tronçon T3), chantant souvent près du micro. L'espèce n'est pas détectée sur le site non restauré (tronçon T1).

Une des préoccupations initiales du biologiste Émile Brisson Curadeau était que l'espace entre les deux enregistreurs soit trop restreint et que des doublons soient enregistrés. Après écoute, il estime que l'espace séparant les deux sites est suffisant pour éviter que les espèces d'un site ne soient détectées par l'enregistreur de l'autre site, du moins pour la majorité des espèces. Malgré tout, il arrivait parfois qu'un oiseau soit entendu par les deux enregistreurs en même temps (ex. : pioui de l'Est), mais en général, la distance est perceptible sur l'enregistrement et il est possible de déterminer si l'oiseau est plus près d'un site que l'autre.

Un autre problème s'avère plus concret, et consiste à essayer de séparer l'effet du site en soi avec l'effet des habitats qui l'entourent. Les oiseaux sont particulièrement mobiles et peuvent parfois se déplacer hors de leurs territoires. Ainsi, il est difficile de savoir si le site non restauré possédait une communauté plus associée aux bosquets à cause des quelques arbres du site, ou simplement parce qu'il était plus près du boisé. Idéalement, il faudrait rajouter une station d'écoute qui possède un habitat similaire au site non restauré, mais situé en bordure du cours d'eau en aval du site de restauration. Cette station d'écoute permettrait de discriminer l'effet du boisé.

Finalement, deux types d'enregistreurs ont été testés sur le site restauré afin de déterminer la pertinence d'utiliser des enregistreurs à plus faible coût. Le SM4, d'une valeur de 1250$, a été comparé à l'Audiomoth, d'une valeur approximative de 75$. Au final, le constat est que le SM4 a permis d'enregistrer un plus grand nombre d'espèces et n'a pas présenté, au contraire de l'Audiomoth, des problèmes techniques durant la période d'utilisation, qui a empêché de procéder à une deuxième année d'inventaire en 2024. Plus de détails sur cette comparaison sont disponibles à l'annexe H.

3.1.4 Bilan de l'inventaire de la faune ichtyenne

Au cours des années 2022 et 2024, trois inventaires de la faune ichtyenne ont été réalisés en avril, juin, et aout. Ces inventaires ont été effectués en utilisant deux nasses (ou bourroles) dans chacune des trois zones distinctes du site d'étude (T1, T2, T3) (Figure 3 et 4). Plus de détails sur la méthodologie et les résultats des inventaires sont fournis à l'annexe H.

Le suivi de 2022 a mis en évidence la présence au total de 9 espèces différentes, toutes des petits cyprinidés indigènes (tableau 4). En 2022, l'indice de diversité de Shannon était légèrement plus élevé dans le tronçon non dégradé (T2), suivi du tronçon non restauré (T1) et finalement le tronçon restauré

obtenait le plus faible score. En termes d'abondance, le site restauré (T3) et non restauré (T1), présentaient les valeurs le plus élevées, bien que ces différences ne soient pas significatives statistiquement.

Des changements majeurs entre 2024 et 2022 ont été observés dans les inventaires en ce qui a trait à la composition et l'abondance des espèces, avec une nette baisse du nombre d'espèces inventoriées par site et au total en 2024, passant de 9 à 5 espèces en tout (tableau 4). Au site restauré (T1), cette baisse est par contre moins drastique (6 espèces en 2022 et 5 espèces en 2024). En revanche, l'abondance a drastiquement augmenté, passant de 65 individus en 2022 à 518 en 2024, tous sites confondus. C'est l'épinoche à cinq épines qui s'est démarquée, représentant plus de 98% des captures, alors que cette espèce représentait 45% des captures en 2022.

Tableau 4 : Résumé des inventaires de poissons réalisés sur le site d'étude en 2022 et 2024

		T1: site amont non restauré		T2: site amont non dégradé		T3: site restauré	
	Année d'inventaire	2022	2024	2022	2024	2022	2024
Crapet soleil	*Lepomis gibbosus*	0	0	0	0	1	0
Épinoche à cinq épines	*Culaea inconstans*	10	120	3	296	16	90
Fondule barré	*Fundulus diaphanus*	0	0	0	0	0	1
Mené à nageoires rouges	*Luxilus cornutus*	0	1	1	1	0	2
Méné jaune	*Notemigonus crysoleucas*	1	0	0	0	1	0
Mulet à cornes	*Semotilus atromaculatus*	5	1	2	1	5	4
Tête-de-boule	*Pimephales promelas*	6	0	2	0	6	0
Umbre de vase	*Umbra limi*	0	0	0	0	0	1
Ventre-Pourri	*Pimephales notatus*	2	0	1	0	3	0
	Abondance	**24**	**122**	**9**	**298**	**32**	**98**
	Richesse	**5**	**3**	**5**	**3**	**6**	**5**
	Indice Shannon	**1.59**	**0.239**	**1.68**	**0.424**	**1.25**	**1.07**

Les calculs d'ANOVA (annexe H) indiquent qu'il n'y a pas de différence significative dans les résultats d'inventaire de poissons, ni entre les sites ni entre les années. Il est tout de même intéressant de constater que le classement de l'indice de diversité de Shannon s'est inversé entre 2022 et 2024. Alors qu'en 2022, l'indice de Shannon du site restauré était le plus faible des trois sites, en 2024, il présente le score le plus élevé.

Il est difficile d'expliquer les différences observées entre les trois sites pour les deux années d'inventaire. Il est possible que l'usage d'appâts différents (nourriture à chat versus canne de thon) entre les années ait favorisé ou attiré davantage certaines espèces (ex. épinoches à cinq épines) au détriment des autres espèces. Il est également possible que les conditions hydrologiques et climatiques prévalant dans les jours précédant les inventaires aient influencé la présence et l'abondance de certaines espèces.

Le niveau de connaissances par rapport à la dynamique écologique des poissons fourragers dans les petits cours d'eau agricoles au Québec est encore fragmentaire (Gravel, 2021). La variabilité de l'abondance (à la hausse) et de la diversité (à la baisse) au niveau des deux sites témoins (T1 et T2) suggère qu'il peut y avoir une forte variabilité interannuelle et intra-annuelle dans la taille et la composition des communautés ichtyennes qui fréquentent autant des tronçons dégradés que relativement naturelles. Certaines pistes d'analyses seraient intéressantes à développer, par exemple, l'impact des infrastructures de traverse sur la mobilité des poissons ainsi que l'impact de la concentration de certains intrants d'origine agricole dans l'eau.

En ce qui concerne le site en restauration (T3), il n'est pas possible d'affirmer que le tronçon abrite une communauté plus abondante et diversifiée que les autres tronçons. Le maintien d'un plus grand nombre d'espèces différentes entre 2022 et 2024 par rapport aux sites témoins suggère que le site présente des conditions d'habitats favorables pour un grand nombre d'espèces, mais il serait prématuré d'y associer

l'effet de la restauration passive de l'espace de liberté, ou l'effet de la réfection du ponceau qui a eu lieu seulement en septembre 2024 (voir section 3.2). Il est possible qu'une abondance d'insectes dans le milieu riverain plus élevée dans ce tronçon favorise une plus grande occupation du site, mais il n'est pas possible de le démontrer.

Les résultats d'inventaire de 2022 et 2024 montrent une communauté de poissons composée uniquement d'espèces omnivores et tolérantes, indiquant une qualité d'habitat relativement pauvre. Le tronçon T2, malgré son état moins dégradé, n'a pas montré de meilleure richesse spécifique, possiblement en raison d'anciens ponceaux sous-dimensionnés limitant la connectivité écologique en amont et en aval du tronçon. Les inventaires au site de restauration montrent un nombre total d'espèces inférieur à celui des inventaires historiques (1970-2016), où 15 espèces, dont certaines sportives, vulnérables et envahissantes, avaient été recensées (Couture et coll., 2024). Ces mêmes inventaires indiquent qu'au cours de la période étudiée, la diversité et la composition trophique ont décliné, passant d'un ratio omnivore/insectivore de 40%/60% à 75%/25%, suggérant une détérioration de l'habitat. La différence entre les résultats d'inventaire actuels et historiques peut s'expliquer par la variété des engins de pêche utilisés historiquement (nasses, pêche électrique, filet) et les variations de conditions environnementales entre les différents sites d'inventaire au sein du bassin versant. Il est également possible que des obstacles naturels et anthropiques affectent la dispersion ou la présence de certaines espèces.

Bien que la comparaison statistique de nos données avec les données historiques soit difficile, cette analyse semi-quantitative révèle des objectifs potentiels pour les mesures de restauration implantées sur le site d'étude. Par exemple, une augmentation du ratio d'espèces insectivores et l'apparition de nouvelles espèces pourraient indiquer un retour à une plus grande naturalité dans le tronçon de cours d'eau étudié.

Pour approfondir notre compréhension, nous suggérons de poursuivre les inventaires de la faune ichtyenne. Idéalement, un inventaire combinant l'utilisation de nasses et de pêches électriques serait envisagé dans les années ultérieures.

3.2 Suivi floristique

La méthodologie complète du suivi floristique effectué sur le site de restauration peut être consultée à l'annexe H. L'ensemble des données brutes d'inventaires floristiques est disponible à l'annexe I.

3.2.1 Associations végétales sur l'ensemble du site d'étude

Entre 2019 et 2022, sur 9000 m^2 de nouvelle surface végétalisée, environ 2000 m^2 sont identifiés à une association végétale de milieux humides (Figure 15). Ce résultat découle en grande partie de la conversion, entre 2019 et 2022, de friches à verge d'or déjà existante en bandes riveraines en marais à verge d'or ou à Alpiste roseau, constaté également dans le tronçon non restauré (T1). Il est possible qu'en trois ans, en absence d'entretien du cours d'eau, les associations végétales de la bande riveraine aient adopté des caractéristiques de milieux humides. Dans le tronçon restauré (T3), il ya eu expansion d'un modeste 100 m^2 de marais à verge d'or au-delà de la bande riveraine réglementaire qui était déjà en place avant le retrait des cultures.

Entre 2022 et 2024, il y a eu une évolution significative des unités végétales homogènes (UVH), avec un remplacement complet de certaines unités (friche à Laitue scariole), l'apparition de nouvelles unités (friche à Phléole des prés), ainsi qu'un morcellement avec l'apparition de friche à Verge d'or du Canada au

sein d'une friche à Brome inerme. Les ratios d'associations végétales humides et terrestres sont demeurés stables.

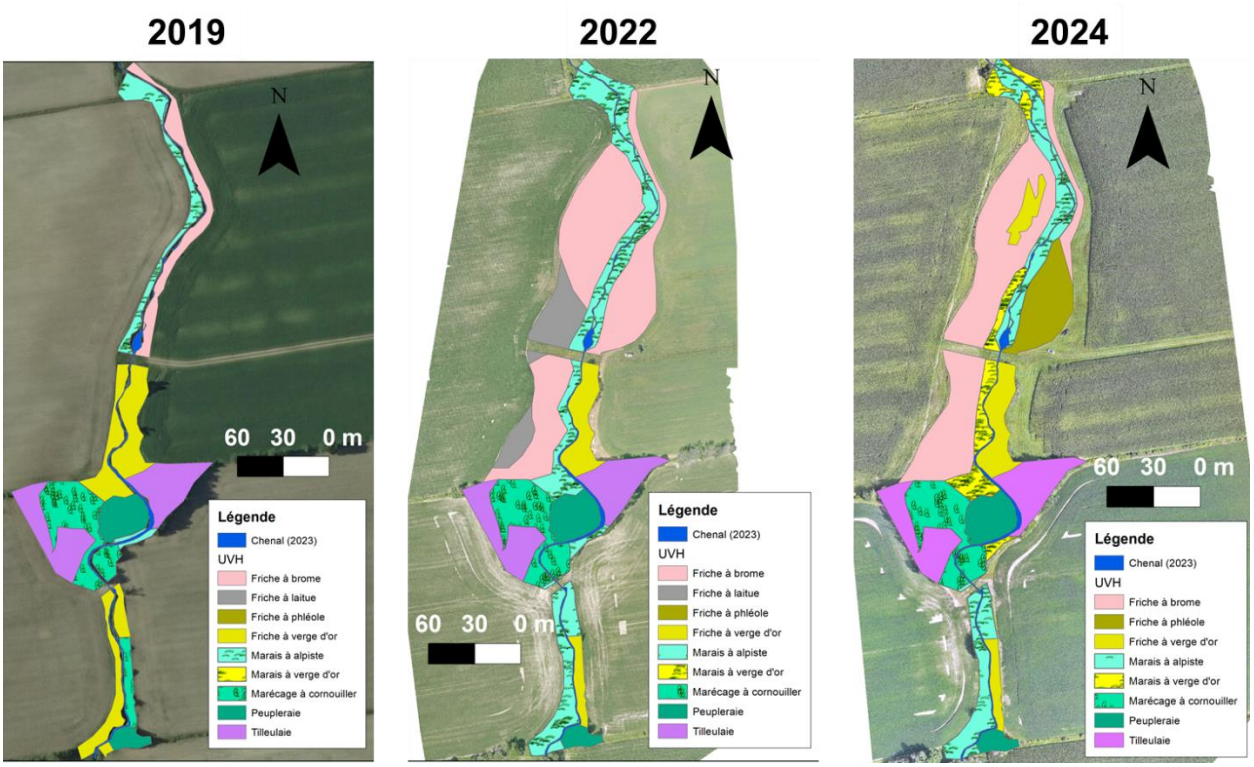


Figure 15. Évolution des unités végétales homogènes (UVH) sur le site de restauration de la branche 13 de la Petite-Pot-au-Beurre entre 2019 et 2024.

3.2.2 Inventaire dans les parcelles dans le site de restauration

Les données d'inventaires floristiques par parcelle entre 2022 et 2024 suggèrent qu'il y a en moyenne, pour tous les transects et pour toutes les années de suivi, un pourcentage de recouvrement par les espèces floristiques exotiques plus élevées (entre 54 et 84%), suivies par les espèces floristiques exotiques et envahissantes (EFEE, entre 34 et 13%)) et enfin, par les espèces indigènes (entre 12 et 2%) (tableau 5). Le même ordre s'applique également aux valeurs moyennes de richesse de chaque sous-groupe d'espèces dans les transects. Il y a cependant beaucoup de disparités entre les parcelles, ce qui confirme la pertinence de les distinguer selon leur position à l'intérieur ou à l'extérieur de l'ancienne plaine alluviale.

Tableau 5. Récapitulatif des inventaires d'espèces floristiques (par parcelle) dans l'espace de liberté

	Variable	2022		2023		2024		
		Intérieur	Extérieur	Intérieur	Extérieur	Intérieur	Extérieur	Tendance 2022-2024
TOTAL	% recouvrement EFEE	34.0	22.3	31.0	18.7	22.2	13.4	Diminution
	% recouvrement E	54.4	75.3	59.9	79.8	66.9	84.4	Légère hausse
	% recouvrement I	11.6	2.4	9.1	1.5	11.0	2.2	Stable
	richesse	6.1	7.0	5.6	4.7	5.2	4.4	Légère baisse
	richesse des exotiques	4.8	6.5	4.7	4.4	4.4	4.1	Légère baisse
	richesse des indigènes	1.3	0.5	0.9	0.3	0.8	0.4	Légère baisse
	richesse des EFEE	1.5	1.8	2.0	1.7	1.2	1.3	Légère baisse

En général, les différents paramètres étudiés varient peu d'une année à l'autre. La seule tendance significative est la diminution progressive du % de recouvrement des EFEE dans les parcelles situées à l'intérieur de l'ancienne plaine.

Cette tendance s'observe également dans les données détaillées d'inventaires des EFEE identifiés dans les parcelles dans la zone de retrait de cultures (tableau 6). En tout, 9 EFEE ont été identifiées entre 2022 et 2024. Pour la majorité de ces espèces, le pourcentage de recouvrement moyen est en baisse au cours de la période d'étude ou bien disparait totalement des inventaires. Par contre, une espèce semble tirer avantage de la situation, soit l'Alpiste roseau, avec un pourcentage de recouvrement moyen par parcelles passant de 2% en 2022, à 20 % en 2023 en enfin à 15% en 2024. Il en va de même pour le nombre de parcelles d'inventaires dominées par une des neuf EFEE (Tableau 7). En 2002, 11 parcelles d'inventaires sur 24 (soit 46%) étaient dominées par une EFEE alors qu'en 2024, c'est 13 parcelles sur 32, soit 40%.

Tableau 6. Récapitulatif des % moyen de recouvrement par quadrat des EFEE dans l'espace de liberté

		% moyen de recouvrement parmi les différentes parcelles		
Espèces exotiques envahissantes (FR/latin)		**2022**	**2023**	**2024**
Chénopode blanc	*Chenopodium album*	1%	n.d	n.d
Chardon des champs	*Cirsium arvense*	Moins de 1%	1%	1%
Echinochloa pied-de-coq	*Echinochloa crus-galli*	Moins de 1%	n.d	Moins de 1%
Chiendent commun	*Elymus repens*	6%	Moins de 1%	n.d
Panais sauvage	*Pastinaca sativa*	1%	1%	Moins de 1%
Alpiste Roseau	*Phalaris arundinacea*	2%	20%	15%
Sétaire glauque	*Setaria pumila*	13%	n.d	n.d
Laiteron des champs	*Sonchus arvensis*	1%	2%	1%
Pissenlit officinal	*Taraxacum officinale*	3%	2%	2%

Tableau 7. Récapitulatif des quadrats dominés par les EFEE dans l'espace de liberté

	Nb de quadrats (sur 32) où l'espèce est dominante		
Espèces exotique envahissante	**2022 (sur 24)**	**2023 (sur 32)**	**2024 (sur 32)**
Alpiste Roseau	1	15	13
Chiendent commun	2	0	0
Chénopode blanc	1	0	0
Sétaire glauque	6	0	0
Pissenlit officinal	1	1	0
Panais sauvage	0	1	0

3.2.3 Distinction entre les parcelles situées à l'intérieur et à l'extérieur de la plaine alluviale

Les données suggèrent que les pourcentages de recouvrement d'espèces exotiques sont légèrement inférieurs dans les parcelles situées à l'intérieur de l'ancienne plaine alluviale que celles situées à l'extérieur. En 2022 et 2023, les tests statistiques n'indiquent pas de différence significative, bien qu'il y ait

une tendance. En 2024, cependant, une différence significative est observée et le pourcentage de recouvrement d'espèces exotiques à l'intérieur est inférieur à celui à l'extérieur de l'ancienne plaine.

