UNIVERSITÉ DU QUÉBEC À MONTRÉAL

ASSESSING THE ROLE OF WETLANDS IN THE RIVER CORRIDOR THROUGH GROUNDWATER AND STREAM INTERACTIONS

THESIS

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ÉVALUATION DU RÔLE DES MILIEUX HUMIDES DANS L'ESPACE DE LIBERTÉ PAR L'ÉTUDE DE LA CONNECTIVITÉ NAPPE-RIVIÈRE

MÉMOIRE

PRÉSENTÉ

COMME EXIGENCE PARTIELLE

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PAR

MICHAEL NEEDELMAN

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RÉSUMÉ

Dans le contexte de la gestion intégrée des bassins versants, les milieux humides riverains peuvent jouer un rôle important dans le corridor fluvial (aussi appelé espace de liberté). Les milieux humides riverains peuvent surtout contribuer à la normalisation des interactions nappe-rivière et dans une certaine mesure aider à atténuer les effets des pressions anthropiques et des changements climatiques. Cependant, les connaissances sur la connectivité aquifère-rivière sont très limitées dans le sud du Québec et il est très difficile de quantifier les fonctions hydrologiques des milieux humides riverains dans les conditions actuelles. L'objectif de ce projet était d'améliorer la compréhension de la connectivité entre la rivière de la Roche située en Montérégie, deux milieux humides situés à l'intérieur de l'espace de liberté de cette rivière, et l'aquifère. Pour déterminer si ces milieux humides riverains jouent un rôle important dans la dynamique de la rivière, ceux-ci ont été instrumentés pour surveiller les niveaux et les températures de l'eau à l'aide de sondes Hobo et d'un Distributed Temperature Sensor. Les chroniques ainsi mesurées ont été traitées au moyen d'analyses corrélatoires. Les échanges nappe-rivière ont également été mesurés au moyen de l'analyse de l'activité ^{222}Rn. Les deux milieux humides riverains présentaient de nombreuses similitudes en termes de taille, de végétation et de leur proximité au cours d'eau. Toutefois, des différences significatives ont été observées en ce qui a trait aux fluctuations des niveaux d'eau entre la nappe phréatique et la rivière. Le milieu humide A est relié de façon plus dynamique à l'aquifère comparé au milieu humide B où les sédiments sont plus fins et les conductivités hydrauliques sont plus faibles. Les différences hydrogéomorphologiques jouent probablement un rôle dans la réponse hydrologique distincte des deux milieux humides, car le milieu humide A est situé dans une ancienne boucle de méandre du chenal, et le milieu humide B est situé là où le lit de la rivière est resté dans la même position pendant au moins les 83 dernières années. En outre, les apports d'eau souterraine à la rivière sont apparemment diffus pour la majorité de la zone d'étude, à l'exception d'une contribution locale d'eau souterraine immédiatement en amont du milieu humide B révélée par les données de température de l'eau et de l'activité du radon. Toutefois, cette contribution de l'aquifère située proche de la zone humide B ne peut pas être directement liée à la présence du milieu humide étant donné le comportement très différent des deux milieux humides relativement similaires à bien des égards. Cette variabilité marquée observée entre les deux milieux humides étudiés suggère que la prudence est requise lorsque l'on regroupe ensemble tous les milieux humides riverains. Leur impact hydrologique peut être plus variable que prévu dans la plupart des systèmes de gestion de rivière.

MOTS-CLÉS : milieux humide riverain, connectivité nappe-rivière, espace de liberté, hydrogéomorphologie, distributed temperature sensor, radon.

ABSTRACT

In the context of integrated watershed management, riparian wetlands can play an important role within the river corridor (also called freedom space). In particular, riparian wetlands can contribute to the regulation of aquifer-river interactions and to some extent help mitigate the effects of anthropogenic pressures and climate change. However, knowledge about aquifer-river connectivity is very limited in southern Quebec and it is currently almost impossible to quantify the hydrological functions of riparian wetlands in today's conditions. The objective of this project was to increase the understanding of interactions between the Rock river in the Montérégie region, two wetlands located within the freedom space of this river, and the aquifer. To determine whether these riparian wetlands played an important role in controlling river dynamics, they were instrumented to monitor water levels and temperatures using Hobo sensors and a Distributed Temperature Sensor. The time series were subsequently analyzed using cross-correlation analyses. Interactions between the river and wetlands were also assessed through measurements of ^{222}Rn activity. The two riparian wetlands exhibited many similarities in terms of size, vegetation and proximity to the channel. However, significant differences were noted in the relationship between water table and river channel levels fluctuations. Wetland A is more dynamically connected to the aquifer than wetland B where sediments are finer and hydraulic conductivities lower. Differences in hydrogeomorphology probably play a role in the distinct hydrological response at these two wetlands, as wetland A is located in a former meander loop of the channel, and wetland B is located where the river channel has remained in the same position for at least 83 years. In addition, groundwater inflow to the river is apparently diffuse over most of the study area with the exception of a local groundwater contribution immediately upstream of wetland B, which was evident from both water temperature data and radon activity. However, this aquifer contribution in the surrounding wetland B cannot be directly linked to the presence of the wetland given the very different behavior of the two relatively similar wetlands in most respects. This marked observed variability between the two studied wetlands suggests that caution is required when grouping all riparian wetlands together. Their hydrological impact may be more variable than assumed in most river management schemes.

KEYWORDS: riparian wetland, aquifer-river interactions, river corridor, hydrogeomorphology, distributed temperature sensor, radon.

CHAPTER I

INTRODUCTION

1.1 Context

Sustainable and integrated management of rivers entails several issues related to the quantity and quality of water, the prevention of water damage to homes and infrastructure, the possible loss of agricultural land and forest from bank erosion, the conservation of biodiversity in rivers and in the riparian zone and finally the use of the water resource for recreation and recreational tourism. All these issues must contribute to the sustainable management of river systems by taking into account the fluvial dynamics and its response to environmental changes. Indeed, whether they are undisturbed or severely destabilized by frequent anthropogenic interventions (e.g. changes in land use, changes in a river's course, dredging), river systems remain both sensitive across the flow section and resilient at the scale of a homogeneous reach. This dynamic balance between rivers and the many related issues is intrinsically linked to the need to adapt the current management of rivers to climate change, because the variations in temperature and especially in the intensity, duration and volume of rainfall, could have a major impact on rivers in the coming decades.

Wetlands can play an important role in the regulation of aquifer-river interactions and could to some extent help mitigate the effects of anthropogenic pressures and climate change. However, knowledge about aquifer-river connectivity is very limited in southern Quebec and it is currently almost impossible to quantify the hydrological functions of riparian wetlands in today's conditions. It is even more difficult to estimate how these functions could help mitigate the effects of anthropogenic pressures and climate change.