Les données suggèrent également que les pourcentages de recouvrement d'espèces indigènes ainsi que la richesse des espèces indigènes sont supérieurs à l'intérieur de l'ancienne plaine qu'à l'extérieur. Ces observations sont validées par des différences significatives en 2022 et 2023. En 2024, il y a encore une tendance, mais celle-ci n'est pas significative. La seule tendance qui est significative en 2024 est que le % de recouvrement des espèces exotiques non envahissantes est plus élevé à l'extérieur qu'à l'intérieur de l'ancienne plaine. On décèle également une tendance de % de recouvrement plus important des EFEE à l'intérieur du méandre qu'à l'extérieur, mais celle-ci n'est pas significative.

3.2.4 Bilan de l'inventaire floristique:

Le bilan des inventaires floristiques montre une progression modeste de la superficie de milieux humides (MH) au-delà de la bande riveraine. Cependant, sans modification de l'hydrologie ou de la piézométrie, les conditions nécessaires à la création de ces milieux seront difficiles à atteindre. Pour y parvenir, un coup de pouce sous forme de déblai mécanique léger et d'implantation d'espèces indigènes de milieux humides semble nécessaire. En ce qui concerne la conversion des associations végétales dans la bande riveraine, il est difficile de dire si cela est le fruit direct de la restauration ou si cela reflète une tendance régionale ou est lié à la fréquence des entretiens ; cette question mérite d'être étudiée davantage.

Les résultats montrent un dynamisme important au sein des unités végétales, ce qui est particulièrement propice à la biodiversité. Toutefois, une faiblesse méthodologique a été identifiée : il aurait été préférable de délimiter les unités végétales homogènes (UVH) avec un DGPS pour plus de précision dans le suivi des superficies. Un autre constat notable est la forte dominance des espèces exotiques dans la zone de retrait des cultures, phénomène qui est normal dans un contexte agricole, où des espèces comme le Brome inerme ont été plantées par les producteurs, contribuant à une banque de graines dans le sol. Malgré cela, aucune différence significative n'a été observée dans les pourcentages de recouvrement et l'indice de richesse des espèces indigènes. Cela suggère que, dans un contexte de restauration passive, les progrès sont soit à retardement (effet de lag), soit en stagnation. Un soutien pour l'implantation d'espèces indigènes semble nécessaire. Le retour des milieux humides pourrait favoriser les espèces indigènes, mais la forte compétition avec l'alpiste roseau, une EFEE, reste un obstacle majeur. Cependant, cette espèce n'est pas nécessairement nuisible, comme l'indiquent les ouvrages de Claude Lavoie (2019, 2022).

Une tendance intéressante est la baisse significative des EFEE dans l'ancienne plaine, ce qui mérite d'être suivi de près. Cela pourrait être dû à une compétition plus intense avec les espèces indigènes. De plus, une comparaison entre les parcelles intérieures et extérieures suggère des différences notables dans le pourcentage de recouvrement des espèces indigènes dans l'ancienne plaine (et, dans une moindre mesure, pour les EFEE en 2024). Cela pourrait être attribué à une plus grande distance avec les champs (où les exotiques sont plus présentes) et à une proximité accrue avec le cours d'eau. Ce dernier contient et véhicule à la fois des stocks de graines indigènes et des EFEE provenant du bassin versant. Les espèces exotiques sont plus présentes dans les parcelles extérieures, probablement en raison de leur proximité avec les champs et d'une exposition moins forte aux conditions hydrologiques variables. Ce résultat est particulièrement pertinent, car il peut aider à optimiser la configuration des mesures de restauration, notamment les retraits de cultures visant l'implantation de milieux naturels riverains.

Les données variables témoignent de l'existence d'un environnement dynamique au niveau végétal, propice à la biodiversité. Cependant, favoriser le retour des espèces indigènes et des milieux humides dans un cadre de restauration passive pourrait être un objectif difficile à atteindre sans végétalisation active. Un suivi à long terme de la biodiversité floristique est essentiel pour mieux comprendre les gains potentiels de la restauration passive. Des techniques de restauration plus actives pourraient accélérer le processus, mais elles viennent avec des coûts importants. Il sera également nécessaire d'accompagner cette approche active d'un suivi rigoureux des EFEE pour éviter des impacts négatifs sur les pratiques agricoles adjacentes et intervenir avec des mesures de restauration plus actives lorsque la restauration passive ne donne pas les résultats escomptés.

3.3 Suivi de la qualité des habitats

En 2022, une caractérisation du cours d'eau a été réalisée en utilisant l'index d'évaluation qualitative de l'habitat (QHEI). L'évaluation du QHEI a été réalisée sur les trois tronçons homogènes : T1, T2 et T3 (figures 3 et 4). Le QHEI évalue la nature, la qualité et l'origine du substrat, l'ensablement et l'envasement, la présence de structures d'habitat favorable à l'habitat du poisson, la morphologie du cours d'eau, l'érosion des berges, la qualité de la plaine inondable et la diversité des habitats et des régimes de vélocité présents.

En complément, l'indice de tolérance à la pollution de la communauté de macro invertébrée au niveau de la famille (FBI) a été déterminé à partir des inventaires de terrain sur les transects T2 et T3. Cet indice permet d'évaluer la susceptibilité du milieu d'être touché par un stress selon l'échelle présentée dans le tableau 8.

Tableau 8: Échelle d'interprétation des résultats obtenus pour le FBI selon les classes de tolérances à la pollution.

Cote de tolérance	Tolérance de la communauté
0.00 à 3.75	Excellente : sans pollution organique
3.76 à 4.25	Très bonne : légère pollution organique possible
4.26 à 5.00	Bonne : pollution organique probable
5.01 à 5.75	Moyenne : pollution organique assez substantielle
5.76 à 6.50	Plutôt mauvaise : pollution organique substantielle
6.51 à 7.25	Mauvaise : pollution organique très substantielle
7.26 à 10.00	Très mauvaise : pollution organique grave

Afin de caractériser les communautés présentes aux sites échantillonnés, d'autres indicateurs de biodiversité ont également été quantifiés, permettant de calculer l'indice de santé du benthos (ISB_q) sur les transects T2 et T3 du site d'étude. Il s'agit d'un indice multimétrique composé de six (6) variables calculées au niveau des communautés. Ces variables, ainsi que les méthodes de calcul qui y sont reliées, sont présentées dans le tableau 9. L'ISB_g est utilisé par le MELCCFP pour effectuer le suivi de l'intégrité biotique des cours d'eau basé sur les macroinvertébrés benthiques (MDDEFP, 2012).

Tableau 9 : Indice de santé du benthos pour les cours d'eau sur substrat grossiers (ISBg-f) calculé sur des identifications au niveau de la famille.

Variable ou indice (X)	Réponse prévue selon l'augmentation des perturbations	Valeur de référence	Formule de standardisation
Nombre total de taxons	↓	27	(X / 27) x 100
Nombre de taxons EPT*	↓	17	(X / 17) x 100
% d'EPT sans *Hydropsychidae*	↓	72,5	(X / 72,5) x 100
% de *Chironomidae*	↑	4,1	[(100 – X) / (100 – 4,1)] x 100
% du taxon dominant	↑	32	[(100 – X) / (100 – 32)] x 100
FBI	↑	3,04	[(10 – X) / (10 – 3,04)] x 100

* EPT = Tous les taxons appartenant à des familles d'éphéméroptères, de plécoptères ou de trichoptères.

Le tronçon T1 obtient un score de QHEI de 40, le classant dans la catégorie « mauvaise », tandis que le tronçon T2 obtient un score de 57 (catégorie « bonne ») et le tronçon T3 un score de 47 (catégorie « modérée »).

Le FBI moyen de la communauté pour le transect T2 est de 6,23 (catégorie « plutôt mauvaise »). Ce résultat indique que cette section du cours d'eau présente vraisemblablement une pollution organique substantielle. Le FBI moyen de la communauté pour le transect T3 est de 6,94 (catégorie « Mauvaise »).

Le ISBg-f moyen de la communauté des transects T2 et T3 est respectivement de 54 et 60 (catégorie « Précaire »), indiquant que l'intégrité biotique de la communauté est peu élevée, en raison d'une faible diversité et d'une forte tolérance à la pollution.

Le transect T2 dans la zone boisée présente donc une abondance et une diversité de macroinvertébrés et de poissons plus faibles que le transect T3 dans la zone non boisée. Toutefois, la communauté de la section boisée est moins tolérante à la pollution que la communauté de la section ouverte et se mérite le plus haut score de l'indice QHEI.

Le QHEI plus élevé de la section boisée s'explique principalement par la présence d'une végétation ligneuse sur une grande superficie de la plaine inondable, ce qui contribue au maintien de la qualité de l'eau. Il semble donc logique que la communauté de macroinvertébrés qui s'y trouve soit moins tolérante à la pollution. Toutefois, les sections où la végétation est ouverte présentent une plus grande quantité et qualité de structures d'habitat utilisables par la faune, telles que de la végétation surplombante et des plantes aquatiques. La plus grande abondance et richesse en poissons et en macroinvertébrés des sections ouvertes pourrait donc être expliquée par la plus grande abondance de structures d'habitats de qualité pour ces organismes.

L'aire d'étude présente donc une qualité d'habitat pour les poissons et les macroinvertébrés qui varie en fonction des zones. Globalement, cette qualité est plutôt modérée. Une diversification du substrat, des régimes de vélocité et une augmentation de l'abondance et de la qualité des structures d'habitat pourraient contribuer à l'amélioration des conditions environnementales pour ces organismes.

3.4 Suivi de la qualité des processus hydrogéomorphologiques (IQM)

La caractérisation hydrogéomorphologique du site d'étude a été effectuée entre 2018 et 2022. Certaines données ont déjà fait l'objet de publications scientifiques (Massey et coll., 2019; Lemay et coll., 2021; Marchand et coll., 2022). L'analyse des formes, des dépôts et des processus géomorphologiques actuels du site d'étude (T1-T2-T3) ainsi qu'une caractérisation du régime hydrologique et de certains paramètres hydrauliques de l'écoulement sont disponibles à l'annexe A, de même qu'une explication de l'indice de qualité morphologique (IQM) et le détail de ces analyses à l'annexe J. Les résultats de l'IQM sont résumés ci-dessous.

Une caractérisation de l'IQM du site a été effectuée en octobre 2020 sur un tronçon regroupant l'ensemble du site de la présente étude (T1-T2-T3) (Lemay et coll., 2021), avec un score de 0,55, ce qui équivaut à une qualité morphologique modérée. Les critères les plus significatifs pour expliquer ce bas score sont la discontinuité de la plaine alluviale, l'absence généralisée de végétation fonctionnelle (arbres et arbustes), la forte homogénéité morphologique au niveau des sections transversales du lit mineur et la présence d'une structure de passage bloquant la connectivité.

En 2023, la caractérisation de l'IQM a été faite à nouveau, mais cette fois-ci le tronçon à l'étude a été subdivisé pour mieux comprendre l'état de la dégradation des processus HGM et ainsi affiner la stratégie de restauration. Le tronçon à l'étude a été subdivisé selon les limites du protocole expérimental (T1-T2-T3). Cependant, le tronçon T3 a été subdivisé en deux (T3A-T3B) pour mieux représenter les modifications anthropiques ayant lieu sur le site (Figure 16). En effet, en amont de la traverse, le tronçon T3A n'a pas subi historiquement de redressement de son chenal, alors que le tronçon aval T3B a été le lieu du redressement du chenal, menant à la déconnexion de trois méandres.

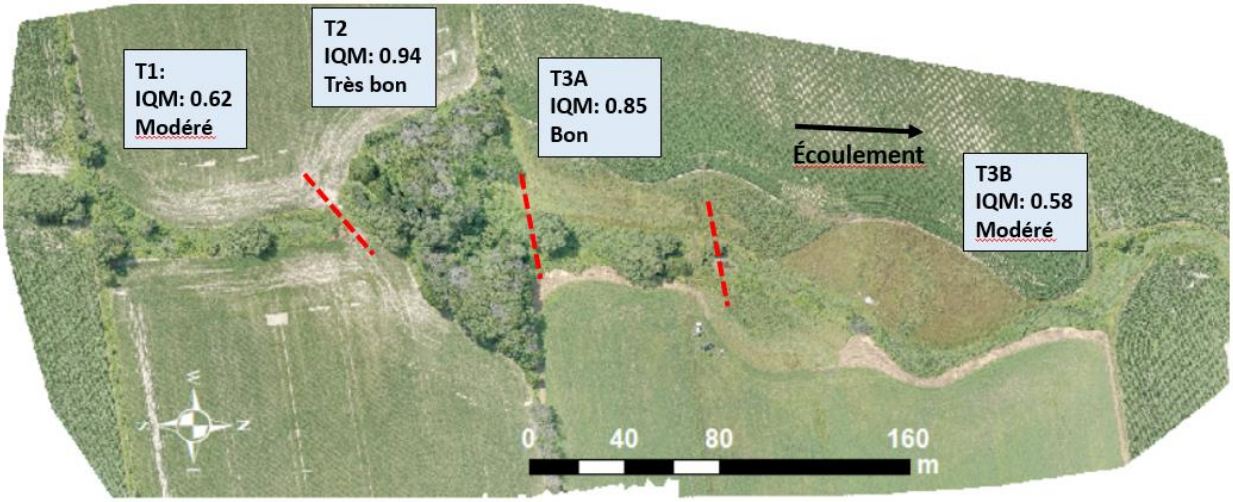


Figure 16. Segmentation des tronçons homogènes et résultats de score IQM de 2023 pour le site d'étude

Les scores finaux d'IQM pour les différents tronçons varient entre 0,58 et 0,94, soit une qualité morphologique variant de modéré à très bonne (Figure 16).

Le score le plus élevé est décerné au tronçon T2, où l'on retrouve un chenal sinueux non altéré et une plaine alluviale entièrement forestière. Le tronçon T3A (visé par la restauration) obtient un score

relativement élevé étant donné la faible intensité des altérations historiques ou actuelles au chenal. Par exemple, à l'inverse du tronçon 3B, le tronçon 3A n'a pas été redressé historiquement et aucune structure anthropique (enrochement, seuil, pont) n'affecte les processus hydrosédimentaires. La largeur de la végétation riveraine fonctionnelle est cependant limitée à la largeur réglementaire en milieu agricole (3 m) et les formes de la plaine alluviale ont été altérées par du remblaiement, ce qui engendre un score plus faible. Il est important de noter que dans le calcul de l'IQM, la végétation riveraine fonctionnelle concerne seulement les arbres et arbustes étant donné l'impact potentiel de la végétation ligneuse sur l'écoulement de l'eau et le transport de sédiments. Ceci veut donc dire que bandes riveraines herbacées, même si elles sont élargies, ne permettent pas d'augmenter le score de l'IQM.

Les tronçons T1 et T3B obtiennent les plus faibles scores d'IQM, indiquant une qualité modérée des processus hydrogéomorphologiques. Les principaux facteurs expliquant ces scores plus faibles sont : la présence de ponceau sous-dimensionné limitant la continuité longitudinale dans le transport de bois et sédiments, la quasi-absence de végétation fonctionnelle (particulièrement pour T3B, figure 17), la forte altération des unités géomorphologiques dans le chenal et la plaine et la rectification historique du tracé du cours d'eau et le changement du style fluvial (de sinueux à linéaire).



Figure 17. Photo du tronçon T3B qui illustre l'absence de végétation fonctionnelle.

Il est pertinent de souligner que plusieurs mesures de restauration projetées sur le site de la Ferme Parentall dans la phase 2 (voir section 10), soit celles de réactiver le transport sédimentaire et le reméandrage t le retour éventuel de végétation arborescente et arbustive sont toutes susceptibles de faire hausser l'indice de qualité morphologique.

3.5 Bilan des suivis écologiques

Les suivis écologiques réalisés dans le cadre du projet *Un Méandre à la fois* ont révélé plusieurs faits saillants sur l'évolution et la pertinence des indicateurs fauniques et floristiques. Concernant les indicateurs fauniques, la réponse à la restauration varie en fonction des groupes étudiés. Les araignées ont montré une réponse rapide, avec des résultats positifs après seulement trois ans, tandis que les oiseaux et les poissons ont également montré des signes d'amélioration, bien qu'un suivi à moyen terme (5-10 ans) soit nécessaire pour mieux documenter leur évolution. Des inventaires complémentaires, tels que l'étude d'autres organismes pris dans les pièges fosses ou l'observation de l'herpétofaune, pourraient fournir des informations plus détaillées sur l'état écologique du site.

Le recours à des méthodes d'inventaire simples et peu coûteuses, comme les pièges fosses pour les insectes et les enregistreurs pour les oiseaux, s'est révélé efficace et pourrait être reproduit par des organisations régionales, comme la MRC ou l'OBV, avec des moyens financiers limités. Toutefois, des améliorations sont nécessaires, comme l'utilisation d'un enregistreur pour les oiseaux (et éventuellement l'herpétofaune) qui allie efficacité et économie, tel que le SM4 mini, qui permettrait de surmonter les problèmes rencontrés avec les enregistreurs bon marché comme les audiomoths, qui ont montré des complications techniques et des résultats moins fiables.

La restauration passive de l'espace de liberté du cours d'eau par le retrait des cultures a engendré le retour d'une prairie herbacée ainsi que la création de 0,2 ha de milieux humides riverains dans l'empreinte de l'ancienne bande riveraine réglementaire. Toutefois, bien que cette approche soit prometteuse, une restauration active pourrait être nécessaire pour accélérer la progression des milieux humides et favoriser l'établissement d'espèces indigènes sur le site de la Ferme Parentall.

Concernant les espèces floristiques, une forte dominance d'espèces exotiques a été observée, ce qui est habituel dans un contexte agricole, où les banques de graines exotiques sont abondantes. Toutefois, les espèces floristiques exotiques envahissantes (EFEE) montrent une tendance à la baisse en termes de pourcentage de recouvrement et de diversité, suggérant ainsi une compétition accrue entre les espèces indigènes et exotiques. Cela est particulièrement plausible dans une ancienne plaine alluviale où les conditions hydrologiques sont très variables, et où les stocks de graines (exotiques et indigènes) peuvent être abondants. Cette dynamique met en évidence la forte variabilité interannuelle des assemblages floristiques dans l'espace de liberté des cours d'eau, ce qui souligne l'importance d'un suivi à moyen terme pour mieux évaluer les progrès de la restauration passive.

Le suivi des indicateurs floristiques, en distinguant les zones à l'intérieur et à l'extérieur de la plaine, s'avère essentiel pour optimiser les projets de restauration d'habitats riverains. Toutefois, un suivi à long terme sera nécessaire pour affiner les tendances et mieux comprendre l'évolution de la diversité floristique sur ces sites. Quant aux indicateurs de qualité de l'eau et aux processus hydrogéomorphologiques, les résultats n'indiquent pas encore de tendance claire. Cela est dû à l'absence d'interventions globales sur l'ensemble du bassin versant et de mesures de restauration ciblées sur les processus HGM (à l'exception du ponceau qui est survenu lors de la dernière année dans le projet et limitant ainsi les suivis qui ont pu être réalisés). Le suivi des effets du nouveau ponceau et l'ajout de mesures de restauration visant à rétablir des processus hydrogéomorphologiques, comme l'augmentation de la végétation riveraine, pourraient améliorer les résultats dans ce domaine.

4. Portrait de la collaboration mise en place avec les agriculteurs sur le site du projet

4.1 Portrait global de la collaboration

La collaboration entre les propriétaires de la Ferme Parentall et l'équipe de recherche de l'Université Concordia repose sur une relation de confiance établie au fil des années, appuyée par une entente contractuelle. Tel que mentionné précédemment, le projet « *Un Méandre à la Fois* » trouve ses origines dans les travaux de doctorat en géographie de Jean-Philippe Marchand, aujourd'hui coordonnateur du projet. Dès 2017, le site de la branche 13 de la Petite Pot-au-Beurre avait été identifié, par photo-interprétation, comme un lieu d'intérêt pour étudier les interactions hydrologiques entre les petits cours d'eau agricoles linéarisés des basses terres du Saint-Laurent et leur espace de liberté résiduel. Les producteurs de la Ferme Parentall avaient alors été approchés pour permettre à l'équipe de Concordia d'instrumenter un méandre abandonné sur leur terrain. Ceux-ci avaient accepté par gentillesse et curiosité.

En 2022, une entente contractuelle est établie entre la Ferme Parentall et l'Université Concordia. Cette entente stipule que l'Université loue l'espace de restauration (0,93 hectare) le long de la branche 13 de la rivière Petite Pot-au-Beurre pour un montant annuel de 2 100 $, plus les taxes applicables, pour la durée de l'entente. Celle-ci prendra fin le 19 juin 2025. De manière informelle, mais néanmoins respectée, la Ferme Parentall s'est engagée à ne pas effectuer d'activités agricoles dans cet espace ciblé par le projet de restauration pendant toute la durée de l'entente.

4.2 Description des interactions

Les interactions entre les propriétaires de la Ferme Parentall et l'équipe de recherche se sont articulées autour de rencontres planifiées et d'échanges ponctuels, favorisant une communication continue et constructive.

Chaque année, une à deux rencontres planifiées ont été organisées. Chaque année, une rencontre se tenait en début d'été et visait à présenter les travaux et les suivis prévus pour la saison. Une seconde rencontre, en fin d'année, permettait de faire le bilan des activités réalisées. Lors de ces rencontres, un questionnaire personnalisé a été utilisé (Annexe K), et un entretien semi-dirigé était mené en personne ou par visioconférence. Les questions abordées portaient sur la perception des producteurs à l'égard des travaux de restauration, leur collaboration avec le coordonnateur du projet, ainsi que les mécanismes à mettre en place pour assurer la pérennisation du projet. Ces rencontres, d'une durée de deux à trois heures, étaient enregistrées, et un compte-rendu détaillé était rédigé par la suite.

En complément de ces rencontres planifiées, des échanges informels ont eu lieu lors des nombreuses visites de terrain, qui se déroulaient entre cinq et sept fois par année. Avant chaque visite, un message était envoyé aux producteurs pour les informer quelques jours à l'avance. Ces échanges, souvent de courte durée (entre 10 et 30 minutes), se tenaient soit à la maison familiale, soit directement sur le terrain de la ferme. Ces visites, qualifiées de courtoises, permettaient des discussions spontanées sur des sujets variés,

allant des observations sur le terrain aux enjeux spécifiques liés au projet. Lorsque les producteurs étaient occupés par leurs activités agricoles, ces rencontres étaient parfois reportées ou raccourcies.

Enfin, des réunions par visioconférence ont occasionnellement été organisées pour aborder des sujets nécessitant une attention rapide. Ces réunions impromptues étaient planifiées avec un préavis d'au moins une semaine, afin de respecter les disponibilités des producteurs.

4.3 Niveau de participation et d'engagement

Le niveau de participation des producteurs de la Ferme Parentall a été constant depuis le début du projet. Dès les premières discussions, Judith Allard et Denis Parent avaient exprimé leur volonté d'appuyer la démarche de recherche tout en précisant que leur implication devait rester limitée. Gestionnaires d'une entreprise agricole de grande envergure comprenant plus de 125 hectares en grandes cultures et une pouponnière de vaches, ils souhaitaient éviter toute charge de travail additionnelle liée au projet, qu'il s'agisse de travaux manuels ou administratifs. À l'exception de quelques cas spécifiques, les producteurs n'ont donc pas eu à investir de temps, d'argent, ou de ressources matérielles dans la conduite des travaux de suivi, les études préalables ou la mise en œuvre des mesures de restauration. Leur participation s'est essentiellement concentrée sur les rencontres planifiées et ponctuelles décrites précédemment.

Deux exceptions méritent toutefois d'être soulignées :

- Espace de rangement : La Ferme Parentall a gracieusement mis à disposition un espace de rangement d'environ 9 m² dans un de leurs ateliers pour entreposer le matériel de suivi, notamment des tuyaux PVC pour les piézomètres, des sacs de sable et des bourroles.
- Démarches administratives : Judith Allard s'est impliquée dans la validation et l'autorisation des transferts d'argent, conformément à l'entente contractuelle, ce qui a représenté un total d'environ 2 à 3 heures de travail.

Malgré un niveau de participation restreint, les producteurs ont démontré un engagement croissant au fil du projet. Cet engagement s'est traduit par une implication plus active dans les discussions, un intérêt accru pour les enjeux écologiques et une promotion spontanée du projet. Ce sentiment de collaboration s'est traduit par des initiatives spontanées de la part des producteurs, comme la prise de photos du site pour les publier sur les réseaux sociaux ou bien leur participation à un reportage télévisé (tournage en juin 2024; diffusion prévue en 2025 sur MaTV), mettant en lumière le projet comme un exemple d'adaptation aux changements climatiques en milieu agricole.

D'autre part, les chercheurs de l'Université Concordia ont pu approfondir leur compréhension des réalités agricoles, notamment les contraintes réglementaires et économiques auxquelles sont soumises les entreprises agricoles, ainsi que les particularités du drainage souterrain et des opérations culturales. Ces échanges ont non seulement renforcé la relation de confiance entre les parties, mais ont aussi mené au développement d'une relation d'amitié.

4.4 Faits marquants:

- **L'importance d'une relation de confiance pour la flexibilité et l'apprentissage mutuel.**
  L'établissement d'une relation de confiance entre des producteurs agricoles et une équipe de

coordination de projet constitue un levier fondamental pour favoriser l'adhésion et la flexibilité des parties prenantes dans l'adoption de mesures de restauration. Cette confiance facilite la mise en place d'approches expérimentales, comme les essais d'implantation sur de petites surfaces ou pour une durée limitée, permettant ainsi des ajustements progressifs basés sur les apprentissages.

Du côté des producteurs, cette flexibilité se traduit par une ouverture à accepter que la restauration basée sur les processus naturels exige du temps et que les résultats ne soient pas toujours garantis. Ils développent une meilleure compréhension des objectifs écologiques à long terme, tout en appréhendant les incertitudes inhérentes à ce type de démarche.

Du côté des équipes de coordination, la confiance nécessite une grande transparence quant aux défis et incertitudes du projet. Elle impose également une résistance à l'envie de pérenniser ou d'officialiser trop rapidement les mesures de restauration, ce qui pourrait décourager les producteurs si ceux-ci ne se sentent pas pleinement outillés pour évaluer les impacts du projet sur leur entreprise ou leur patrimoine. La pérennisation demeure un objectif essentiel pour maximiser les bienfaits écologiques et assurer la cohérence socio-économique du projet, mais elle doit être introduite de manière progressive et collaborative.

- **Une collaboration individuelle comme fenêtre sur les enjeux collectifs**
  Les échanges approfondis avec une seule entreprise agricole, comme la Ferme Parentall, peuvent offrir une compréhension précieuse des enjeux et des besoins de l'ensemble d'une communauté agricole, à condition que ces interactions s'inscrivent dans un climat de confiance et dans une temporalité suffisamment étendue. Ces discussions permettent non seulement d'identifier des solutions concrètes et adaptées, mais aussi de mieux cerner les perceptions, les craintes et les motivations des producteurs face aux projets de restauration.

  Dans le cas du projet *Un Méandre à la fois*, cette collaboration a permis de tester des approches innovantes tout en intégrant progressivement les préoccupations des producteurs, comme l'impact potentiel des mesures sur la productivité agricole, le patrimoine familial, et les contraintes réglementaires. Cette démarche a également contribué à construire une méthodologie de restauration et de suivi qui pourrait être déployée à l'échelle régionale, en servant de modèle inspirant pour d'autres entreprises agricoles.

- **Le rôle des échanges interpersonnels dans l'évolution du projet**
  Les rencontres régulières, formelles et informelles, ont permis d'approfondir non seulement la relation entre les chercheurs et les producteurs, mais aussi les connaissances des deux parties sur leurs réalités respectives. Les producteurs de la Ferme Parentall ont progressivement développé une appréciation des bénéfices écologiques et régionaux du projet, tandis que l'équipe de coordination a enrichi sa compréhension des contraintes et des priorités du milieu agricole. Ces échanges ont favorisé l'émergence d'un sentiment d'appartenance des producteurs envers le projet, renforçant ainsi leur engagement et leur rôle comme ambassadeurs des bonnes pratiques agroenvironnementales.

- **Un projet pilote transformé en modèle régional**
  En trois ans, *Un Méandre à la fois* est passé d'un projet pilote à un exemple phare en restauration écologique en milieu agricole au Québec. La collaboration avec la Ferme Parentall a non seulement

permis de tester des approches novatrices, mais aussi d'établir un modèle de partenariat qui met de l'avant l'importance des relations humaines et des ajustements progressifs pour la réussite des projets de restauration.

5. Portrait socio-économique de la perception et des besoins des agriculteurs pour les projets de restauration

(Un regard croisé sur les dynamiques à l'échelle du bassin versant et à l'échelle locale.)

Cette section explore la perception et les besoins des agriculteurs concernant les projets de restauration de cours d'eau en milieu agricole, en s'appuyant sur diverses approches méthodologiques. Ces démarches incluent des entretiens semi-dirigés approfondis avec les producteurs de la Ferme Parentall, ainsi que des entrevues semi-dirigées précédées de présentations du projet auprès de producteurs externes. Par ailleurs, une participation opportuniste à des activités de consultation et de concertation à l'échelle régionale a permis de recueillir des perspectives supplémentaires. Les données issues de ces interactions sont complétées par des questionnaires détaillés et succincts, dont les modèles sont disponibles en annexes K (pour le questionnaire personnalisé de la Ferme Parentall) et L (pour les entretiens semi-dirigés avec d'autres producteurs). Les résultats bruts des entretiens réalisés sont disponibles à l'annexe M.

Cette section est structurée en trois sous-sections. La première met en lumière les mobilisations et initiatives issues des producteurs agricoles au niveau du bassin versant, en analysant les actions collectives et les préoccupations des producteurs dans le bassin versant de la Pot-au-Beurre. La seconde sous-section porte sur les activités de concertation à l'échelle régionale, avec une description sommaire des démarches collaboratives, notamment celles des Laboratoires Vivants du lac Saint-Pierre et du Plan régional des milieux naturels de la MRC Pierre de Saurel. La troisième aborde les perceptions du projet de restauration à l'échelle locale, offrant un portrait des perceptions des producteurs de la Ferme Parentall ainsi que d'autres producteurs, locaux ou autres régions.

5.1 Mobilisation et initiatives issues des producteurs agricoles au niveau du bassin versant de la Pot-au-Beurre

Dans le bassin versant de la Pot-au-Beurre, la mobilisation des agriculteurs pour mieux comprendre et contrer la dégradation de la qualité de l'eau remonte à plusieurs années. Cette démarche collective découle d'une prise de conscience des impacts négatifs de certaines pratiques agricoles sur les habitats aquatiques, notamment ceux du lac Saint-Pierre. En effet, de nombreux chercheurs universitaires et experts gouvernementaux ont documenté les pressions exercées par les bassins versants tributaires, incluant celui de la rivière Pot-au-Beurre, sur ce lac d'importance internationale (Congrès de l'ABQ, 2024).

En 2017, un comité de bassin versant dédié à la rivière Pot-au-Beurre a été créé sous l'impulsion de l'UPA Montérégie. Ce comité, connu sous le nom de "Pot-au-Beurre en actions", a permis de fédérer les efforts des agriculteurs autour de solutions concrètes, tout en offrant une plateforme de communication grâce à une page web dédiée.

Sous l'égide de ce comité, plusieurs mesures agroenvironnementales ont été mises en place entre 2017 et 2023. Parmi les réalisations notables figurent :

- 3 200 hectares de pratiques de conservation des sols pour réduire l'érosion et améliorer la rétention des nutriments.
- 300 ouvrages hydroagricoles tels que des déversoirs de drains enrochés et des bassins de sédimentation pour limiter les apports sédimentaires et nutritifs aux cours d'eau.
- Près de 40 km de bandes riveraines élargies et de haies brise-vent, visant à améliorer la biodiversité, réduire les ruissellements et limiter les pertes de sols agricoles (UPA, 2023).

Ces initiatives ont bénéficié du soutien actif de Yasmina Larbi-Youcef, conseillère agronome de l'UPA, qui a coordonné le comité jusqu'en 2023. Le financement de ces actions a été rendu possible grâce à plusieurs programmes, notamment Prime-Vert, le Programme services-conseils, et l'Initiative ministérielle de rétribution des pratiques agroenvironnementales (RPA) du MAPAQ (voir la description détaillée de ces programmes à l'annexe O). Entre 2019 et 2023, plus d'un million de dollars ont été investis par le MAPAQ pour soutenir ces pratiques dans le bassin versant (UPA, 2023).

Depuis 2020, de nouvelles pratiques agroenvironnementales sont également soutenues via le programme ALUS de l'UPA Montérégie. Parmi les actions financées figure l'implantation de bandes riveraines élargies fleuries et de haies brise-vent, qui offrent des bénéfices écologiques tout en respectant les réalités agricoles locales. En parallèle, divers suivis de la qualité de l'eau ont été menés dans les cours d'eau du bassin par la Direction de l'Agroenvironnement du MELCCFP et par Environnement Canada, permettant de mesurer les impacts des actions entreprises.

Cependant, avec le départ de Mme Larbi-Youcef en 2023, le comité de bassin versant a vu ses activités ralentir, entraînant une période de restructuration. Les efforts pour relancer le comité devraient aboutir en 2025, avec l'objectif de maintenir cette dynamique collective essentielle pour préserver et restaurer les milieux humides et hydriques du bassin versant.

5.2 Activités de concertation environnementale à l'échelle régionale

Entre 2020 et 2023, un Laboratoire Vivant portant sur le lac Saint-Pierre a été mis sur pied par Agriculture et Agro-Alimentaire Canada avec la collaboration de l'UPA, auxquelles participaient les acteurs du bassin versant de la Pot-au-Beurre. Cette démarche fut l'occasion pour des agriculteurs, des chercheurs et des acteurs du milieu d'échanger et de co-développer des pratiques agroenvironnementales pour améliorer la qualité de l'eau, la biodiversité, la santé des sols et la réduction des gaz à effet de serre.

Un volet spécifique de cette démarche portait sur les bonnes pratiques liées aux cours d'eau. Une rencontre clé a été consacrée à la compréhension des processus hydrogéomorphologiques dans les rivières des Basses-Terres du Saint-Laurent et à l'exploration d'approches innovantes intégrant ces processus. Lors de cette rencontre, une présentation conjointe du coordonnateur du projet *Un Méandre à la fois* et de Sylvio Demers de la firme Rivières a mis en lumière l'importance des processus hydrosédimentaires – érosion, transport et accumulation – pour maintenir un équilibre morphologique dynamique au sein des bassins versants. Il a été souligné que la modification ou l'élimination de ces processus à un endroit donné peut entraîner des déséquilibres en cascade ailleurs dans le bassin, exacerbant des phénomènes tels que la sédimentation excessive ou l'érosion. Cette présentation a

également permis de confirmer comment les enjeux varient en fonction de la position des producteurs dans le bassin versant, qu'il s'agisse de problèmes d'érosion, de sédimentation ou de gestion des sorties de drains agricoles.

Malgré l'intérêt suscité par ces échanges, le Laboratoire Vivant du lac Saint-Pierre n'a pas été prolongé au-delà de 2023. Bien que cela ait limité les avancées concrètes en matière de restauration des cours d'eau, quelques pratiques novatrices ont néanmoins vu le jour dans le bassin versant de la Pot-au-Beurre, notamment l'aménagement de bandes riveraines élargies avec des configurations variées (5, 10, 20 mètres) et des végétaux indigènes, ainsi que la création d'un bassin de sédimentation sur la propriété de la Ferme Bellevue à Saint-Robert. Certaines initiatives bénéficient toujours d'un suivi par Environnement Canada, même si les suivis fauniques et floristiques associés aux Laboratoires vivants ont cessé en 2023.