1.2 State of knowledge

1.2.1 Groundwater-surface water interactions along rivers corridors

Integrated watershed management is increasingly recognizing that rivers are not a linear entitity in space, but that by integrating their temporal dynamics, they occupy a larger space, often called a corridor. A river corridor represents a complex system of land, plants, animals and streams that is not yet well understood. Within the broader context of the "Freedom space" research project, of which this project is a sub-component, the river corridor is defined as the flooding space and the mobility space required by a river to function nominally. A river corridor is an integrated management framework based on the hydrogeomorphology of rivers. It is a relatively new concept, not yet implemented in Quebec, but which is gaining popularity in different parts of the world (Parish Geomorphic, 2004; Piégay et al., 2005; Kline and Cahoon, 2010). A river corridor approach aims to identify the flooding and mobility spaces required by the river and allows it to evolve in these areas rather than forcing it to move in a way that is shaped by human interventions. This framework appears to be much more promising for sustainable management in a changing climate, because it helps maintain the natural physical features of rivers (transporting water and sediment) and thus increases their resilience.

A natural river has a complex and diverse flora and fauna habitat compared to a straightened river: alternating between fast sections and slower, deeper sections (pools), a varied granulometry and heterogeneous banks. Therefore, improved flood mitigation also results in the improvement of the ecological functions of streams and their biodiversity, and of their ecological goods and services (Kline and Cahoon, 2010). In addition, a river corridor recognizes the importance of connectivity between the river and the aquifer, notably through wetlands which can contribute to flood mitigation (Bullock and Acreman, 2003; Piégay et al., 2005; Arnaud-Fassetta et al., 2009), lessen the severity of low flows, as well as filter underground contaminants and provide healthy ecosystems.

Aquifer-river interactions in the presence of wetlands may be highly variable in time and space (Krause et al., 2007; Baskaran et al., 2009) and are influenced by a variety of factors (e.g. topography, geology, river discharge). In humid climates, rivers can receive a significant contribution of groundwater for a large part of the year (Hayashi and Rosenberry, 2002; Hayashi and van der Kamp, 2009). The hydrological modeling completed by Lavigne et al.

(2010) for example showed that the contribution of groundwater discharge to the Châteauguay River can reach 66% of the total river discharge. However, there are few of these studies in Quebec where the size of the fluxes exchanged between surface and ground water flows, their location and the local processes involved in these interactions are little known. The areas where groundwater discharges into the river can alternate with areas where the river feeds the aquifer (Datry et al., 2008). These interactions take place in the hyporheic zone, an intermediate zone between the river sediments and the underlying geological materials, where different types of water mixes from different sources. This zone is influenced by heterogeneities in the sediment hydraulic conductivity distribution and the topography of the streambed (Woessner, 2000). Channel morphologic features can also interact with changes in stream stage and lateral groundwater inputs in ways that can substantially influence the amount of hyporheic exchange flow (HEF) over time, across seasons or within a single storm event. At low stage, the water surface more closely follows streambed topography that creates steeper head gradients that support more HEF (Wondzell and Gooseff, 2013). The hyporheic zone also plays an important role in the transfer of pollutants and of heat fluxes, and is an important component of the riparian ecosystem (Brunke and Gonser, 1997; Alexander et al., 2002). In general, groundwater is cooler than surface water in the summer months and during periods of low flow it is expected that groundwater inflow to the river might be detected via a cooler temperature signature near the riverbed.

1.2.2 Wetlands

According to article 1.1 of the Ramsar Convention, wetlands are defined as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres" (Ramsar Convention Secretariat, 2006). This is clearly a very broad definition, and several classifications are used to distinguish the different types of wetlands in terms of vegetation, slope, groundwater and surface water connection. A simple classification is that of Keddy (2010), which distinguishes four types: swamps, marshes, bogs and fens. This type of classification is mainly based on vegetation. The Cowardin wetland classification system (Cowardin et al. 1979), on the other hand, combines hydrology and vegetation characteristics to define five categories, namely riverine, lacustrine, palustrine, marine, and estuarine (the latter being associated with saltwater and/or coastal waterbodies). In Canada, the usual classification system is that of Warner and Rubec (1997) which has one more class than the Keddy (2010) classification, namely swamps, marshes, bogs, fens and shallow water. Finally, the hydrogeomorphic classification (HGM) aims at classifying wetlands based on a clarification of the relationship between on three components: geomorphic setting (topographic location within the surrounding landscape), water source (precipitation, surface/near surface flow, groundwater discharge) and hydrodynamics (direction and strength of flow (hydrologic head)) (Brinson, 1993). Originally, there were four wetland classes in the HGM approach, namely depressional, extensive peatland, riverine and fringe wetlands. These were later developed into seven classes, i.e. riverine, depressional, slope, mineral soil flats, organic soil flats, estuarine fringe, lacustrine fringe (Smith et al. 1995).

It is clearly difficult to determine which classification approach is best to cover the wide range of wetland types in given areas. For example, Brooks et al. (2011) use a combination of the HGM and National Wetland Inventory (NWI) to determine classes for the Mid-Atlantic Region in the U.S.A. The approach relies less on vegetation than the NWI since similar species composition can be observed in very different geomorphic contexts and flow dynamics (Figure 1.1, Brooks et al. 2011). In this revised classification scheme, seven classes are used: marine tidal fringe, estuarine tidal fringe, flats, slope wetlands, depressions, lacustrine fringe and riverine wetlands. Figure 1.1 shows that the geomorphic setting has a clear influence on the dominant water source to the wetland.

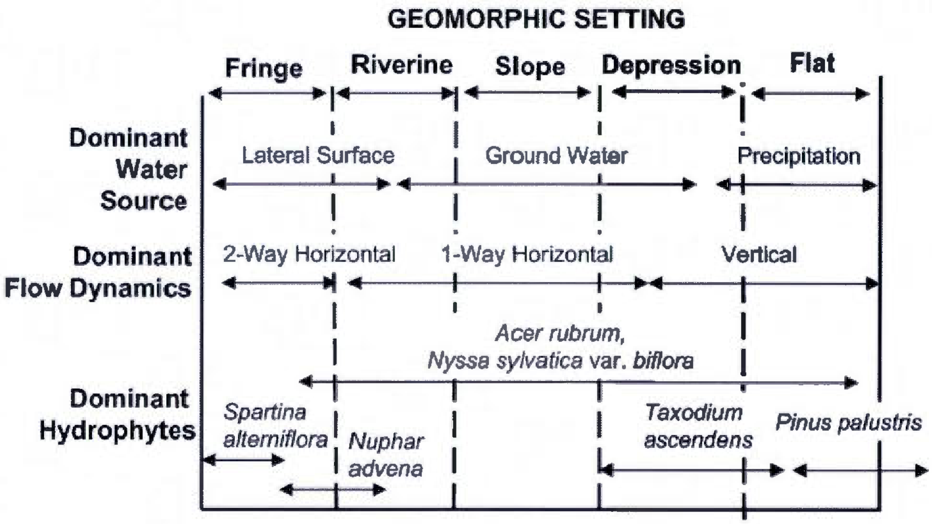

Figure 1.1 The relationship of geomorphic settings and dominant waters source and flow dynamics and dominant hydrophytes for the HGM categories of wetlands (Brooks et al. 2011).

Wetlands located in floodplains are considered to have the capacity to store flood waters and thus effectively reduce or delay the risk associated with flood peaks (Bullock and Acreman, 2003; Piégay et al., 2005; Barnaud and Fustec, 2007; Hudson et al., 2012). This buffering keeps flood waters in the wetland for a while and releases them in the dry period, contributing to the maintenance of river flows during the driest times of the year (Dennison and Berry, 1993; Barnaud and Fustec, 2007; Mitsch and Gosselink 2007; Morley et al., 2011). This contribution is even more important in the case of wetlands connected to groundwater. Several studies show that between 30 and 70% of water supplied to rivers may come from groundwater discharge through wetlands (Warwick and Hill, 1988; Cole et al., 1997; Uchida et al., 2003; Krause et al., 2007. Morley et al., 2011;. Bourgault et al., 2014).

Riparian wetlands are known to play several ecosystem services (Figure 1.2). In agricultural watersheds, they are particularly effective at reducing nitrate reaching streams (Zedler, 2003). It is now recognized that the oxygen-starved Gulf dead zone (approximately 15,000 km^2, NOAA, 2013) is directly connected to the lost ecosystem services provided by wetlands in the states of Illinois, Iowa, Minnesota, Wisconsin, Indiana, Ohio, Illinois, and Iowa have removed over 85% of the wetlands (Zedler, 2003). Increasingly, restoring wetlands in agricultural watersheds is seen as one of the solutions to the problem. However, this requires a sound understanding of their hydrological and ecological roles. For example, large wetlands can support many bird species (Mensing et al., 1998) and smaller wetlands can host rare plants (Zedler, 2003). Upstream wetlands play a minor role in trapping nutrients, whereas downstream wetlands in some agricultural watersheds can remove up to 80% of nitrates (Crumpton et al. 1993). It is thus very important to better understand riparian wetland processes to prioritize those which would need protection or restoration of ecosystem services such as biodiversity support, nutrient removal and flood reduction.

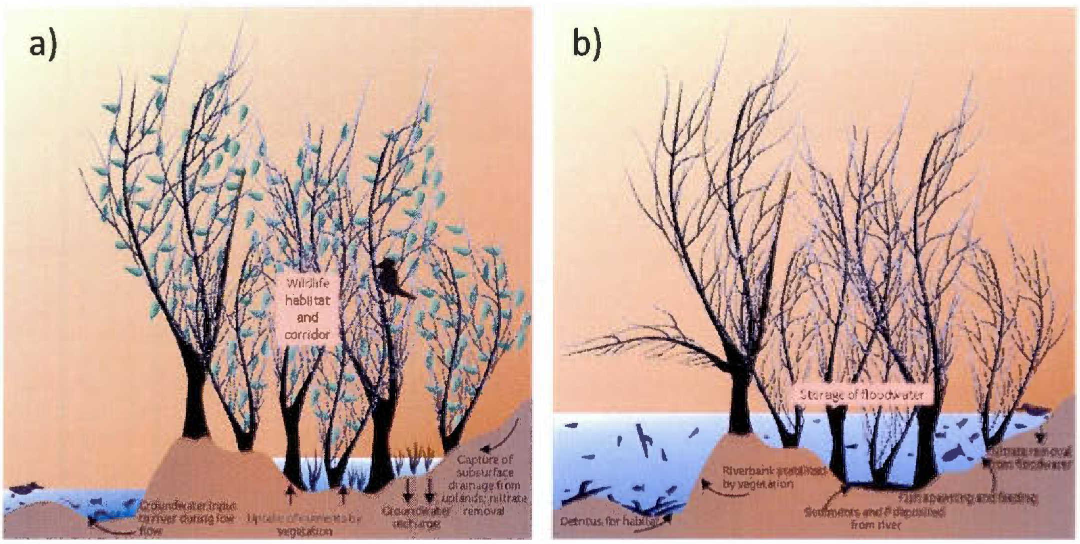

Figure 1.2 Illustration of several potential ecosystem values for riparian wetlands during a) dry season and b) flood season (from Mitsch and Gosselink, 2007)

Hydrological connectivity of riparian wetlands is particularly important since it may affect their potential for nitrogen removal via denitrification (Racchetti et al., 2011; Roley et al. 2012). Aquatic and wetland biodiversity are also often related to hydrological connectivity (Phillips, 2013). Connectivity is often assessed using map elevation and water levels in the river, but it is also strongly related to abandoned channel water bodies such as meander loops (Phillips, 2013). As such, it is a dynamic concept which can evolve over time following geomorphic evolution of the river channel (Amoros and Bornette, 2002; Phillips, 2013). New oxbow lakes tend to vary in stage in a similar way to the river channel, whereas older oxbow lakes, even if located very close to the channel, can be essentially isolated from it, at least in terms of surface water (Hudson, 2010). Overall, channel-floodplain connectivity is complex and cannot simply be determined by variables such as distance from channel and differences in elevation between the channel and the wetlands (Phillips, 2013). In some cases, flow into floodplain depressions can occur even if flow stage in the channel is below bankfull, with impacts on both cross- and down-valley fluxes (Phillips, 2008).

There is a lack of understanding of hydrological connectivity between riparian wetlands formed through meander cut-off, mainly because most studies of hydrologic connectivity use a simple discharge threshold approach instead of an analysis of the actual water level data to assess connectivity (Hudson et al. 2012). Wetlands that are located within a river corridor ("freedom space") are intrinsically related to hydrogeormorphological processes of meander dynamics. Because of lateral migration and resulting chute cutoff in meanders (Hooke, 1995; Zinger et al. 2011), meander oxbows are formed. Four evolutionary stages of geomorphic adjustment normally follow meander cutoff, which are known as the "oxbow lake cycle" (Gagliano and Howard, 1984). The first stage is the intial cutoff wheras the final stage consists of the near complete sedimentary infilling of the oxbow lake, which remains as an arcuate wetland (Hudson et al., 2012). A good illustration of this process is provided by a recent cutoff in the Ain River, in France (Dieras et al., 2013). A large wetland is now occupying the former course of the channel after the cutoff which occurred between 2000 and 2005 (Figure 3.4).

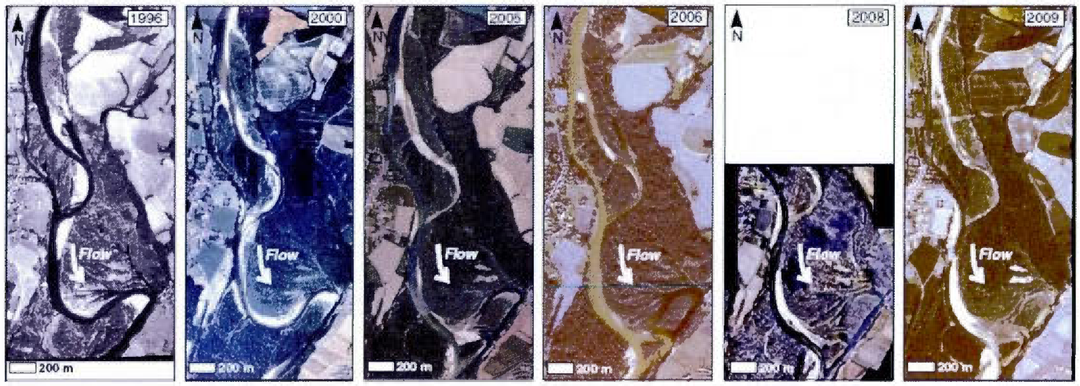

Figure 1.3 Aerial photographs showing the Ain River (France) between 1996 and 2009. A riverine wetland was formed after the cutoff of the meander loop in the bottom right part of the photos (Dieras et al. 2013).