Durant la même période de 2020 à 2023, la démarche des Plans régionaux des milieux humides et hydriques (PRMHH) a également offert une plateforme précieuse pour la concertation à l'échelle régionale. Sous l'égide de la MRC Pierre-De Saurel, cette démarche a impliqué la création d'un comité technique auquel a participé le coordonnateur du projet *Un Méandre à la fois* en tant qu'expert scientifique. Contrairement à d'autres régions, la MRC a choisi d'élargir le mandat des PRMHH pour inclure tous les milieux naturels (forêts, friches), renforçant ainsi la prise en compte des connectivités écologiques.

Les consultations publiques et les discussions au sein du comité ont permis de définir une série d'enjeux prioritaires pour le bassin versant de la Pot-au-Beurre :

- La dégradation des cours d'eau (érosion, sédimentation, qualité de l'eau, habitats aquatiques).
- La prolifération des espèces exotiques envahissantes.
- La déconnectivité écologique et la fragmentation des habitats.
- Les impacts des changements climatiques (inondations, approvisionnement en eau, résilience des écosystèmes).
- Les divergences de visions des enjeux environnementaux entre acteurs.
- Le financement des actions de conservation et de restauration.

En réponse à ces enjeux, le comité a formulé des orientations stratégiques, incluant :

- La conservation et la restauration des milieux humides, forestiers et riverains.
- La priorisation des corridors écologiques pour renforcer la connectivité.
- La sensibilisation et la communication entre les acteurs locaux.
- L'équité entre les mesures environnementales en milieu urbain et rural.
- Le développement de mécanismes de financement durable pour les actions de restauration.

Le PRMHH a également intégré une méthodologie de priorisation des tronçons de cours d'eau à restaurer en fonction de leur état et de leur potentiel de restauration. Le site de la Ferme Parentall a ainsi obtenu une priorité modérée pour la conservation et une priorité élevée pour la restauration, confirmant l'importance de ce site dans les efforts régionaux.

5.3 Perceptions du projet de restauration de la Ferme Parentall

Alors que les initiatives à l'échelle du bassin versant de la Pot-au-Beurre témoignent d'un engagement collectif en faveur de pratiques durables, il est essentiel de porter une attention particulière aux

perceptions spécifiques vis-à-vis du projet de restauration à la Ferme Parentall. À travers des entretiens approfondis et des échanges informels, notre équipe a cherché à documenter les perceptions, les besoins et les impacts du projet pour les agriculteurs directement impliqués. De plus, nous avons recueilli des informations sur les perceptions extérieures, provenant d'acteurs du milieu agricole dans le bassin versant ainsi que dans d'autres régions du Québec.

5.3.1 Perceptions des producteurs de la Ferme Parentall

Les entretiens semi-dirigés menés en décembre 2023 et novembre 2024, ainsi que de nombreux échanges informels, permettent d'analyser l'évolution de la perception des producteurs de la Ferme Parentall vis-à-vis du projet.

Dès le début du projet en 2022, les producteurs exprimaient une fierté personnelle quant à leur contribution à un effort environnemental, mais les préoccupations restaient centrées sur l'absence de contraintes majeures pour leurs activités agricoles. Lors du premier entretien semi-dirigé en 2023, le sentiment d'appartenance au projet était encore limité, et leur satisfaction reposait principalement sur l'aide financière reçue (2100 $/ha/an), qui compensait largement les pertes de revenus associées à la mise en retrait des terres cultivées.

Selon leurs estimations, leur revenu brut à l'hectare pour le maïs fourrager variait entre 3000 $ et 4500 $ par hectare, des chiffres cohérents avec les données de La Financière Agricole du Québec (2024), qui évalue le revenu brut moyen de la zone (6.1) à 4772 $/ha. Avec des coûts de production représentant environ deux tiers du revenu brut, leur marge nette est estimée à environ 1500 $/ha. Le montant versé dans le cadre du projet dépasse donc cette marge, rendant l'entente avantageuse.

Au fil des années, les discussions se sont enrichies. Les producteurs ont manifesté un intérêt croissant pour mieux comprendre les enjeux écologiques, notamment le rôle des milieux humides riverains et des processus hydrogéomorphologiques dans les petits cours d'eau agricoles. Les problématiques environnementales documentées au Lac Saint-Pierre, où se déverse la rivière Petite Pot-au-Beurre, ont renforcé leur volonté de comprendre les impacts régionaux du projet. Un sentiment de fierté s'est progressivement développé autour de l'idée que les producteurs agricoles peuvent contribuer positivement à la restauration de l'environnement.

Lors de l'entretien de 2024, les producteurs ont donc témoigné d'une reconnaissance accrue des bénéfices environnementaux et socio-économiques du projet. Ils notent que ce dernier a renforcé l'image positive de leur entreprise en tant qu'entreprise engagée dans des pratiques agricoles durables. En outre, ils considèrent que le projet les a rendus plus résilients face aux aléas climatiques, notamment lors de la tempête Debby en aout 2024, lorsque l'espace de retrait a joué un rôle de zone tampon, évitant des pertes significatives sur leurs cultures (voir section 8.5). Judith Allard et Denis Parent ont exprimé le souhait que le site de restauration continue de faire l'objet de mesures de restauration additionnelles ainsi que de nouveaux projets de recherche dans les années à venir. Ces commentaires témoignent à la fois d'un fort niveau d'attachement et de leur reconnaissance pour l'importance du projet comme modèle unique au Québec.

Les propriétaires ont tout de même relevé quelques petits enjeux associés au projet. En premier lieu, la configuration courbe de l'espace de liberté restauré a entraîné des complications mineures pour la circulation des grandes machines agricoles. Pour y remédier, les producteurs ont aménagé une bande

tampon allant jusqu'à 10 mètres de cultures de foin fourragé entre les parcelles de maïs et l'espace restauré pour obtenir une configuration plus rectiligne, une solution qui illustre leur appropriation progressive du projet et leur vision multifonctionnelle à long terme du site.

Lors de la dernière rencontre en novembre 2024, ils ont également exprimé des interrogations par rapport à la démarche de pérennisation du projet. Ils désirent rester propriétaires du terrain où se déroule le projet de restauration, mais comprennent la pertinence d'appliquer un outil légal de conservation pour assurer la durabilité des mesures de restauration implantées, s'ils venaient à vendre ou à décéder. Par ailleurs, ils ont exprimé le souci de ne pas savoir avec quel organisme un tel outil de conservation serait appliqué. Ils ont mis de l'avant le besoin de prendre leur temps pour prendre une décision relativement à la pérennisation du projet. Ils veulent à la fois du temps pour rencontrer des représentants d'organismes de conservation ainsi que pour permettre l'émergence au Québec de nouveaux outils de pérennisation innovants.

5.3.2 Perceptions générales des producteurs extérieurs au bassin versant de la Pot-au-Beurre

Plusieurs producteurs rencontrés en dehors du bassin versant ont montré un intérêt général marqué pour le projet. Parmi les 32 producteurs sondés, 41 % se sont dits très intéressés à explorer des mesures similaires sur leur propriété, 28 % modérément intéressés, tandis que 31 % ont exprimé peu ou pas d'intérêt. Les commentaires positifs soulignent l'approche gagnant-gagnant du projet, qui équilibre gains écologiques et respect des exigences logistiques et économiques du milieu agricole, tout en s'appuyant sur des bases scientifiques solides.

Cependant, des incertitudes subsistent quant à la gestion du drainage agricole dans la zone de retrait de cultures et la durabilité des soutiens financiers et techniques, ce qui explique la réticence de certains producteurs. Ces préoccupations soulignent l'importance d'une communication continue pour maintenir un soutien et dissiper les doutes.

Une disparité régionale est également observée : 60 % des producteurs en Outaouais se disent fortement intéressés, contre 38 % en Montérégie et seulement 11 % en Estrie. Ces différences pourraient refléter des spécificités régionales, telles que le degré de mobilisation collective ainsi que les types de contraintes associés à différents types de cultures (grandes cultures, fourrages, élevage, etc.).

5.3.3 Observations sur la perception locale (dans le bassin versant)

La perception du projet à la Ferme Parentall au sein du bassin versant de la Pot-au-Beurre est globalement positive, bien que la démarche reste encore relativement méconnue. Des producteurs du bassin versant, ainsi que des professionnels de la MRC et de l'UPA, ont exprimé leur intérêt pour les transformations observées sur le site. Les travaux sur le ponceau, menant à moins d'obstruction sur l'écoulement, ainsi que le versement d'une aide financière pour les retraits de cultures dans l'espace de liberté, sont mentionnés comme des points très positifs de la démarche. Un producteur voisin, ayant survolé le site en avion, note également l'aspect fonctionnel des modifications apportées, notamment avec l'implantation de la bande tampon aux abords de l'espace de liberté pour accommoder la circulation de la machinerie agricole.

Seuls trois producteurs du bassin versant ont été rencontrés individuellement pour des entretiens semi-dirigés. Sur les trois, deux ont indiqué être très intéressés et un moyennement intéressé à ce qu'une visite soit effectuée sur leur terrain pour tester la faisabilité d'implanter des mesures de restauration de cours

d'eau. Néanmoins, les disparités régionales dans les perceptions soulignent l'importance d'accroître la sensibilisation locale et de multiplier les interactions avec les producteurs du bassin versant pour mieux comprendre et répondre à leurs attentes. Une attention particulière doit être portée aux mécanismes de soutien, afin de consolider l'acceptation sociale et de favoriser une plus grande participation.

En somme, le projet *Un Méandre à la fois* est généralement perçu comme une initiative positive et bien intégrée à l'échelle du bassin versant de la Pot-au-Beurre, mais son rayonnement au-delà de la Ferme Parentall nécessite encore des efforts soutenus (voir à la section 8.6 le projet de restauration du ruisseau Parent en Outaouais). Le succès du projet repose sur une collaboration continue, une transparence accrue et une démonstration claire des résultats écologiques et socio-économiques à long terme. Ces éléments sont essentiels pour assurer une pérennité durable et un soutien élargi au sein de la communauté agricole.

5.4 Faits saillants

Les éléments clés qui ressortent de l'analyse de la perception et des besoins des agriculteurs pour les projets de restauration sont les suivants :

- Le niveau élevé de mobilisation dans le bassin versant de la Pot-au-Beurre (le comité de bassin versant (UPA Montérégie), les Laboratoires vivants du lac Saint-Pierre et le Plan régional des milieux naturels (PRMN) de la MRC Pierre de Saurel), particulièrement des producteurs agricoles, autour de la gestion environnementale est un atout majeur, avec plusieurs mesures agroenvironnementales aux champs déjà en place (ex. conservation des sols, bandes riveraines élargies, ouvrages hydroagricoles). Les actions spécifiques dans les cours d'eau, bien qu'encore modestes, croissent lentement.
- La mobilisation des acteurs dépend souvent de leaders clés, comme Yasmina Larbi-Youcef, dont le départ a ralenti les activités du comité de bassin versant. Cela souligne l'importance de renforcer une mobilisation institutionnelle, soutenue par des règlements, des politiques et un financement durable. Les difficultés à trouver des ressources financières à long terme et les programmes de financement de courte durée, comme le Laboratoire vivant du Lac Saint-Pierre (3 ans), peuvent décourager les parties prenantes et générer de la frustration, limitant ainsi l'impact à long terme des initiatives.
- Il est essentiel de travailler à l'échelle régionale (MRC ou bassin versant) et de viser des actions de concertation renforçant la littératie environnementale des producteurs, favorisant une meilleure compréhension des défis collectifs et des solutions adaptées à leurs besoins individuels.
- L'acceptabilité sociale des projets repose sur une intégration des enjeux écologiques aux problématiques agricoles. Les politiques agricoles passées, responsables de certains problèmes environnementaux actuels, doivent être prises en compte dans les solutions proposées. Pour inspirer davantage de producteurs, il faut accroître la visibilité des projets, et idéalement faire un recensement des initiatives individuelles existantes qui pourrait servir de base à une démarche collective. Les producteurs de la Ferme Parentall ont exprimé une fierté croissante vis-à-vis du projet, particulièrement en raison de son équilibre entre impacts environnementaux positifs et absence de contraintes majeures sur leurs activités agricoles, notamment grâce à l'aide financière reçue (2100 $/ha/an) jugée satisfaisante.
- Malgré quelques défis opérationnels, comme l'adaptation à la configuration courbe de l'espace restauré, les producteurs ont trouvé des solutions pragmatiques, et ont une volonté de maintenir

le site actif à long terme, notamment par des visites de chercheurs ou des aménagements multifonctionnels (p. ex., zones fruitières), ce qui témoigne d'un fort attachement au projet.

- La flexibilité est nécessaire pour le succès de projets collectifs à l'échelle du bassin versant, avec par exemple des mécanismes de soutien pour s'adapter aux disparités d'intérêt, aux problématiques amont aval, et aux contraintes propres à chaque producteur.

En s'appuyant sur des exemples tels que la Ferme Parentall, ce projet a pu démontrer que les producteurs agricoles peuvent jouer un rôle actif dans la définition de stratégies adaptées à leurs réalités spécifiques, tout en contribuant à des objectifs environnementaux régionaux.

6. Mécanismes de pérennisation à mettre en place pour les travaux de restauration de cours d'eau en milieu agricole

La pérennisation des mesures de restauration de cours d'eau constitue un enjeu central, tant pour les producteurs agricoles que pour les bailleurs de fonds du projet. Pour les producteurs, elle garantit un soutien continu, qu'il soit technique, logistique ou financier, et facilite ainsi l'intégration durable de ces mesures dans leurs pratiques agricoles. Pour les bailleurs de fonds, la pérennisation assure des bénéfices écologiques à long terme, essentiels pour atteindre les objectifs environnementaux fixés. Cette convergence d'intérêts met en lumière la nécessité de disposer d'outils réglementaires adaptés et efficaces.

Dans cette section, nous examinons les avantages et les limites de divers outils réglementaires, en nous appuyant sur des lectures de documents officiels ainsi que sur des analyses et des recommandations d'experts. L'équipe de projet a notamment reçu l'aide *pro bono* de maitre Mélissa Devost, avocate spécialisée en droit de l'environnement au sein de la firme Norton Rose Fulbright Canada, ainsi que Karine Labelle, avocate et chargée de projet chez Nature Avenir, une organisation du Centre-du-Québec dédiée à la conservation de la nature. Les analyses portent sur leurs conditions de mise en application, leur durée, leurs effets sur les droits de propriété et les restrictions d'usage, ainsi que sur leur impact fiscal et les mesures financières associées. La description des mécanismes de pérennisation et le détail de l'analyse des outils sont présentés à l'annexe N. Les mécanismes de pérennisation décrits dans cette annexe incluent **la réserve naturelle en milieu privé, le don à un organisme reconnu à des fins de conservation via le programme de don écologique, la servitude réelle de conservation, la servitude personnelle de conservation, la fiducie d'utilité sociale et les milieux naturels délimités par un plan**. La présente section de ce rapport se concentre sur la justification des mécanismes les plus adaptés pour des projets de restauration de cours d'eau en milieu agricole, comme celui de la Ferme Parentall.

Enfin, il est important de noter que la mise en œuvre de tous les outils légaux discutés ci-dessous nécessitent de soumettre une demande à la Commission de protection du territoire agricole du Québec (CPTAQ), lorsqu'un projet se situe en milieu agricole, afin d'utiliser un lot (ou une partie de lot) à une fin autre qu'agricole, ainsi que d'obtenir l'autorisation. Une telle démarche n'ayant pas été entreprise dans le cadre de ce projet, il est actuellement impossible de prévoir la réponse de la CPTAQ.

6.1 Meilleur scénario pour la Ferme Parentall

Les producteurs de la Ferme Parentall ont exprimé des attentes claires concernant la démarche de pérennisation du projet :

- **Rester propriétaires du terrain :**
  Ils souhaitent conserver la propriété du terrain où se déroule le projet de restauration tout en comprenant la nécessité d'appliquer un outil légal de conservation pour garantir à long terme la durabilité des mesures de restauration entreprises, au-delà de la durée du projet pilote mené par l'Université Concordia, ou bien en cas de vente ou de décès.

- **Prendre le temps de décider :**
  Ils ont souligné l'importance de prendre le temps nécessaire pour rencontrer des représentants d'organismes de conservation, créer des liens de confiance et évaluer toutes les options disponibles.

- **Suivre les avancées en conservation écologique :**
  Ils souhaitent également profiter des éventuelles innovations législatives et institutionnelles dans le domaine de la conservation écologique en terres privées au Québec.

Sous réserve des points ci-haut mentionnés, **l'outil de pérennisation le plus approprié dans le contexte du projet de la Ferme Parentall est la servitude personnelle**. Ce choix repose sur plusieurs arguments :

- **Simplicité et flexibilité :**
  La servitude personnelle est simple à mettre en œuvre et offre une grande flexibilité dans la définition des restrictions ou des droits d'usage convenus entre le propriétaire (cédant) et le bénéficiaire (cessionnaire). Cela permet de répondre aux besoins spécifiques des producteurs agricoles tout en garantissant la durabilité des mesures de restauration.

- **Maintien de la propriété** :
  Contrairement à d'autres outils tels que la fiducie d'utilité sociale, la servitude personnelle permet aux producteurs de la Ferme Parentall de rester propriétaires du terrain restauré. Ce maintien de la propriété est crucial pour garantir leur acceptation du projet et leur sentiment d'appartenance aux mesures mises en place. Ce critère pourrait également être avantageux quand la pérennisation de l'espace de liberté devra être soumise à une autorisation de la Commission de protection du territoire agricole du Québec (CPTAQ), puisqu'il permet d'éviter le morcellement du terrain agricole et de conserver ainsi l'intégrité du territoire agricole.

- **Continuité des engagements** :
  En désignant un organisme de conservation, tel que Nature Avenir par exemple, comme cessionnaire, la continuité des engagements de conservation peut être assurée, même en cas de dissolution de l'organisme. Les lettres patentes de Nature Avenir prévoient que ses droits seraient transférés à un autre organisme en cas de cessation d'activités, garantissant ainsi la pérennité des mesures.