A better assessment of hydrologic connectivity of the HGM-defined riverine (or riparian) wetlands, is needed for integrated floodplain management, particularly in the context of climate change (European Commission, 2009). It is also essential to understand the variability of hydrologic connectivity in riverine wetlands within the river corridor, as wetlands in these zones may have been created by different processes (e.g. meander cutoff, beaver dam construction), and they may be at different geomorphological stages of evolution (Cabezas et al. 2011). The first stage of evolution is the initial cutoff whereas the final stage consists of the near complete sedimentary infilling of the oxbow lake, which remains as an arcuate wetland (Hudson et al. 2012). As shown in Figure 1.1, the dominant water source in these types of wetlands should be a combination of lateral source and groundwater, with mainly a one-way horizontal flow dynamic.

1.3 Objectives and methodology

Given its importance in the hydrological dynamics of rivers, a better understanding of the river-water connectivity and the contribution of riverine or riparian wetlands to this connectivity is fundamental in improving the management of floodplains and streams. The objective of this research is to better understand interactions between a river, wetlands and the aquifer and hence reinforce the beneficial hydrological functions of the river corridor. To attain this objective, the study is conducted along a 9 km section of the Rock River, a small agricultural river in southern Quebec, where two riparian wetlands are studied. The river corridor ("freedom space") of the Rock River has been recently characterized by Biron et al. (2013). This analysis revealed that one of the wetlands is created following a meander cutoff that occurred between 1930 and 1964, whereas the other wetland is located in a zone where the river channel has not moved in the last 83 years.

To determine whether these riparian wetlands play an important role in controlling river dynamics such as flooding (in the vertical plane) and meandering (in the horizontal plane), they were instrumented to monitor water levels and temperature. These data were cross-correlated and analyzed at different timescales. A distributed temperature sensor was utilized in the river adjacent each wetland to measure the water temperature and look for signs of groundwater recharge. Surface and groundwater samples were collected for ^{18}O, ^{2}H and ^{222}Rn analysis. A Quaternary deposit survey was performed to validate the existing map, soil samples were collected for granulometry analyses and slug tests were done to determine hydraulic conductivity.

This thesis is divided in four chapters. The Introduction presents the general context, followed by a description of the state of the knowledge in river-aquifer-wetland interactions. Chapter II presents the methods used in this research, while Chapter III describes and discusses results. The Conclusion summarizes the results and brings some opening thoughts that go beyond this research.

This project is a part of the larger "Freedom space" project that was funded by the Ouranos consortium (PACC-26 program). Partial results were presented during the "Earth, Wind and Water - Elements of Life" CWRA-CGU conference in Banff, Alberta from June 5-8, 2012.

CHAPTER II

METHODOLOGY

2.1 Study area

The Rock River is located in the Montérégie region, 80 km southeast of Montreal. The Rock River watershed drains a surface area of approximately 145 km^2, of which 55 km^2 is Quebec territory. The 27 km long river flows northward from its source in Vermont to Saint-Armand in Quebec, and southward from there to its mouth Missisquoi Bay in Vermont (Figure 2.1A). The study area is limited to the 9 km river section located in Quebec. In this section, the tributaries Brandy, Swennen and au Ménés enter the Rock River (Figure 2.1B).

The watershed land use is predominantly agriculture (41%), particularly in the downstream sector, and forest (40%) (Hegman et al., 1999; MAPAQ, 2002). Residential land is uncommon (5.4%) and commercial/industrial land is nearly non-existent. The profound loss of sediment and nutrient storage functions at a watershed scale due to channelization, drainage works, and flood plain encroachments, has resulted in an increase in fluvial erosion hazards such as flood and erosion damage, and an upward trend in sediment, soil, and nutrient exports (VANR, 2009).

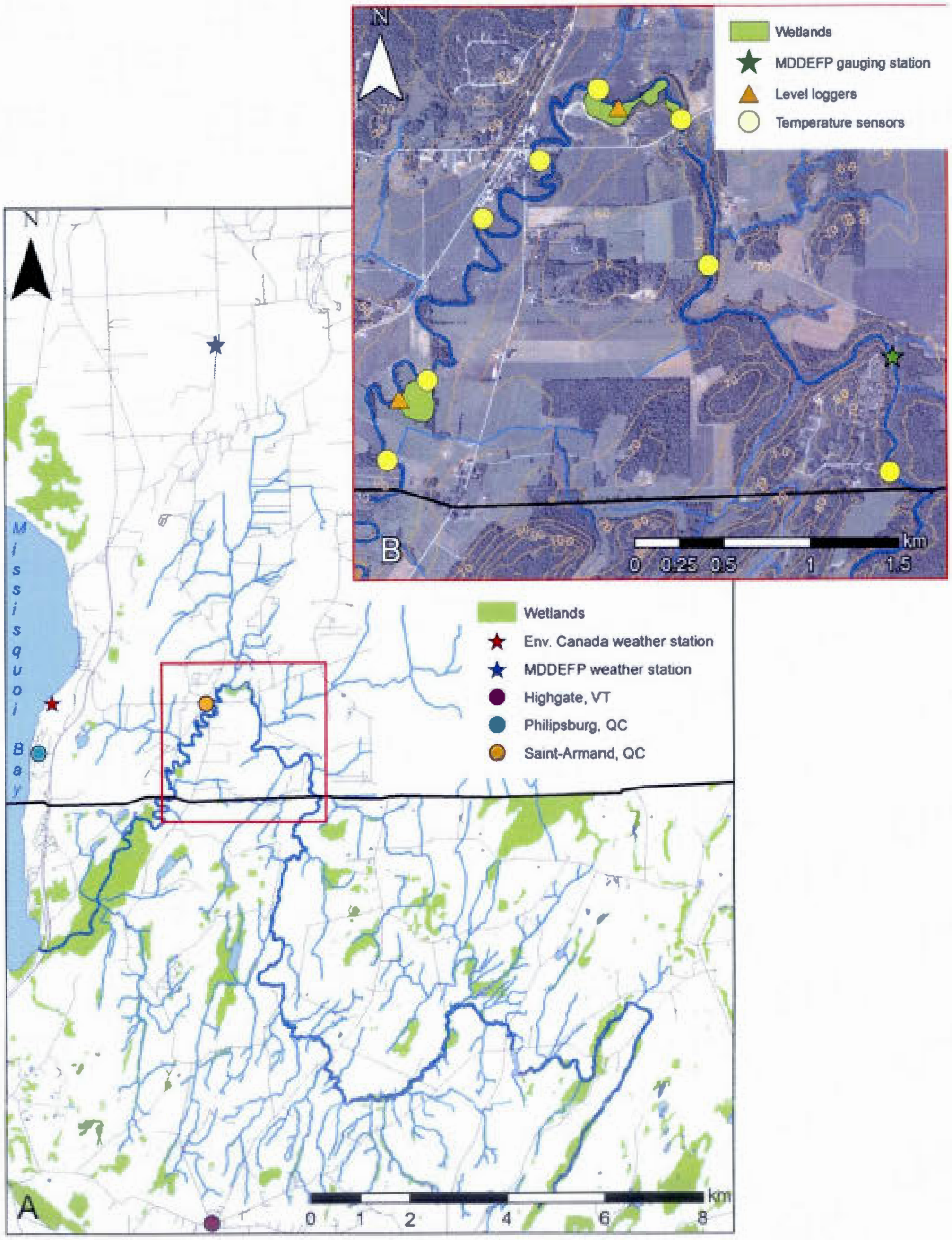

Figure 2.1 Localization of the study area, A) the complete Rock river watershed andB) the 10 km study reach (VANR, 2010; Moisan, 2011).