- **Potentiel de combinaisons avantageuses :**
  La cession d'une servitude liée à l'espace de liberté du cours d'eau au prix de sa juste valeur marchande pourrait représenter une compensation monétaire intéressante pour les producteurs de la Ferme Parentall. De plus, la servitude personnelle pourrait être combinée à des outils complémentaires tels que le Programme de dons écologiques, offrant ainsi des avantages fiscaux additionnels. Par exemple, des crédits d'impôt pourraient être inclus pour les coûts liés à la conservation. Cela pourrait aussi permettre une inscription officielle au Registre des aires protégées du Québec, si le projet répond aux critères demandés.

- **Adaptabilité au contexte local :**
  La servitude personnelle permet d'aligner les actions de conservation avec les besoins spécifiques de la Ferme Parentall. Les producteurs pourraient, par exemple, continuer à pratiquer certaines activités agricoles dans des zones désignées (en dehors des zones restaurées), comme la production de cultures à faible impact environnemental ou la production fruitière dans la zone tampon ceinturant l'espace de liberté, tout en maintenant les fonctions écologiques du site restauré.

En somme, la servitude personnelle, sur 25 ans ou à perpétuité, associée à un partenariat solide avec un organisme de conservation, représente un scénario idéal pour pérenniser les mesures de restauration à la Ferme Parentall. Elle répond aux besoins des producteurs, assure une flexibilité dans les usages et garantit la durabilité écologique à long terme. Cette approche équilibrée peut également servir de modèle pour d'autres projets similaires en milieu agricole.

6.2 Outils de pérennisation pertinents pour les projets de restauration en milieu agricole

De manière générale, les outils de pérennisation utilisés dans le contexte des projets de restauration de milieux humides et hydriques en territoire agricole doivent être flexibles, adaptés aux réalités agricoles spécifiques (par région ou selon la position dans le bassin versant), et conçus pour favoriser l'engagement des producteurs. Des solutions comme les servitudes personnelles ou réelles, les dons écologiques, ou encore les fiducies d'utilité sociale peuvent convenir, mais leur pertinence varie selon les spécificités du projet, des objectifs de conservation et des contraintes des propriétaires.

Le choix de l'outil doit également tenir compte des coûts, de la complexité des démarches et des incitatifs financiers associés. Une approche combinant plusieurs outils, comme une servitude associée à un don écologique, pourrait maximiser les bénéfices pour les propriétaires tout en assurant la durabilité des mesures de conservation.

Des initiatives récentes, comme l'activité La conservation de la nature en terres privées au Québec organisée par l'Université Laval en 2022, recommandent une réforme législative pour surmonter les flous juridiques et rendre les mesures de conservation plus accessibles (Racicot, 2022). Ces discussions mettent en lumière les défis liés à la promotion et à l'acceptabilité des mesures de conservation auprès des propriétaires privés. Les experts consultés lors de cette activité affirment également qu'il serait pertinent

de s'inspirer des *conservation easements* appliqués ailleurs au Canada, qui sont perçus comme des outils efficaces, simples et intuitifs, adaptés aux réalités agricoles, incluant la restauration de sites écologiques (Racicot, 2022). Un *conservation easement* (ou servitude de conservation) est un accord légal entre un propriétaire foncier et une organisation de conservation (publique ou privée) qui limite les droits de développement sur une portion de la propriété afin de protéger ses valeurs écologiques, tout en permettant au propriétaire de conserver la propriété du terrain. Cela permet de préserver des terres agricoles ou naturelles, tout en offrant des avantages fiscaux et en garantissant la pérennité des mesures de conservation.

7. Mécanismes de financement dans le cadre du projet et pour les autres travaux de restauration de manière générale en milieu agricole

Dans le contexte de projets de restauration écologique de milieux humides et hydriques en zones agricoles, fournir un soutien financier pour l'implantation de mesure de restauration ainsi que pour assurer la pérennisation des projets constitue un aspect important à considérer pour favoriser l'acceptabilité ainsi que l'adhésion des producteurs à de tels projets. Au Québec, plusieurs programmes existent pour financer la planification et l'implantation de mesures de restauration, mais le nombre de programmes et de mécanismes destinés à fournir de l'aide financière pour compenser les pertes de revenus par les retraits ou adaptation de culture au profit des milieux hydriques et humides est limité. L'annexe O présente la description détaillée 1) des programmes accessibles directement aux agriculteurs, soit Prime Vert, la rétribution des pratiques agroenvironnementales de La Financière agricole du Québec, une initiative basée sur l'augmentation de la résilience du territoire face aux changements climatiques de Canards illimités, les compensations financières d'ALUS Montérégie, les programmes de mise en valeur de la biodiversité en milieu agricole la Fondation de la Faune du Québec, ceux de restauration et de création des milieux humides et hydriques (PRCMHH) du MELCCFP et de Carbone Riverain; et 2) des programmes ou mécanismes accessibles seulement par les municipalités ou MRC, soit le PRAFI (Programme de résilience et d'adaptation face aux inondations), le Programme Accélérer la transition climatique locale (ATCL), le financement de la mise en oeuvre des plans régionaux des milieux humides et hydriques (PRMHH) via le Fonds bleu et les rétributions de biens et services écosystémiques.

À noter que plusieurs personnes avec une expertise professionnelle dans le domaine ont été contactées afin de valider l'information concernant les différents outils et programmes que nous avons pu consulter sur le web. Parmi les experts consultés, il y a Jean-François Bissonnette, professeur agrégé en géographie à l'Université Laval, ainsi que Faby-Anne Mimeault, doctorante à la Chaire de recherche du Canada en économie écologique. Cette section documente les perspectives pour définir une approche de financement et de pérennisation combinée qui pourrait s'appliquer au projet de la Ferme Parentall.

Les orientations proposées pour la Ferme Parentall s'appuient sur trois années d'échanges avec des experts, d'analyses de programmes de financement et de pérennisation, ainsi que sur les rétroactions des producteurs agricoles, notamment à travers des entretiens semi-dirigés. L'objectif est de développer une approche réaliste et réplicable, adaptée aux besoins des producteurs, tout en assurant la durabilité des

mesures de restauration du cours d'eau. Évidemment, la mise en œuvre de cette approche doit se faire en tout respect des besoins et des exigences exprimées par les propriétaires de la Ferme Parentall (voir section 6.1.

7. 1 Pérennisation des mesures de restauration

À court terme, **la meilleure option consiste à établir une servitude personnelle avec un organisme de conservation** tel que Nature Avenir ou Canards illimités (ou une combinaison des deux). Cette servitude pourrait être accompagnée d'un financement pour les producteurs pour la mise en œuvre d'un mécanisme de pérennisation via le programme Protéger les habitats – Volet Principal de la Fondation de la faune du Québec, qui couvre 75 % des dépenses admissibles, ou par le PRCMHH, qui finance 100 % des coûts. Toutefois, pour ce qui est du PRCMHH, les fonds disponibles à l'échelle régionale sont limités (47 290 $ dans la MRC Pierre-De Saurel), mais l'adoption du projet de loi 81 pourrait permettre une plus grande flexibilité dans l'allocation des fonds.

À moyen terme, une souscription au programme de don écologique pourrait être envisagée pour maximiser les incitatifs financiers et fiscaux. Toutefois, la compatibilité entre ce programme et d'autres sources de financement (notamment pour une servitude personnelle) demeure à clarifier.

Les discussions avec une trentaine de producteurs agricoles ont révélé que l'application d'une servitude soulève certaines réticences, notamment en raison d'un manque de compréhension et d'une confusion avec le concept d'expropriation (Racicot, 2022). Ce constat souligne l'importance d'une sensibilisation accrue sur les avantages et les modalités des servitudes de conservation. Parmi les options évaluées dans le cadre des entretiens semi-dirigés, une entente contractuelle renouvelable qui imposerait aux producteurs une obligation de ne pas cultiver ni de modifier les aménagements tout en maintenant leur autonomie foncière a reçu le meilleur taux d'acceptation.

7.2 Soutien financier pour les mesures de restauration et le retrait durable des cultures dans l'espace de liberté

Les mesures de restauration additionnelles sur le site de la Ferme Parentall pourraient être financées par différents programmes :

- Le PRCMHH, qui couvre 100 % des dépenses admissibles, bien que son financement demeure limité à l'échelle régionale.
- Le programme Prime-Vert et La Financière agricole du Québec, qui subventionnent jusqu'à 75 % des coûts pour les plantations et modifications aux ouvrages hydroagricoles.
- Le programme Protéger les habitats (avec l'application d'une servitude) ou le PRCMHH pourrait financer le retrait de cultures (bien qu'il subsiste des incertitudes quant à l'admissibilité de cette option au PRCMHH).

Une approche plus large pourrait être envisagée à travers la réactivation du comité de bassin versant Pot-au-Beurre de l'UPA, afin de structurer un projet de restauration à l'échelle territoriale. Cela permettrait d'accéder au programme Mise en valeur de la biodiversité en milieu agricole de la Fondation de la Faune

et de travailler de concert avec l'OBV Yamaska et un ou des organismes de conservation pour assurer une approche cohérente et durable.

Finalement, le financement de l'entretien et du suivi des aménagements pourrait être pris en charge par Protéger les habitats ou le PRCMHH, garantissant ainsi une gestion à moyen terme des investissements réalisés.

7.3 Détermination des modalités de l'aide financière pour le retrait des cultures dans l'espace de liberté

Les entretiens semi-dirigés avec une trentaine de producteurs révèlent qu'il n'existe pas de consensus clair sur la méthode optimale pour déterminer les aides financières liées au retrait de cultures aux abords d'un cours d'eau. Les trois approches qui sont généralement utilisées, soit la méthode basée sur la valeur foncière, la méthode basée sur le coût d'opportunité (revenu agricole perdu) ou la méthode basée sur les services écosystémiques rendus sont tous perçus comme moyennement pertinentes parmi les producteurs rencontrés.

Pour la Ferme Parentall, deux estimations de l'aide financière ont été réalisées :

- Méthode du revenu net perdu : Somme des revenus nets/hectare multipliée par 25 ans, indexée à 2 % par année → 44 700 $/ha.
- Méthode basée sur la valeur marchande des terres en Montérégie Est (2024) → 55 700 $/ha.

Ces montants sont cohérents avec les évaluations de Nature Action (2020), qui estimaient les compensations entre 23 900 $ et 48 300 $/ha selon des critères similaires. De plus, Buffin-Bélanger et coll. (2015) évaluaient en 2015 à 1 000 $/ha/an la valeur des services écologiques rendus par un cours d'eau et son milieu riverain.

Finalement, concernant le mode de versement des aides financières, les résultats des questionnaires indiquent que les producteurs préfèrent soit les paiements annuels indexés sur une période déterminée ou un modèle hybride avec des paiements annuels dans une première phase, puis un versement unique et définitif dans un deuxième temps.

8. Portrait du potentiel de restauration de cours d'eau en milieu agricole, au niveau écologique et socio-économique

L'objectif de cette section est d'évaluer les gains écologiques et socio-économiques potentiels découlant de la restauration des cours d'eau agricoles, incluant leur plaine alluviale. Plutôt que de dresser un inventaire exhaustif des pratiques agroenvironnementales et des ouvrages hydroagricoles qui permettent de mieux gérer les flux hydrologiques, sédimentaires et d'intrants (ex. : culture de couverture, optimisation des fertilisants, bassins de rétention, avaloirs), nous nous concentrerons ici sur les approches qui visent directement à restaurer les processus hydrogéomorphologiques (HGM) dans les milieux hydriques.

Nous structurerons notre analyse en fonction des grandes catégories de processus HGM impliqués dans le fonctionnement des cours d'eau agricoles : (1) la connectivité hydrologique latérale et verticale (ex. :

connexion avec la nappe phréatique et avec les zones humides riveraines) (2) la connectivité hydrologique longitudinale (ex. : continuité hydrosédimentaire amont aval) (3) la mobilité latérale (ex. : formation des méandres) et (4) la végétation riveraine en considérant son rôle clé dans la dynamique HGM des cours d'eau, particulièrement ceux de basses terres.

L'espace de liberté des cours d'eau sera abordé séparément, car il constitue une approche intégrée qui englobe plusieurs de ces processus simultanément et représente une stratégie particulièrement holistique en matière de restauration par les processus.

Il est pertinent de rappeler que les mesures ou approches de restauration ici présentées ne sont pas nécessairement applicables dans tous les contextes, dépendant de l'état initial du cours d'eau et du niveau d'acceptabilité des propriétaires et des communautés du bassin versant.

Pour plus de détails sur les différentes mesures spécifiques de restauration, leurs impacts potentiels et sur leurs modalités de conception et d'implantation, on peut se référer au guide web de Restauration et de méthodes alternatives à l'entretien des cours d'eau de l'Association des gestionnaires régionaux des cours d'eau du Québec (AGRCQ) qui verra le jour au cours de l'année 2025.

8.1 Amélioration de la connectivité hydrologique latérale et verticale

La connectivité hydrologique latérale et verticale désigne les échanges d'eau entre un cours d'eau et son milieu riverain ainsi qu'avec les eaux souterraines (hyporhéiques et aquifères) (Figure 18). Ces interactions jouent un rôle clé dans la régulation des flux hydrologiques, la dynamique de transport sédimentaire et la qualité de l'eau. Une connectivité hydrologique latérale et verticale accrue permet aux cours d'eau de mieux interagir avec le milieu sédimentaire adjacent (c.-à-d. leur plaine alluviale) ou sous-jacent (i.e., lit), favorisant l'infiltration et le stockage temporaire de l'eau, la filtration des sédiments et des nutriments, et la régulation des crues et des étiages. Une faible connectivité, souvent causée par des structures artificielles, des remblais ou des pratiques agricoles intensives en zone riveraine, limite ces échanges et entraîne une dégradation des fonctions écologiques du système fluvial.

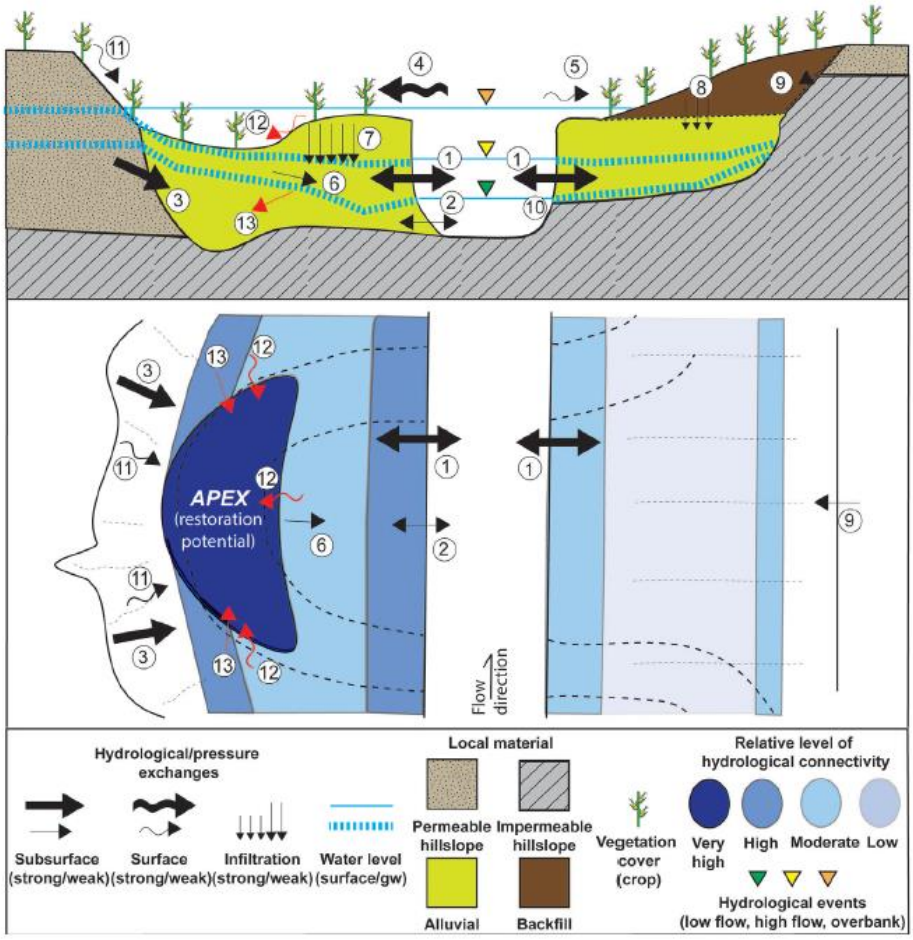


Figure 18. Modèle conceptuel qui illustre la variabilité des échanges hydrologiques latéraux qui peuvent opérer entre un cours d'eau linéarisé de milieu agricole et son milieu riverain : (1) stockage transitoire dans les berges pendant la période de crue et (2) pendant la période de faible débit; (3) écoulements souterrains à partir d'un versant perméable; (4) écoulement de surface sur une plaine non perturbée et (5) remblayée; (6) écoulements souterrains vers la limite de la plaine d'inondation lorsque le gradient hydraulique orienté vers le cours d'eau est rétabli; (7) infiltration dans la plaine non perturbée; (8) infiltration limitée dans la plaine remblayée; (9) écoulements souterrains limités provenant d'un versant imperméable; (10) échanges limités entre les eaux de surface et les eaux souterraines en raison de la présence d'une unité de berge imperméable; (11) ruissellement de surface provenant du versant; (12) ruissellement de surface et (13) écoulements souterrains provenant de la plaine d'inondation environnante vers la dépression de l'apex d'un méandre abandonné pendant les évènements hydrologiques. Dans l'ensemble, ces mécanismes définissent des zones de connectivité hydrologique très élevée à modérément faible dans la plaine d'inondation historique des cours d'eau redressés, la zone focale étant située à l'apex du méandre abandonné. Les flèches rouges représentent les mécanismes d'échange directement associés à la présence de l'apex de l'ancien méandre. (Tirée de Marchand et coll. 2022)

8.1.1 Mesures de restauration associées à la connectivité latérale et verticale

Les mesures de restauration visant à améliorer la connectivité hydrologique latérale et verticale dans les cours d'eau agricoles incluent diverses stratégies permettant de restaurer ou d'améliorer les interactions

entre le cours d'eau, les milieux riverains et les eaux souterraines. Le **retrait des pratiques agricoles** ou **l'adoption de meilleures pratiques agroenvironnementales en zone riveraine** permet de réduire le compactage des sols, favorisant ainsi l'infiltration de l'eau et réduisant le ruissellement direct des intrants agricoles (Morra et coll. 2023). L'**excavation ou le déblai de la zone riveraine**, en particulier dans les plaines alluviales remblayées, restaure la capacité d'inondation naturelle du site et améliore le stockage temporaire de l'eau lors des crues. La **création d'un chenal à deux niveaux** est une mesure utilisée pour restaurer partiellement la plaine inondable (Paradis et Biron, 2017), notamment dans les zones où une expansion latérale complète est impossible. Le **reméandrage, qu'il soit actif ou passif,** augmente la surface de contact entre l'eau et les berges, ce qui favorise les échanges latéraux et aide à la recharge des nappes phréatiques.