2.1.1 Climate

Daily temperature and precipitation measurements are available from the Philipsburg Environment Canada weather station, located approximately 3 km west of Saint-Armand. Hourly precipitation measurements are available from the Philipsburg weather station, located approximately 7 km north of Saint-Armand (Figure 2.1A). The climate of the region is characterized by moderate temperatures, a sub-humid volume of precipitations and a long growing season. The climate normals for the period 1971-2000 indicate an average daily temperature of 6.8°C and total annual precipitations of 1096 mm (Environment Canada, 2013).

2.1.2 Geology

The Rock River watershed geology is composed of shale and slate-fractured shale, and to a lesser extent dolomite, sandstone and limestone (Dennis, 1964; Stewart, 1974; Mehrtens and Dorsey, 1987). The bedrock geology (Figure 2.2) largely determines the topography of the watershed. The terrain along the Champlain fault directs the watershed drainage towards the north, to Quebec. Several outcrops also influence the position and profile of the channel.

The Rock River is located at the boundary of two physiographic units, the St. Lawrence Lowlands and the Appalachian Plateau. The first outcrops belonging to the Plateau appear as elongated ridges that dominate the lowest few meters of land, as seen in the towns of Philipsburg and Saint-Armand (Dubois et al., 2011). The surface deposits of the area consist primarily of deep-water marine sediments (MGa), till blanket (Tc), thin till (Tm), reworked till (Tr) and many sections of extruded rock at the peaks of nearby hills. The river itself rests on alluvium (Ap) and there are few areas of alluvium from ancient river terraces (At) due to minimal meandering of the river over the past century (Figure 2.3). Till covers much of the watershed due to its glacial history. The fine, silty and clayey glaciolacustrine deposits mask the till underneath, which resulted from the presence of glacial and proglacial lakes during the deglaciation that began about 13,000 years BP (Dubois et al., 2011). There are also marine sediments reflecting the intrusion of the Champlain Sea about 12800 to 10200 years BP (Stewart and McClintock, 1969; Cronin, 1977). The downstream portion of the Rock River flows mainly on marine sediments (Figure 2.3). The river is also much more sinuous than in the upstream portion where it flows directly on till or on the bedrock. Organic deposits are of limited extent, and are usually found in forested depressions in the land, ancient and isolated water bodies clogged and some bowls of floodplains (Dubois et al., 2011). The surface deposits map in Figure 2.3 was modified in the course of this project after surveying twenty eight different locations in the Saint-Armand area. The quaternary deposits were characterized by hand drilling with an auger approximately 40 cm deep. An updated map is presented in section 3.1.1 of the next chapter.

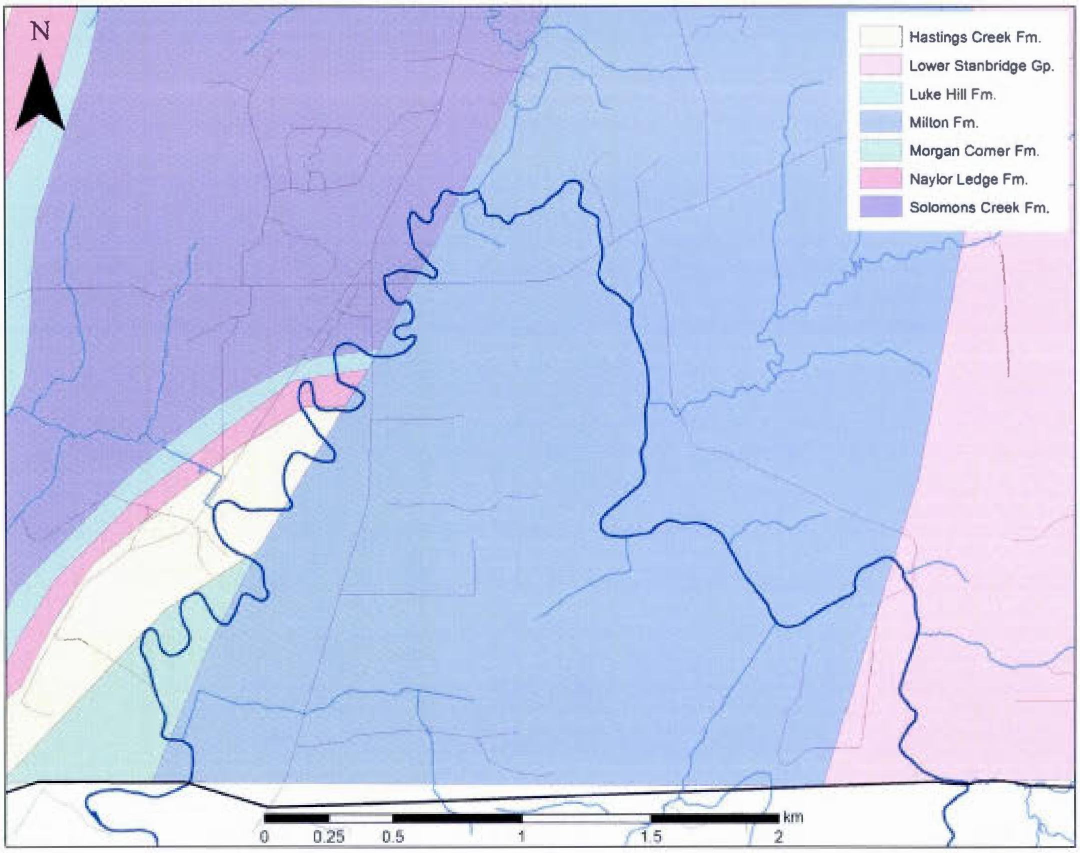

Figure 2.2 Bedrock geology in the study area (MRN, 2013).