Le **retrait de structures artificielles en berge**, telles que les enrochements, murs et digues, est une autre mesure clé. Cette action réduit l'effet de confinement du chenal et permet une meilleure interaction hydrologique avec les aquifères et la plaine alluviale. Le **reprofilage des berges**, passant d'une berge verticale à une berge étagée, accroît également la surface de contact entre le cours d'eau et ses berges, facilitant ainsi les échanges avec les nappes phréatiques. Enfin, **l'ajout de bois mort dans le cours d'eau** crée des zones de retenue qui favorisent l'infiltration latérale et verticale, contribuant ainsi au stockage temporaire de l'eau et à l'échange avec les nappes phréatiques. Ces différentes mesures visent toutes à renforcer la connectivité hydrologique, en améliorant les processus naturels du système fluvial et en renforçant la résilience des écosystèmes agricoles.

8.1.2 Gains écologiques et socio-économiques potentiels

Les gains écologiques et socio-économiques potentiels associés à la restauration de la connectivité latérale et verticale dans des cours d'eau agricoles sont nombreux et variés. Sur le plan écologique, ces mesures favorisent le stockage temporaire des sédiments et des nutriments en période de crue, tout en favorisant l'accumulation de matière organique dans les sols riverains, ce qui améliore la qualité de l'eau en limitant l'exportation de polluants vers l'aval et en contribuant au contrôle des émissions de gaz à effet de serre. La régulation des crues et des étiages est un autre gain significatif, car, en période de crue, la capacité de rétention accrue réduit l'intensité des inondations en aval, et en période d'étiage, la recharge des nappes assure un débit de base plus stable. De plus, l'augmentation des échanges hyporhéiques favorise la transformation et l'élimination de certains polluants, comme les nitrates, le phosphore et les contaminants organiques, améliorant ainsi la qualité de l'eau.

La création ou la restauration de milieux humides riverains est également un bénéfice potentiel, augmentant la biodiversité et améliorant les services écosystémiques tels que la filtration de l'eau, la séquestration du carbone et la fourniture d'habitat pour la faune. En outre, l'amélioration de la qualité des habitats aquatiques, grâce à la diversification des structures d'écoulement et à la création de refuges pour la faune aquatique, renforce la résilience de ces écosystèmes.

D'un point de vue socio-économique, la restauration de la connectivité hydrologique latérale et verticale dans les cours d'eau agricoles peut permettre de réduire les coûts de traitement de l'eau potable en diminuant la charge en sédiments et en nutriments à traiter par les municipalités. Elle peut également engendrer des économies collectives dans les dépenses associées à la gestion des aléas d'inondation dans un bassin versant. Pour les producteurs eux-mêmes, la création d'habitats propices aux espèces pollinisatrices en zones riveraines peut être bénéfique, en soutenant les insectes et les oiseaux essentiels à la production agricole en termes de potentiel de pollinisation et de contrôle des ravageurs. Dans certains

contextes, l'accroissement des réserves d'eau souterraine peut contribuer à rendre les entreprises agricoles plus résilientes en période de stress hydrique.

Les mesures telles que le retrait de cultures et la végétalisation passive impliquent des coûts relativement modérés. Cependant, des travaux plus complexes, comme le déblai ou le retrait de structures artificielles, entraînent des coûts plus élevés en raison de l'utilisation de machinerie et de la mise en place de structures complexes, nécessitant des investissements plus importants.

8.1.3. Enjeux potentiels et défis

L'un des principaux enjeux associés à la restauration de la connectivité hydrologique latérale et verticale dans un cours d'eau agricole est la diminution potentielle de la productivité des sols en raison de conditions de saturation d'eau souterraine accrues. Par exemple, le retrait de digues ou d'infrastructures imperméabilisantes le long des berges, qui permet de rétablir la dynamique naturelle du cours d'eau, peut entraîner un rehaussement de la nappe phréatique ou une accumulation d'eau dans les sols. Cela modifie les conditions de drainage des terres agricoles et peut provoquer une saturation excessive du sol, ce qui est défavorable aux espèces cultivées, particulièrement celles sensibles à l'excès d'humidité, comme les cultures de céréales ou les légumes racines. Dans certains cas, cela peut rendre certaines terres inutilisables pour l'agriculture ou nécessiter une adaptation des cultures en choisissant des variétés plus tolérantes à l'humidité. Dans d'autres cas, il peut être nécessaire d'envisager le retrait de certaines cultures pour éviter des pertes économiques.

La complexité d'accès aux sorties de drains agricoles peut aussi représenter un obstacle pour la mise en œuvre des projets visant à restaurer la connectivité latérale. Un réaménagement des sorties de drains ou des corridors d'accès peut être nécessaire pour maintenir l'efficacité du drainage agricole et garantir l'adhésion des producteurs au projet.

En ce qui concerne les chenaux à deux niveaux, il est important de respecter un ratio optimal entre la largeur du chenal et la zone inondable pour maximiser la sédimentation et la rétention des nutriments. Hallberg (2024) recommande un ratio de 3 à 5 fois la largeur du chenal pour atteindre ces objectifs. De plus, il est important de rappeler que certaines mesures de restauration lourdes, comme le reméandrage ou la création de chenaux à deux niveaux, engendrent des coûts substantiels. Ces interventions nécessitent une planification soignée et un financement adéquat pour être mises en œuvre efficacement.

Lorsque des déblais en rives ou dans plaine alluviale sont prévus, une évaluation fine des conditions pédologiques avant toute intervention est essentielle. Selon Booth et Loheide (2010), un retrait excessif des dépôts superficiels peut assécher le sol riverain et réduire la production végétale, puisque cela peut diminuer la réserve d'humidité disponible pour les racines des plantes, entraînant ainsi un régime de sol plus sec, surtout en période sèche. Un autre défi potentiel associé aux travaux d'excavation et de déblai est la prolifération d'espèces envahissantes. Ces types de travaux peuvent créer des conditions favorables à l'apparition d'espèces floristiques nuisibles à l'agriculture. Il est donc recommandé de surveiller la machinerie utilisée et de prendre des mesures pour limiter cette prolifération. Une végétalisation active avec des espèces indigènes peut parfois également être nécessaire dans cet espace excavé qui devient moins propice à l'agriculture.

Toutefois, il est important de souligner que dans le contexte de projets de restauration en milieu agricole, la prolifération des espèces exotiques est inévitable considérant les intenses perturbations historiques. Une forte dominance des espèces exotiques ne veut pas dire à tout coup qu'un projet de restauration en

milieu agricole est un échec. Un cadre de réflexion innovant vis-à-vis les inventaires floristiques en contexte de projet de restauration en milieu agricole est proposé à l'annexe P.

8.2 Amélioration de la connectivité hydrologique longitudinale

La connectivité longitudinale désigne la continuité des écoulements et des processus HGM tout au long du cours d'eau, sans interruption causée par des obstacles physiques ou hydrauliques. Elle influence la migration des sédiments, le transport des nutriments et la libre circulation des organismes aquatiques (Figure 19). La fragmentation longitudinale d'un réseau hydrique peut être causée par des infrastructures humaines telles que des ponceaux sous-dimensionnés, des seuils, des barrages ou des digues, entraînant une altération des dynamiques fluviales, une accumulation excessive de sédiments en amont et une érosion accrue en aval. Restaurer cette connectivité permet de rétablir un équilibre morphologique et écologique essentiel au bon fonctionnement des écosystèmes aquatiques.

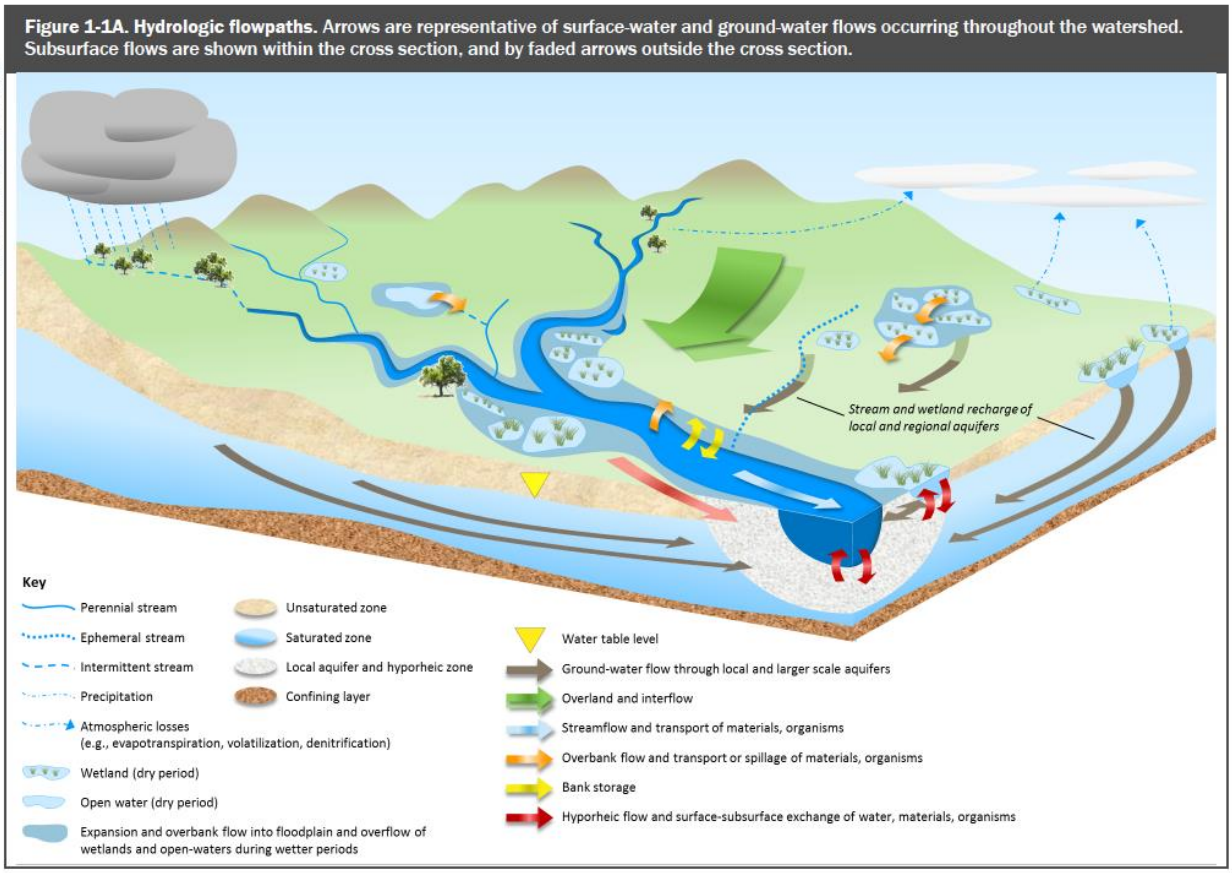


Figure 19 Modèle conceptuel qui illustre la variabilité des échanges hydrologiques latéraux et longitudinaux qui peuvent opérer au sein d'un bassin versant (Tirée de EPA, 2015)

8.2.1 Mesures de restauration associées à la connectivité longitudinale

Plusieurs mesures peuvent être mises en place pour restaurer la connectivité longitudinale dans un cours d'eau agricole. Le **retrait ou le remplacement de ponceaux sous-dimensionnés**, ainsi que le **retrait de seuils et de barrages**, sont des interventions qui permettent de rétablir les connexions hydrauliques et

sédimentaires et favorisent la migration des organismes aquatiques, comme l'ont démontré Hester et Doyle (2008). Ces actions permettent de lever les obstacles physiques et d'assurer un écoulement fluide tout au long du cours d'eau.

L'**ajout de bois mort** dans un cours d'eau en incision, comme dans un ravin, est une mesure bénéfique, bien que non pérenne. Ces ouvrages de rétention aident à mieux distribuer les vitesses, dissipant ainsi l'énergie des écoulements, ce qui contribue à réduire l'incision du chenal et à restaurer un profil longitudinal plus équilibré. L'**ajout de sédiments** dans des cours d'eau trop larges ou incisés, comme dans les approches *stage zero* (Powers et coll., 2018), est également une option. Bien que cette méthode puisse être efficace pour restaurer la dynamique du chenal, elle est coûteuse et peut entraîner des risques de transport excessif des sédiments.

8.2.2 Gains écologiques et socio-économiques potentiels

La restauration de la connectivité hydrologique longitudinale peut générer plusieurs gains écologiques et socio-économiques. Du point de vue écologique, cette approche permet une régulation des processus HGM, notamment le transport sédimentaire et les inondations. Cela contribue à réduire les zones d'accumulation excessive de sédiments et améliore la stabilité relative du chenal, favorisant ainsi un écoulement plus naturel. En période de crue, la restauration peut également favoriser une réduction des pics de turbidité, car moins de sédiments sont mis en suspension, ce qui améliore la qualité de l'eau et réduit l'impact des crues sur les habitats aquatiques. La diversification des faciès d'écoulement et l'amélioration des corridors de migration peuvent créer des habitats variés qui favorisent la biodiversité aquatique et augmentent les aires de reproduction pour les espèces piscicoles, contribuant ainsi à la résilience des écosystèmes aquatiques (Sundermann et coll., 2011; Tonkin et al., 2014; Tummers et coll., 2016).

Sur le plan socio-économique, la restauration de la connectivité longitudinale dans les flux hydrosédimentaires peut entraîner une réduction de l'érosion des berges en milieu agricole, ce qui limite l'impact sur les sols cultivables situés à proximité du cours d'eau, réduisant ainsi la perte de terres agricoles. De plus, ce type de restauration peut également diminuer l'ensablement excessif au droit des sorties de drains agricoles, améliorant ainsi les conditions de drainage dans les terres cultivables. Un autre gain économique important est la réduction des coûts d'entretien des cours d'eau par les MRC. En effet, certains tronçons peuvent nécessiter moins d'intervention mécanique en raison de l'atteinte d'un état d'équilibre morphologique relatif dans certains tronçons de cours d'eau. Enfin, l'ajout de bois mort, une mesure peu coûteuse et facilement applicable, permet des gains hydrauliques et écologiques avec un investissement minimal, en favorisant des processus naturels d'amélioration de la dynamique du cours d'eau (Wheaton et coll. 2019).

8.2.3 Enjeux potentiels et défis

La restauration de la connectivité hydrologique longitudinale dans un cours d'eau agricole présente plusieurs enjeux et défis potentiels. L'un des principaux défis concerne la gestion des sédiments accumulés historiquement en amont des obstacles retirés. Dans les cours d'eau à pente faible, notamment en tête de bassin versant agricole, ou en présence de ponceaux sous-dimensionnés, le retrait des obstacles peut provoquer une remise en suspension temporaire, mais massive, de sédiments, souvent enrichis en nutriments (Merrits et coll., 2013). Cette remobilisation peut entraîner des impacts négatifs sur la qualité

de l'eau et les écosystèmes en aval. Pour gérer cette situation, des structures de rétention temporaires ou des déblais mécaniques préventifs peuvent être nécessaires pour contrôler le déplacement des sédiments.

Un autre défi est l'impact sur les fosses d'érosion en aval des ponceaux. Dans certains contextes, ces fosses peuvent jouer parfois un rôle écologique important, servant de refuges thermiques pour la faune aquatique. Le rétablissement d'un flux hydrosédimentaire normal entre l'amont et l'aval d'un ponceau par exemple peut entraîner un comblement rapide d'une fosse. Avant toute intervention, il est donc essentiel de réaliser une analyse de leur rôle écologique local afin d'éviter des impacts négatifs sur les habitats aquatiques et déterminer des mesures pour réduire ces impacts.

La perturbation temporaire des terres agricoles représente également un enjeu potentiel. Le rétablissement de la dynamique naturelle du cours d'eau peut entraîner des décrochements de berge pendant la période d'ajustement vers un profil d'équilibre, ce qui pourrait entraîner des pertes de terres agricoles à proximité de la rive. Des mesures de mitigation, telles que la végétalisation ou le reprofilage des berges, peuvent être nécessaires pour minimiser ces perturbations.

Enfin, les coûts variables pour le reprofilage et le remplacement des infrastructures représentent un autre enjeu. Ces coûts dépendent de plusieurs facteurs, tels que les conditions géotechniques (type de substrat), hydrauliques (vitesse d'écoulement, pente) et d'accessibilité des sites, notamment lorsqu'ils sont encaissés dans des ravins, rendant l'accès et les interventions plus complexes et coûteux. Ces défis nécessitent une planification minutieuse et une gestion attentive pour garantir le succès des efforts de restauration tout en minimisant les impacts sur les activités agricoles et les coûts associés.

8.3 Rétablissement des processus de mobilité latérale

La mobilité latérale désigne la capacité d'un cours d'eau à se déplacer latéralement à travers son lit majeur en érodant et en déposant des sédiments. Ce processus naturel est essentiel pour la création et le renouvellement des habitats fluviaux, le maintien d'un équilibre morphologique et la dissipation de l'énergie des écoulements.

En milieu agricole, et particulièrement dans les basses terres du Québec, de nombreux cours d'eau ont été fortement modifiés par des travaux de linéarisation et sont maintenus linéaires par des interventions répétées d'entretien (curage, stabilisation des berges, redressement des chenaux) (Rousseau et coll. 2009). Ces pratiques, mises en place pour améliorer le drainage des terres agricoles, ont entraîné une perte importante des services écologiques rendus par ces cours d'eau. En réduisant leur capacité à se mouvoir naturellement, les rivières ont perdu leur diversité d'habitats, leur capacité d'auto-ajustement et leur rôle de filtre hydrologique et biogéochimique.

La restauration de la mobilité latérale vise à réintroduire une dynamique naturelle d'érosion et de dépôt, tout en minimisant les impacts sur les activités agricoles environnantes.

8.3.1 Mesures de restauration associées à la mobilité latérale

La restauration de la mobilité latérale d'un cours d'eau implique plusieurs mesures visant à réintroduire une dynamique naturelle d'érosion et de dépôt tout en minimisant les impacts sur les terres agricoles environnantes. L'**excavation mécanique de nouveaux méandres** est une méthode qui permet de recréer une sinuosité naturelle du chenal, lorsque l'état historique du cours d'eau témoigne d'une telle conception

avant sa linéarisation, augmentant ainsi la variabilité des écoulements. Cette approche favorise une meilleure distribution des sédiments et crée de nouveaux habitats aquatiques, essentiels à la biodiversité fluviale. Le **reméandrage passif, par l'ajout de bois mort en tant que déflecteurs hydrauliques**, est une autre technique qui permet de stimuler la migration latérale des cours d'eau sans nécessiter d'excavation lourde. Cette approche, désignée sous le terme de « bank blasters » selon Wheaton et coll. (2019), modifie les courants d'écoulement et favorise l'érosion sélective, ce qui permet de restaurer naturellement la mobilité latérale tout en créant des zones de dépôt de sédiments.

Dans les situations où l'expansion latérale est un facteur limitant, la **création d'un chenal à deux niveaux avec banquettes latérales** offre un compromis entre stabilisation et restauration. Ce type de chenal sinueux permet de dissiper l'énergie des écoulements, réduisant ainsi l'incision verticale tout en favorisant un certain degré de mobilité latérale. Enfin, **le retrait de structures stabilisatrices sur les berges**, telles que les enrochements ou les murs de soutènement, est une mesure essentielle pour restaurer la dynamique naturelle d'érosion et de dépôt des berges. Cette intervention permet aux berges de retrouver leur capacité à s'adapter naturellement aux variations du cours d'eau, favorisant le maintien des habitats aquatiques et soutenant l'autoajustement du chenal au fil du temps.

8.3.2 Gains écologiques et socio-économiques

Les mesures visant à restaurer la mobilité latérale des cours d'eau agricoles peuvent engendrer plusieurs gains écologiques et socio-économiques significatifs. Tout d'abord, ces mesures permettent une augmentation des superficies de nouveaux milieux hydriques, créant ainsi des zones permanentes propices à la biodiversité. Ces habitats variés favorisent le développement d'une faune et d'une flore aquatiques diversifiées. La diversification des faciès d'écoulement contribue également à cette dynamique, en augmentant la variabilité hydrodynamique avec la création de zones calmes et rapides, bénéfiques pour différentes espèces aquatiques en termes de régénération, d'alimentation et de reproduction.

Un autre gain majeur est l'amélioration des échanges hyporhéiques et rivière-aquifère, qui permet une meilleure filtration et épuration naturelle de l'eau. Cette dynamique favorise la réduction des contaminants et des nutriments excédentaires, contribuant ainsi à une meilleure qualité de l'eau. Le meilleur équilibre morphologique du chenal est également un gain important. En réduisant l'incision et en rétablissant une répartition plus naturelle des zones de dépôt et d'érosion, on améliore la stabilité des berges à long terme, renforçant la résilience du cours d'eau face aux variations du régime hydrologique.

Enfin, la restauration de la mobilité latérale peut entraîner une réduction des coûts associés à l'entretien des cours d'eau, car un chenal en équilibre nécessite moins d'interventions mécaniques telles que le curage ou la stabilisation des berges.

8.3.3 Enjeux potentiels et défis

La restauration de la mobilité latérale des cours d'eau présente plusieurs enjeux potentiels pour les infrastructures agricoles et la gestion des terres. Tout d'abord, l'expansion latérale des méandres peut avoir des impacts sur les infrastructures agricoles, notamment sur les sorties de drains agricoles, qui peuvent être compromises par le mouvement naturel du cours d'eau. Cela peut nécessiter un réaménagement de ces infrastructures pour maintenir leur efficacité et assurer une gestion correcte de l'eau sur les parcelles agricoles.

Un autre enjeu important est la perte de superficies cultivables. Si la bande riveraine est respectée conformément aux normes réglementaires (souvent de l'ordre de 3 mètres), la mobilité latérale du cours d'eau pourrait empiéter sur les terres cultivées adjacentes. Cette perte de surface cultivable peut être perçue comme une contrainte par les producteurs. Des mesures d'accommodement pour compenser cette perte de terres agricoles, telles que des compensations financières ou des ajustements de pratiques agricoles, peuvent être proposées pour minimiser l'impact sur la productivité des exploitations agricoles.

Pour assurer un lien de confiance étroit entre les responsables de projets de restauration et les producteurs agricoles, il est absolument essentiel d'être transparent sur le risque inhérent de pertes de terres associées aux mesures de restauration promouvant un accroissement de la mobilité latérale des cours d'eau. L'intégration de mesures de mitigation additionnelles peut constituer un moyen d'assurer la coexistence entre les objectifs de restauration écologique et les besoins agricoles. Des stratégies telles que l'élargissement des bandes riveraines, le retrait des cultures dans l'espace de liberté du cours d'eau, et le réaménagement des infrastructures agricoles (notamment l'adaptation des drains) doivent être priorisées. Ces mesures permettront de trouver un équilibre entre la restauration des processus naturels du cours d'eau et les exigences de la production agricole, tout en maintenant les liens de confiance avec les producteurs.

8.4 Accroissement de la végétation riveraine

La végétation riveraine joue un rôle clé dans le fonctionnement hydrogéomorphologique des cours d'eau et de leurs plaines alluviales. Elle influence directement la rétention des sédiments, la filtration des polluants, la stabilisation des berges et la régulation thermique des milieux aquatiques.

Dans de nombreux bassins versants agricoles, la végétation riveraine a été largement réduite ou éliminée en raison des pratiques agricoles intensives et des interventions d'entretien des cours d'eau. Cette perte a contribué à une augmentation de l'érosion des berges, une diminution de la qualité de l'eau et une dégradation des habitats aquatiques et terrestres. Restaurer la végétation riveraine permet de rétablir ces fonctions essentielles et d'améliorer la résilience des écosystèmes fluviaux face aux stress hydrologiques et climatiques.

8.4.1 Mesures de restauration associées

Le **retrait des pratiques agricoles et/ou le retrait d'ouvrages de stabilisation artificielle des berges sont** des mesures qui permettent de supprimer les barrières physiques qui entravent la dynamique naturelle de la végétation riveraine. Cela permet aux espèces adaptées aux conditions hydrodynamiques locales de se rétablir et de coloniser naturellement les berges, contribuant ainsi à stabiliser le sol et à favoriser la régénération des habitats.

Une mesure complémentaire au retrait des pratiques ou des structures anthropiques est la **végétalisation passive ou active de la zone riveraine ou de la plaine alluviale**. La végétalisation passive consiste à permettre l'établissement spontané d'une végétation indigène, en laissant les plantes s'installer naturellement selon les conditions locales, ce qui favorise la biodiversité et la résilience de l'écosystème. À l'inverse, la végétalisation active implique l'implantation d'espèces spécifiques, choisies pour accélérer la stabilisation des berges, limiter l'établissement des espèces exotiques nuisibles ou envahissantes et maximiser les bénéfices écologiques, comme la filtration des polluants, la rétention des sédiments, et la

réduction de l'érosion ou bien l'accroissement de l'abondance et de la diversité des espèces floristiques indigènes.

Le choix d'une stratégie de végétalisation adéquate sur un site de restauration en milieu agricole dépend de plusieurs facteurs (objectifs spécifiques de la restauration, échéancier, types de perturbations locales et dans le bassin versant, besoins des producteurs, coûts des interventions). Une réflexion des éléments à considérer dans un processus décisionnel pour le choix d'une stratégie de végétalisation est proposée à l'Annexe Q.

8.4.2 Gains écologiques et socio-économiques attendus

Du point de vue écologique, ces mesures favorisent une augmentation de la biodiversité floristique et faunique en créant des habitats variés pour une large gamme d'espèces végétales et animales. Cela permet de restaurer des équilibres écologiques qui ont été perturbés par les pratiques agricoles et l'aménagement des cours d'eau. Par ailleurs, les plaines alluviales, même lorsqu'elles sont dégradées, possèdent souvent une forte connectivité hydrologique avec le cours d'eau, ce qui peut permettre la régénération naturelle de milieux humides riverains (Marchand et coll. 2022). Ces milieux sont essentiels à la filtration de l'eau, à la protection des habitats et à la régulation du cycle de l'eau.

La restauration de la végétation riveraine (surtout arbustive ou arborescente) permet également la création de refuges thermiques en milieu aquatique, en réduisant les températures maximales estivales grâce à l'ombrage des canopées riveraines. Cela est particulièrement bénéfique pour les espèces aquatiques sensibles aux hausses de température, telles que certains poissons. De plus, la végétation riveraine joue un rôle clé dans la fixation des nutriments et des sédiments en suspension et dans la séquestration du carbone, contribuant ainsi à améliorer la qualité de l'eau,à réduire la turbidité et diminuer les gaz à effet de serre, ce qui profite à la fois à la faune aquatique, à l'agriculture et à la société en général.

Un autre gain important est la réduction de l'exportation des sédiments et la limitation de l'érosion fluviale, car les racines des plantes stabilisent les berges et limitent le ruissellement de surface. Certaines espèces excellent plus que d'autres pour fournir ces gains. Cela contribue à préserver les terres agricoles et à réduire la perte de sols. La végétation riveraine bien développée offre également des avantages socio-économiques, notamment l'accroissement des espèces fauniques utiles à la pollinisation et à la gestion des ravageurs ainsi que la réduction des coûts de gestion liés aux aléas fluviaux. En favorisant la rétention d'eau et l'infiltration, la végétation réduit les pics de crue et la vitesse des écoulements, diminuant ainsi les risques d'inondation et les coûts associés à l'entretien des infrastructures hydrauliques.

Enfin, l'amélioration esthétique du paysage peut représenter un gain pour la qualité de vie des usagers et des communautés riveraines. La création d'espaces naturels et la restauration de zones végétalisées augmentent la valeur esthétique des territoires, favorisant des activités récréatives et de loisirs, et contribuent au bien-être des populations locales. Même si l'implantation de bandes riveraines forestières agricoles ne représente pas nécessairement de bénéfices économiques pour les producteurs, les bénéfices sociaux de ce type de mesure peuvent surpasser les coûts d'implantation et d'entretien par les producteurs agricoles (Simard et coll., 2009).

8.4.3 Enjeux potentiels et défis

L'un des enjeux associés aux mesures de restauration favorables à l'accroissement de la végétation riveraine est la propagation d'espèces exotiques floristiques envahissantes (EFEE). Qu'il s'agisse de végétalisation passive ou active, il est crucial de surveiller l'apparition d'espèces floristiques envahissantes, qui pourraient nuire à la biodiversité locale et perturber les activités agricoles. Ces espèces peuvent rapidement se propager et dominer les habitats naturels, réduisant la diversité végétale et affectant les écosystèmes en place. La période initiale (0-3 ans) après la mise en place des mesures de restauration est cruciale et nécessite un suivi floristique pour s'assurer que la végétation évolue vers un état écologique souhaité.

Un autre défi est le risque de prolifération d'espèces fauniques nuisibles pour l'agriculture, comme les rats musqués, qui peuvent profiter des nouveaux habitats créés par la restauration de la végétation riveraine. Cela peut nécessiter des suivis réguliers et des stratégies de gestion adaptés, comme l'implication de trappeurs locaux pour contrôler ces populations et éviter des dommages aux infrastructures agricoles.

Un autre enjeu est le conflit potentiel avec les activités agricoles, notamment l'augmentation de la végétation riveraine qui peut compliquer l'accès aux sorties de drains et entraver la circulation de la machinerie agricole. Cela peut engendrer des contraintes logistiques et nécessiter des ajustements dans les pratiques agricoles pour garantir une cohabitation entre les mesures de restauration et les activités agricoles.

Enfin, la nécessité d'un suivi et d'un entretien à long terme est essentielle. La gestion de la végétation riveraine doit s'inscrire dans une approche durable, avec des ajustements réguliers en fonction de l'évolution des conditions écologiques et des besoins des producteurs.

8.5 Implantation d'un espace de liberté : une approche holistique

L'espace de liberté représente une approche holistique de la restauration des cours d'eau agricoles, permettant le rétablissement simultané des différents types de processus HGM et des services écosystémiques qu'ils fournissent. Plutôt que de considérer séparément la connectivité hydrologique latérale, verticale et longitudinale, ainsi que la mobilité fluviale et la végétation, l'espace de liberté intègre ces dynamiques dans une perspective territoriale cohérente, qui peut s'adapter autant à l'échelle d'un tronçon fluvial que d'un bassin versant.

L'importance de l'espace de liberté s'est manifestée de façon concrète à la Ferme Parentall, lors des inondations estivales causées par la tempête Debby en aout 2024. Lors de cet évènement, l'espace de liberté a été submergé pendant plus de 48 heures (Figure 20). Dans un contexte pré-restauration, de telles conditions auraient généré des pertes agricoles importantes, comme l'ont mentionné les producteurs lors des entretiens menés en section 5.3.1. Avant la mise en place de l'espace de liberté, les producteurs auraient subi des pertes de récolte en plus des coûts initiaux pour l'implantation et la gestion de leur culture en début et mi-saison, des coûts de drainage supplémentaires, ainsi qu'un compactage des sols en raison d'un excès d'humidité prolongé. Cependant, dans le cadre du projet de restauration, la présence d'un espace dédié aux processus naturels a permis d'absorber la surcharge hydrique sans subir des pertes économiques. Cette résilience économique, combinée au revenu de la location des terres dans le cadre

du projet obtenu pour le retrait des cultures dans l'espace de liberté, a démontré la valeur stratégique de cette approche en contexte d'évènements extrêmes accentués par les changements climatiques.

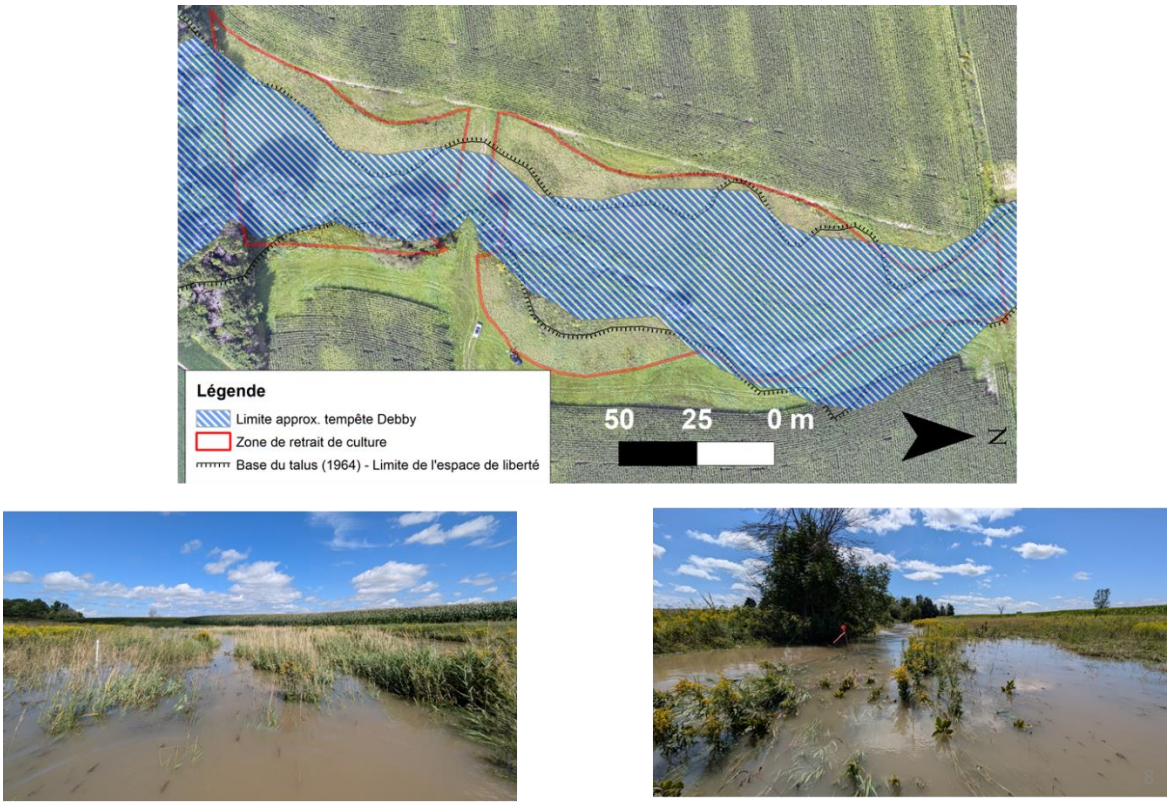


Figure 20. Inondation approximative de l'espace de liberté dans le tronçon restauré de la Ferme Parentall, en aout 2024.

Un élément clé à considérer est que la configuration de l'espace de liberté varie fortement entre les tronçons d'un cours d'eau dans le bassin versant, et même au sein d'un même tronçon. Par exemple, les tronçons T1 et T3 de la branche 13 présentent des configurations spatiales très différentes, tout comme les branches 13 et 17 du cours d'eau (voir figure 6 et annexe B, figure 2). Une meilleure vulgarisation est essentielle auprès des producteurs agricoles afin de leur faire comprendre que l'espace de liberté ne correspond pas toujours à une largeur uniforme par rapport au cours d'eau. Cette variabilité est en réalité une force, permettant d'adapter la restauration aux spécificités locales.