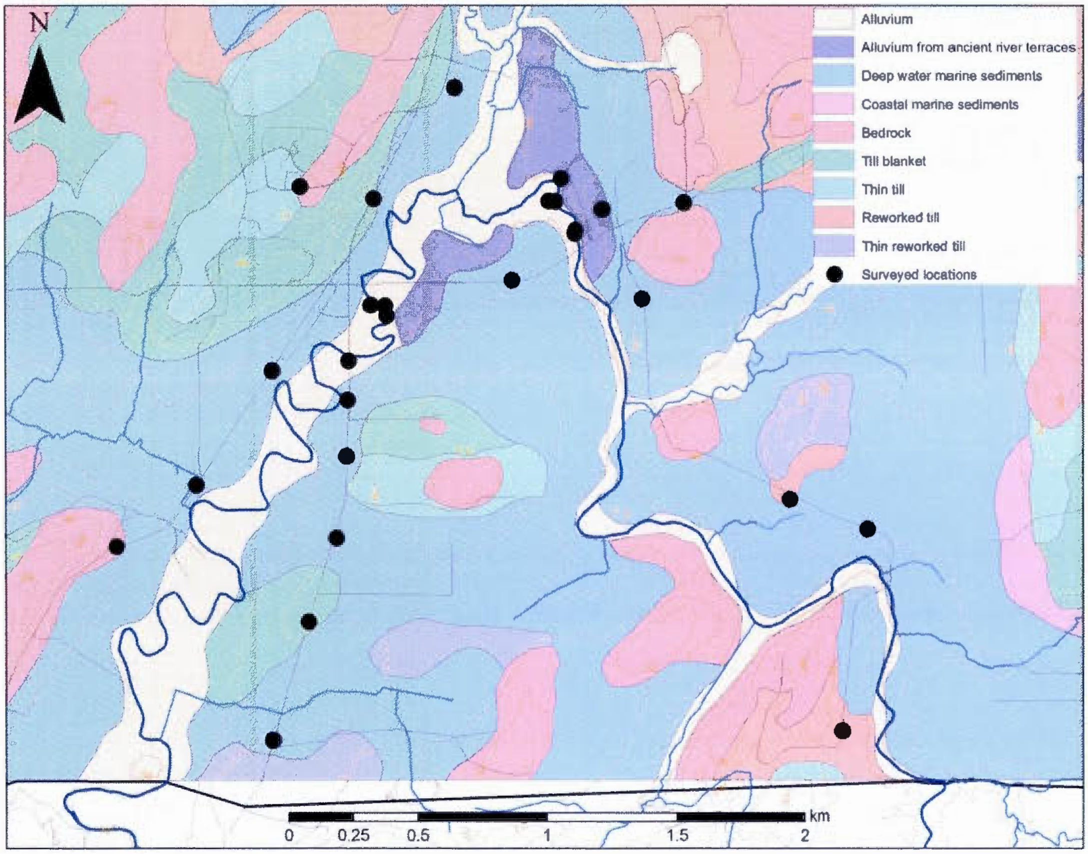

Figure 2.3 Quaternary geology in the study area (MRN, 2012).

According to the Missisquoi Bay watershed portrait (Dubois et al., 2011), a crescent of orthic and humic gleysols with few intrusions of podzols are present along the northeastern boundaries of the watershed. The central part of the watershed is dominated by brunisolic order soils (clay loam to sandy loam). To the north of the watershed, there are also dystric order soils such as humo-ferric, orthic, and gleyed podzols.

Figure 2.4 shows the topography of the study area and was produced with high resolution LiDAR measurements. The upstream portion of the river is visibly more incised than the downstream portion. The highest elevations in the Rock River watershed are approximately 260 m and are located in the upper reaches of the watershed in Vermont. Elevations are in the order of 30 m near the mouth of the Missisquoi Bay. The Quebec portion of the longitudinal river profile lies between the elevations of approximately 62 to 32 m which represents a drop of 30 m and an average slope of 0.32%.

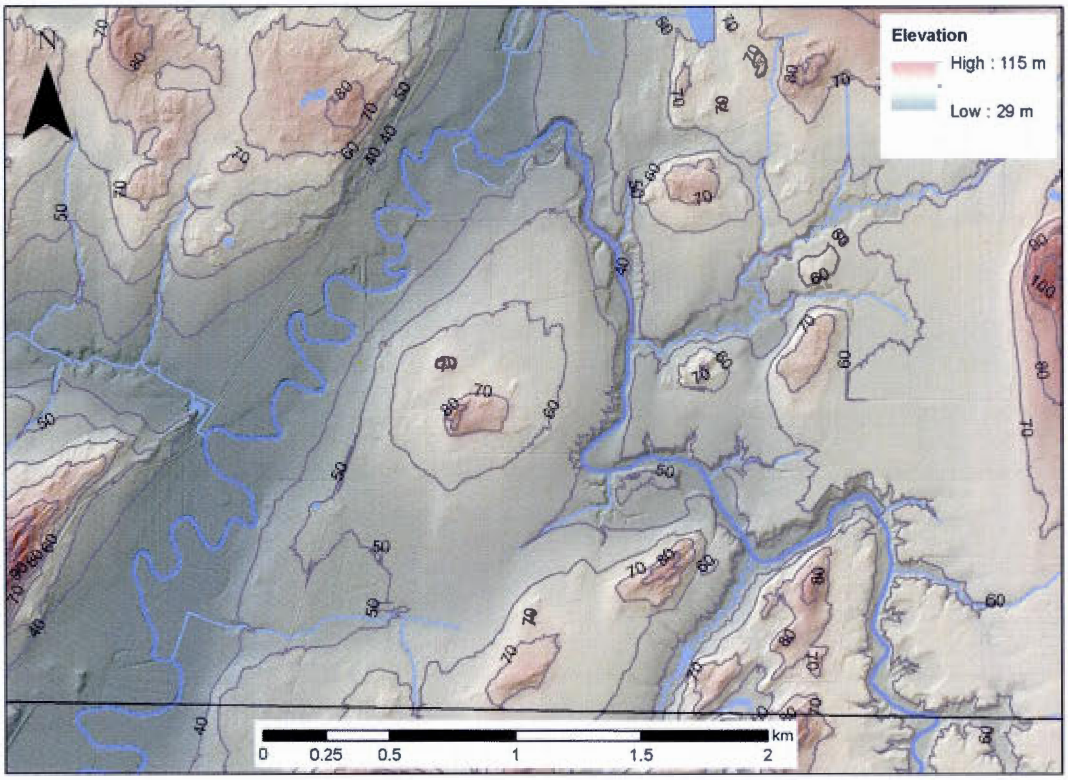

Figure 2.4 Digital elevation model of the study area produced with LiDAR.

2.1.3 Hydrogeology

The main aquifer is unconfined for a large portion of the study area with the exception of the downstream portion of the river where the clayey silts of the Champlain Sea occupy the riverbed. The east Montérégie region has an average annual groundwater recharge of 95 mm, approximately 8.5% of the average annual precipitations (Carrier, 2012). The piezometric map (Figure 2.5) was drawn using 53 head data from the Système d'informations hydrogéologique (SIH, 2012). This map shows that the directions of groundwater flow, generally oriented from south to north, are strongly influenced by the local topography. Piezometric heads vary from approximately 30 m in the downstream meandering portion of the river to over 70 m on the small hilltops that surround the study area. The Rock River drains the aquifer over the entire length of its course in the study area. Hydraulic gradients are generally higher in the upstream portion of the river compared to the downstream portion and average approximately 0.03 m/m.

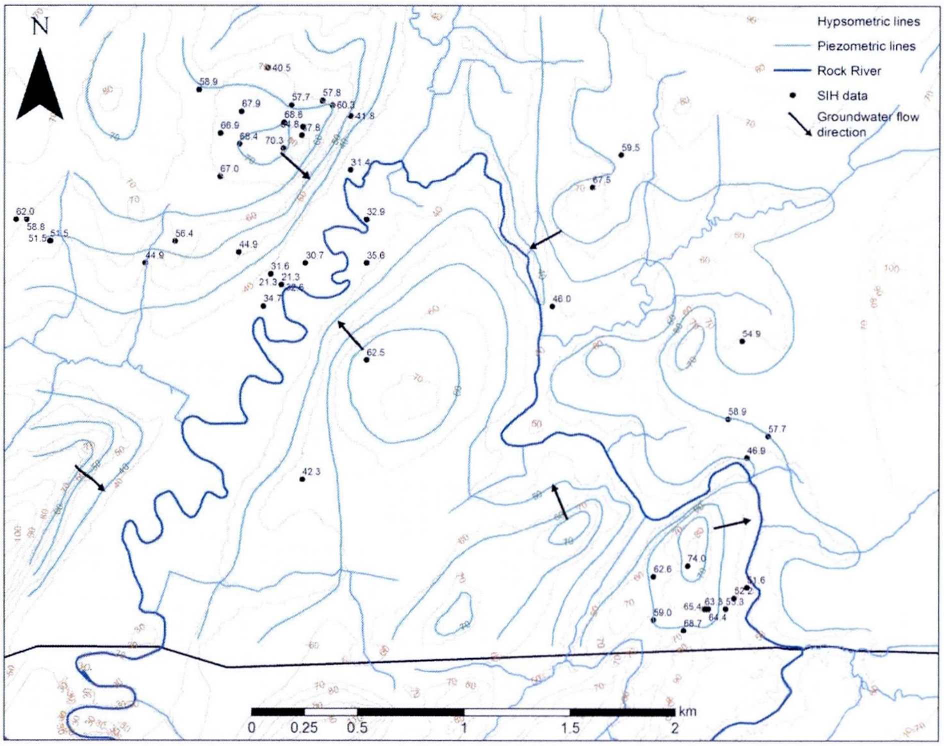

Figure 2.5 Piezometric map of the study area.

2.1.4 Wetlands

Two wetlands (A and B) were analyzed in detail in this study (Figure 2.1). Wetland A covers an area of 0.037 km^2 and wetland B covers an area of 0.034 km^2. Wetland A corresponds to an old meander loop visible on the aerial photographs of 1930 (Figure 2.6). In contrast, the river path around wetland B has not changed significantly in the last 83 years (see Biron et al. 2013 for more details about river meandering). Both wetlands are characterised by plants that fit the description of a swamp, following a detailed botanical analysis. A detailed description can be found in Moisan (2011). The wetlands consist primarily of trees growing on silty soil and the area is periodically inundated by the nearby river when it overflows its banks after high precipitation events.

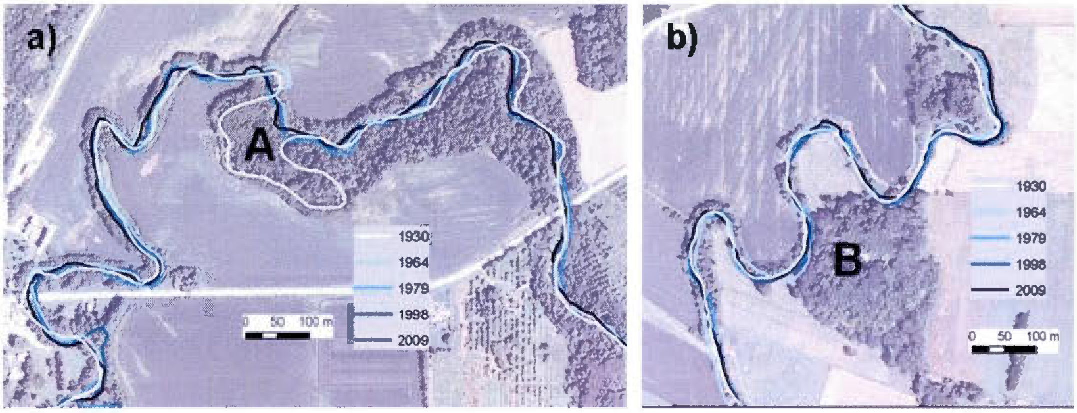

Figure 2.6 Evolution of the de la Roche River between 1930 and 2009 at a) wetland A, and b) wetland B.

2.2 Instrumentation

2.2.1 Piezometer profiles in wetlands A and B

In June 2011, three piezometers nests were hand drilled with an auger along a transect perpendicular to the river within each wetland (Figure 2.7). Each transect position and elevation was accurately determined via differential global positioning system (DGPS, Trimble R8GNN) to produce a digital elevation model of each wetland. Wetland A topography has values ranging from 33 to 43 m. Wetland B is more flat with an elevation of about 31 m throughout the entire area. The piezometric transects have a length of 110 and 190 m for wetland A and B, respectively. The piezometers have a diameter of 2.54 cm, and a total length of 3.45 m and 4.95 m respectively with a screened casing of 0.30 m. The depth of the shallow and deep piezometer in each nest was 3.15 and 4.65 m, respectively (Figure 2.8). From November 2011 to October 2012, Solinst (LTC Levelogger Junior) pressure transducers were placed within each of the shallower piezometers to measure the water table level every 15 min. All time-series were corrected for atmospheric pressure with data produced from a Solinst pressure transducer (Barologger Gold) located at wetland B.