Sur le plan financier, comme discuté dans les sections 6 et 7, des opportunités émergent progressivement pour financer le retrait des cultures dans l'espace de liberté à travers les mécanismes de pérennisation des projets. Par exemple, le PRCMHH et la Fondation de la faune du Québec offrent des avenues potentielles pour soutenir financièrement la mise en œuvre de servitude personnelle. Toutefois, certains enjeux demeurent, notamment l'intégration des sorties de drains et les incertitudes entourant les autorisations de la CPTAQ, qui doivent encore être clarifiées.

Enfin, si des ouvrages hydroagricoles sont aménagés au sein même de l'espace de liberté, des gains d'efficacité peuvent être observés tant sur le plan de l'entretien (moins de sédimentation dans le chenal) que sur le plan écologique. Schilling (2017;2018;2019) a démontré que ce genre d'aménagement (p. ex. sorties de drains aménagés à même un ancien méandre) peut améliorer l'infiltration de l'eau et limiter

l'apport excessif de sédiments vers les cours d'eau. Ce type d'aménagement est également présenté dans le dernier rapport du Centre de référence en agriculture et agroalimentaire du Québec (CRAAQ) comme étant une mesure bénéfique et pertinente pour l'environnement (CRAAQ, 2022)

L'espace de liberté est plus qu'une simple zone tampon : il représente une véritable stratégie de résilience pour les producteurs agricoles, en leur permettant de mieux faire face aux aléas climatiques tout en maximisant la restauration des processus naturels. Il assure un équilibre entre les besoins économiques et environnementaux, facilitant ainsi l'acceptation des mesures de restauration tout en favorisant une approche durable de la gestion des cours d'eau agricoles.

8.6 Expansion et réplicabilité du projet : Collaboration avec le ruisseau Parent (Outaouais)

Un projet de restauration d'un tronçon de cours d'eau agricole linéarisé, inspiré par l'approche du projet "Un Méandre à la fois" et basé sur les processus HGM, a vu le jour en Outaouais. Ce projet, localisé sur le site de la ferme Roots and Shoots à Masham, a été initialement réfléchi par les coordonnateurs du groupe de protection du lac Gauvreau, situé en aval du ruisseau Parent. Suite à des entretiens semi-dirigés réalisés en Outaouais en mars 2023 dans le cadre du projet "Un Méandre à la fois", les coordonnateurs ont invité le responsable du projet "Un Méandre à la fois" à visiter le site en juillet 2023. Cette visite a permis de rencontrer les propriétaires de la ferme Roots and Shoots ainsi que les responsables du Conseil régional de l'environnement et du développement durable de l'Outaouais (CREEDO).

Au cours de cette visite, le principe de restauration basé sur les processus hydrogéomorphologiques a suscité un grand intérêt. Il a été notamment proposé de retirer les cultures de certaines zones de la plaine alluviale, d'implanter des mesures de reméandrage actif, incluant la reconnexion d'anciens méandres et d'ajouter des structures bois morts pour favoriser la migration latérale naturelle du chenal. De plus, un réaménagement des sorties de drains a été envisagé pour mieux gérer les eaux et améliorer la qualité de l'environnement riverain. Les mécanismes de collaboration mis en place dans le cadre du projet "*Un Méandre à la fois*" ont également été reconnus comme pertinents pour ce projet.

Un rapport sommaire, disponible à l'annexe R, a été rédigé à la suite de cette visite de terrain et résume les mesures identifiées et les prochaines étapes du projet. Ce projet a rapidement pris forme grâce à une demande de financement pilotée par le CREEDO et acceptée en 2024 au volet 1 du PRCMHH, assurant ainsi le financement nécessaire aux analyses de préfaisabilité.

Ce projet représente un exemple concret de réplicabilité des approches de restauration dans d'autres contextes agricoles et géographiques, soulignant l'impact positif du projet "*Un Méandre à la fois*" au-delà de la Ferme Parentall. Il illustre aussi comment les synergies de réseautage peuvent être bénéfiques à la mise en place de projets de restauration adaptés aux défis locaux.

9. Recommandations de bonnes pratiques à mettre en place pour la conciliation des usages agricoles et des mesures de restauration de cours d'eau en milieu agricole

9.1 Bilan des entretiens semi-dirigés avec des producteurs agricoles concernant les modalités pertinentes à considérer pour différentes mesures de restauration de cours d'eau agricoles

Les constats des entretiens semi-dirigés avec les producteurs agricoles ont permis d'identifier plusieurs modalités pertinentes pour les mesures de restauration, soit celles qui ont reçu une cote minimale de 2 (modérément pertinentes), selon l'évaluation des producteurs. Concernant le **redimensionnement des ouvrages de traverses**, les modalités jugées pertinentes incluent la capacité de charge en fonction du type de machinerie, la configuration des pentes, la fréquence et les coûts d'entretien, les types de matériaux employés, ainsi que la période d'accessibilité ou d'utilisation. Pour le **retrait des cultures dans la plaine alluviale**, les modalités concernent la configuration des limites extérieures pour faciliter la circulation de la machinerie, la visibilité des limites de la zone de retrait (ex. clôture), et la configuration des voies dégagées pour traverser la zone et accéder aux sorties de drain. En ce qui concerne la **végétalisation** dans la zone riveraine, les modalités pertinentes incluent le mode de végétalisation (naturel/non-assisté ou actif/plantation), le choix des espèces à planter (indigènes, à croissance rapide, fruitiers), la disposition spatiale des types de végétation (herbacées, arbustes, arbres) par rapport aux cultures, ainsi que le suivi et la gestion des espèces nuisibles ou envahissantes. Pour la **reconfiguration des sorties de réseau de drainage**, les modalités incluent l'analyse de l'impact sur la capacité de drainage, la méthode employée pour la déconnexion des drains désuets, le choix de la machinerie utilisée, l'accessibilité aux nouvelles sorties de drain, et la fréquence d'entretien. Enfin, pour **le reméandrage du cours d'eau**, les modalités pertinentes incluent la définition de la largeur finale des méandres, l'établissement du niveau de stabilité des méandres, la pérennité des ouvrages destinés à promouvoir la migration du chenal, et la méthode employée pour le reméandrage (naturel/non-assisté ou actif). Les résultats bruts de ces modalités peuvent être consultés dans l'annexe M.

9.2 Recommandations générales

1. Suivi des indicateurs écologiques et pertinence pour les producteurs

Les indicateurs écologiques utilisés dans les projets de restauration de cours d'eau agricoles ne capturent pas toujours l'évolution complète du système fluvial, en particulier les composantes hydrologiques et géomorphologiques sous-jacentes. En fonction de la nature des indicateurs, certains réagissent rapidement (1-2 ans), comme la flore, les araignées et les oiseaux, tandis que d'autres, comme les poissons ou les processus hydrogéomorphologiques (par exemple, l'IQM), réagissent potentiellement sur une plus longue période (5 ans ou plus) (Brettschneider et coll. 2023). Enfin, certains indicateurs comme ceux relatifs à la qualité de l'eau (indices QHEI et FBI) peuvent prendre plusieurs décennies avant de montrer

des changements notables, et leur capacité à refléter les impacts de la restauration en milieu agricole restent incertains (Sinclair et coll., 2022). En effet, la qualité de l'eau en milieu agricole est fortement influencée par les pratiques agricoles dans le bassin versant et par les sources diffuses de pollution.

Dans le cadre d'un projet de restauration d'un tronçon de cours d'eau agricole, il est crucial de sélectionner des indicateurs qui sont à la fois représentatifs des objectifs écologiques à court, moyen et long terme. Les indicateurs à réponse rapide, tels que la flore, les araignées et les oiseaux, sont particulièrement pertinents pour mesurer les premiers impacts de la restauration, ce qui les rend attractifs pour les producteurs agricoles. Par exemple, les pollinisateurs (insectes et oiseaux), qui bénéficient directement des mesures de restauration, apportent des bénéfices tangibles à l'agriculture, renforçant ainsi l'intérêt des producteurs pour ces projets. Les indices de recouvrement de la flore indigène, des espèces exotiques et des exotiques et envahissantes sont également essentiels, car ils permettent de surveiller l'apparition d'espèces nuisibles pour l'agriculture tout en évaluant l'évolution du site vers un état plus naturel. Les indicateurs qui évaluent la qualité des processus hydrogéomorphologiques, tels que l'IQM, sont moins réactifs et nécessitent des suivis sur plusieurs années, particulièrement pour des mesures de restauration passive. Ces suivis sont néanmoins importants, car ils permettent de refléter une augmentation de la résilience des milieux hydriques pour maintenir les processus et services écologiques de manière durable. Ils sont également peu coûteux, pouvant être réalisés par télédétection.

En ce qui concerne les indices de la qualité de l'eau et des habitats, malgré les limites mentionnées ci-haut sur leur sensibilité moindre aux mesures de restauration à l'échelle des tronçons de cours d'eau en raison notamment de l'influence des sources diffuses de pollution, ils demeurent utiles à long terme et peuvent être maintenus dans un suivi périodique (par exemple, tous les 5 ans), dans le but de déceler progressivement les effets positifs de la restauration.

Enfin, il faut rappeler qu'il est essentiel que les indicateurs choisis aient une signification claire pour les producteurs agricoles. Des indicateurs compréhensibles et pertinents pour eux permettent non seulement de renforcer leur adhésion au projet, mais aussi d'assurer la pérennité des mesures de restauration sur le long terme.

2. Restauration par les processus HGM : la voie d'avenir pour des gains écologiques durables

La restauration des cours d'eau agricoles par les processus (HGM) est la voie d'avenir pour garantir des gains écologiques durables. En rétablissant la connectivité et les processus naturels, on permet au cours d'eau de s'ajuster à son environnement de manière plus résiliente, favorisant ainsi un équilibre morphologique. Cette approche garantit la durabilité des services écologiques du cours d'eau, tout en minimisant les interventions mécaniques coûteuses et récurrentes. Les approches passives, telles que le retrait des cultures ou des infrastructures imperméabilisantes, sont particulièrement intéressantes, car elles permettent d'atteindre un nouvel équilibre morphologique sans nécessiter de grands investissements. Ces pratiques offrent des résultats à des coûts relativement modérés et permettent au cours d'eau de se réajuster progressivement, réduisant ainsi les risques de perturbations majeures.

Il importe de souligner qu'avant d'atteindre un nouvel équilibre morphologique, il est possible que des ajustements du cours d'eau entraînent des désagréments pour les producteurs agricoles, par exemple par des incisions ou des glissements de terrain qui peuvent entraîner des pertes de terres cultivables. Il est donc essentiel de prévoir des pronostics sur la trajectoire morphologique des tronçons visés par la restauration. Ces prévisions doivent être accompagnées de mesures de mitigation pour réduire les impacts

négatifs sur les terres agricoles pendant la période d'ajustement. Ces mesures de mitigation peuvent inclure l'aménagement de zones tampons en haut de talus des berges, la surveillance accrue de l'évolution morphologique, et l'application de techniques de stabilisation temporaires pour minimiser les risques pour les producteurs.

3. Espace de liberté : essentiel pour le rééquilibrage naturel des cours d'eau

Le concept d'espace de liberté est central dans la restauration des cours d'eau. Ces espaces, qui permettent aux cours d'eau de retrouver un équilibre morphologique naturel, sont indispensables pour que les processus de restauration puissent se dérouler de manière efficace. Il est important de cartographier systématiquement ces espaces de liberté et d'en expliquer les objectifs aux producteurs agricoles. Cela leur permettra de mieux comprendre les bénéfices à long terme des projets de restauration, même si cela implique un empiètement sur certaines surfaces cultivées. Ces compromis peuvent être facilités par des mesures compensatoires et des stratégies de gestion collaborative entre les parties prenantes.

4. Végétalisation riveraine et gestion des EFEE

La végétalisation dans la zone riveraine doit être soigneusement planifiée pour limiter l'impact des espèces floristiques exotiques envahissantes (EFEE). Il est nécessaire de faire une caractérisation détaillée des espèces floristiques présentes sur le site de restauration et dans le tronçon amont pour adopter une approche de végétalisation adaptée. La végétalisation passive (naturelle) devrait être privilégiée pour encourager l'établissement spontané d'espèces indigènes, mais lorsque cela est nécessaire, la végétalisation active (plantation d'espèces indigènes et à croissance rapide) peut être utilisée pour accélérer la restauration. Le suivi des espèces invasives et la gestion des espèces nuisibles doivent également être intégrés dès le départ pour éviter toute perturbation à long terme des pratiques agricoles adjacentes.

5. Rayonnement et sensibilisation : promouvoir les bonnes pratiques

Le rayonnement des projets de restauration est crucial pour sensibiliser le public et renforcer la conscientisation des producteurs agricoles. Il est nécessaire de promouvoir médiatiquement (ex. reportage à la chaine MATV prévu à l'été 2025) les réussites des projets dans les communautés agricoles, mais également dans les centres urbains situés en aval des zones agricoles pour les informer des avantages à long terme des mesures écologiques mises en place. Des initiatives de réseautage et de partage d'expériences entre projets, comme l'initiative du CERCEMA (Annexe S) ou l'exemple du ruisseau Parent en Outaouais (voir section 8.6), peuvent également renforcer les connaissances et encourager la participation active des producteurs dans les projets futurs.

En résumé, pour garantir le succès et la réplicabilité de projets comme celui de la Ferme Parentall, il est crucial de promouvoir une vision intégrée des mesures de restauration, de maintenir un dialogue constant avec les producteurs, et de veiller à ce que les projets bénéficient d'un financement stable et durable. Les analyses des processus HGM, la gestion des espèces invasives, et l'intégration des espaces de liberté sont des éléments clés pour créer un modèle de restauration des cours d'eau agricole qui soit à la fois écologiquement durable et économiquement viable. Ces projets doivent être accompagnés de suivi et de sensibilisation pour garantir leur succès à long terme.

10. Description des travaux de restauration prévus pour la phase 2 du projet, s'il y a lieu.

Si le projet *Un Méandre à la fois* est reconduit pour une deuxième phase (2025-2028), il poursuivra ses objectifs de restauration écologique des cours d'eau agricoles, en consolidant les acquis de la phase 1 (2022-2025) et en introduisant des mesures innovantes pour optimiser les bénéfices écologiques, socio-économiques et scientifiques. Les détails des activités de recherche planifiés dans la phase 2 du projet sont disponibles à l'annexe T.

En matière de restauration écologique avancée, la deuxième phase visera la mise en œuvre de techniques de reméandrage passif de type "low-tech" (Wheaton et coll., 2019), telles que l'utilisation de structures en bois mort pour restaurer la sinuosité naturelle du cours d'eau. Ces structures naturelles permettront de réactiver les processus hydrosédimentaires, et des suivis morphologiques seront réalisés par drone pour suivre l'évolution du cours d'eau. En parallèle, le réseau de drainage agricole sera amélioré pour réduire les impacts sur la qualité de l'eau et favoriser l'épuration naturelle grâce à la mise en place de bandes enherbées et de zone tampon humide artificielle (ZTHA). Le réaménagement des sorties de drains permettra de maximiser l'infiltration des eaux et leur purification. La végétalisation ciblée dans la zone riveraine sera également un axe clé pour accroître les habitats d'espèces indigènes et limiter la propagation des espèces floristiques exotiques envahissantes (EFEE). Des parcelles expérimentales seront mises en place pour tester des assemblages herbacés et ligneux, en partenariat avec des experts universitaires.

En ce qui concerne les suivis écologiques renforcés, la deuxième phase poursuivra les suivis amorcés, notamment les inventaires floristiques, d'araignées, aviaires, de poissons et macroinvertébrés. De plus, de nouveaux protocoles seront développés pour mesurer la séquestration de carbone, la qualité des sols et de l'eau, ainsi que les changements morphologiques des cours d'eau. Ces nouveaux indicateurs permettront de mieux évaluer l'efficacité des mesures de restauration à long terme.

Pour la pérennisation des efforts de restauration, l'adoption d'un outil légal de conservation, tel qu'une servitude personnelle ou une entente contractuelle, sera mise en place en collaboration avec des acteurs régionaux pour garantir la durabilité des actions entreprises. En parallèle, une stratégie de financement sera élaborée pour soutenir les producteurs agricoles, en vue de garantir la viabilité à long terme des mesures de restauration, tout en répondant à leurs besoins économiques.

La deuxième phase mettra également un fort accent sur les partenariats stratégiques et la collaboration avec des universités (Laval, McGill, UQTR), des ministères (MELCCFP, MAPAQ) et des organismes de conservation (Canards illimités, Nature-Avenir). Des activités de transfert de connaissances seront organisées avec des partenaires régionaux comme l'OBV Yamaska et la MRC Pierre-De-Saurel. L'implication active des producteurs agricoles dans les démarches de restauration sera essentielle pour garantir l'acceptabilité des mesures et leur viabilité à long terme à l'échelle du bassin versant. Un travail collaboratif sera effectué avec la MRC et l'UPA Montérégie pour intégrer les producteurs au comité de bassin versant de la Pot-au-Beurre.

Concernant le financement et le suivi réglementaire, une demande formelle sera soumise à la CPTAQ pour garantir la pérennité du projet. De plus, des efforts seront déployés pour explorer de nouveaux financements pour soutenir les mesures de restauration et de conservation.

Enfin, la phase 2 du projet mettra un fort accent sur le rayonnement et l'innovation. Le projet visera à se positionner comme un modèle québécois de restauration écologique des milieux agricoles, avec des résultats attendus en matière de connectivité hydrologique, de biodiversité, et de qualité de l'eau. L'objectif sera également de garantir la reproductibilité des techniques testées dans d'autres contextes agricoles, contribuant ainsi à une approche plus large de gestion des cours d'eau agricoles au Québec.

En conclusion, la deuxième phase du projet *Un Méandre à la fois* permettra non seulement de renforcer les acquis de la phase 1, mais aussi d'introduire des pratiques innovantes et de garantir la pérennité des efforts de restauration en milieu agricole. Le projet visera à être un modèle de réplicabilité dans d'autres bassins versants, soutenant ainsi les efforts pour un avenir plus durable des milieux agricoles et des écosystèmes fluviaux.

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