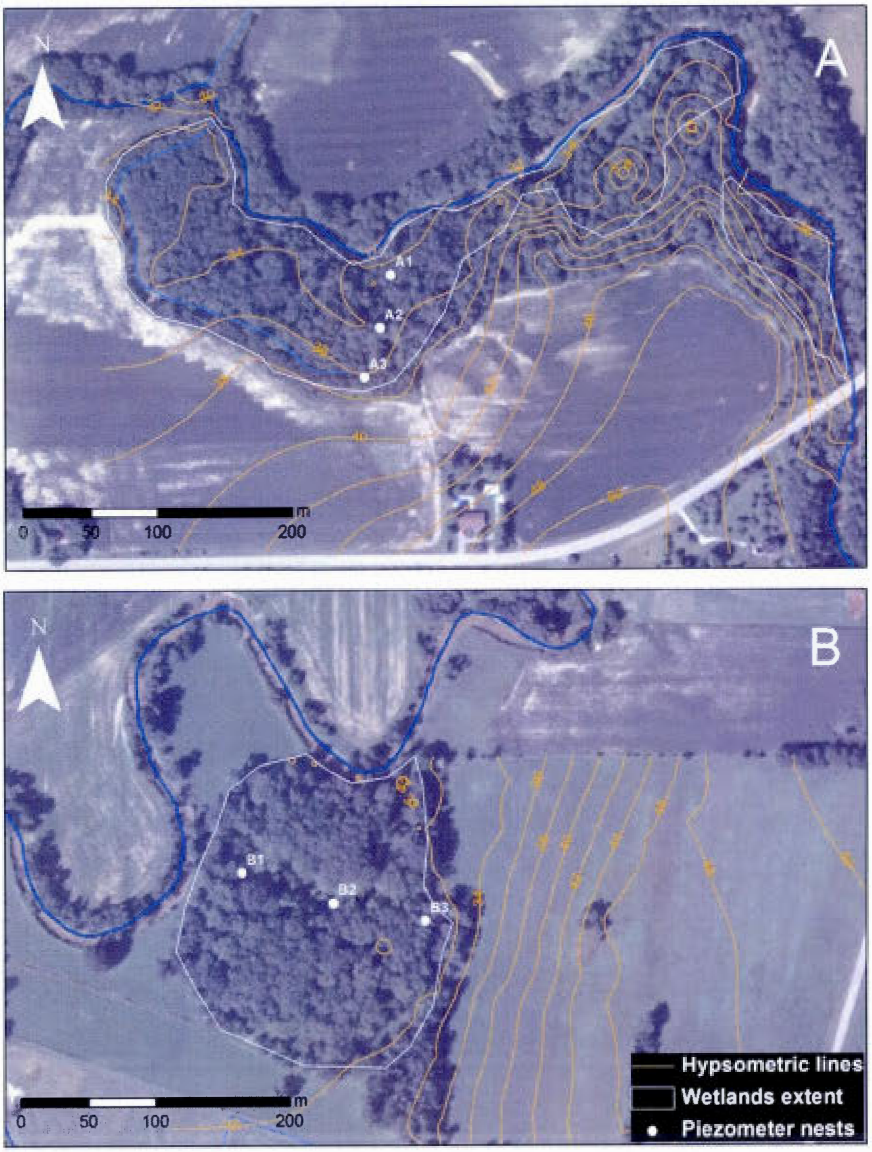

Figure 2.7 Wetland elevation change and piezometer nest locations.

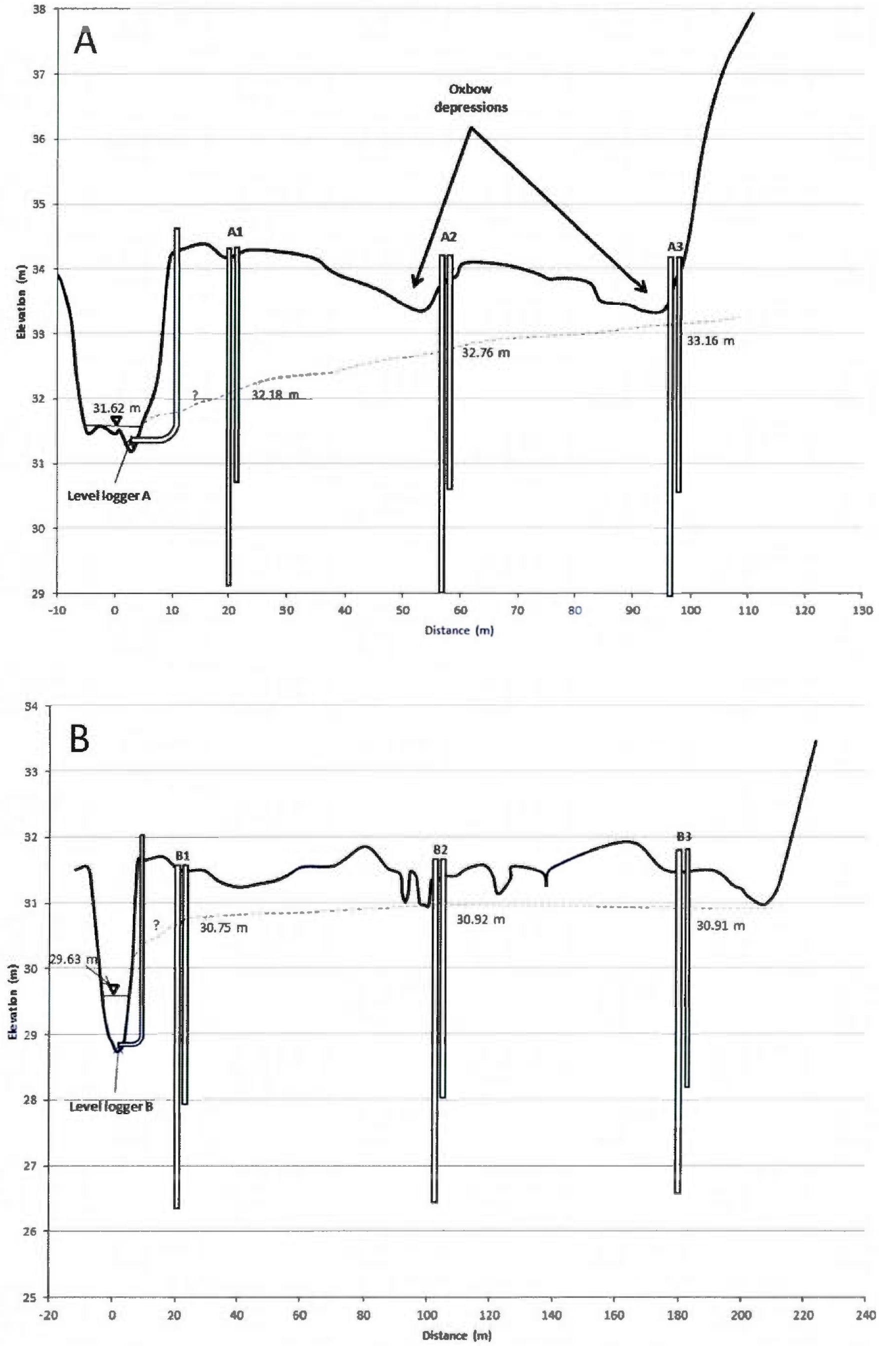

Figure 2.8 Piezometer nest transects.

2.2.2 Temperature sensors in the river

In June 2011, eight Hobo sensors that measure temperature every 15 min were installed on the riverbed over the total river length (Figure 2.1B). Six sensors were recovered in September 2011. In May 2012, eight sensors were re-installed in the same locations and six were recovered in November 2012. The other sensors could not be retrieved from the river sediments and were considered lost. The Solinst sensors installed in the piezometers and in the river (see below) also recorded temperature every 15 minutes (see Figure 2.1B for sensor localization).

In the summer of 2012, a fine-resolution spatial and temporal analysis on the temperature variability in the wetlands was performed using a DTS (Agilent Distributed Temperature Sensor, N4386A). This 1.5 km fibre optic cable was installed in the river for several days and measured the temperature at every meter every 15 minutes (Figure 2.9). Wetland A measurements were recorded from July 9 to 16, and wetland B measurements were recorded from July 29 to August 1. The maximum air temperature during these two periods was 30°C and did not vary significantly during the sampling period. GPS points were recorded at regular intervals to georeference the DTS and analyze the spatial variability of the temperature. The vegetation cover and depth of the river were also georeferenced to determine the cause of the detected cooler zones (shaded area, greater depth, groundwater inflow).

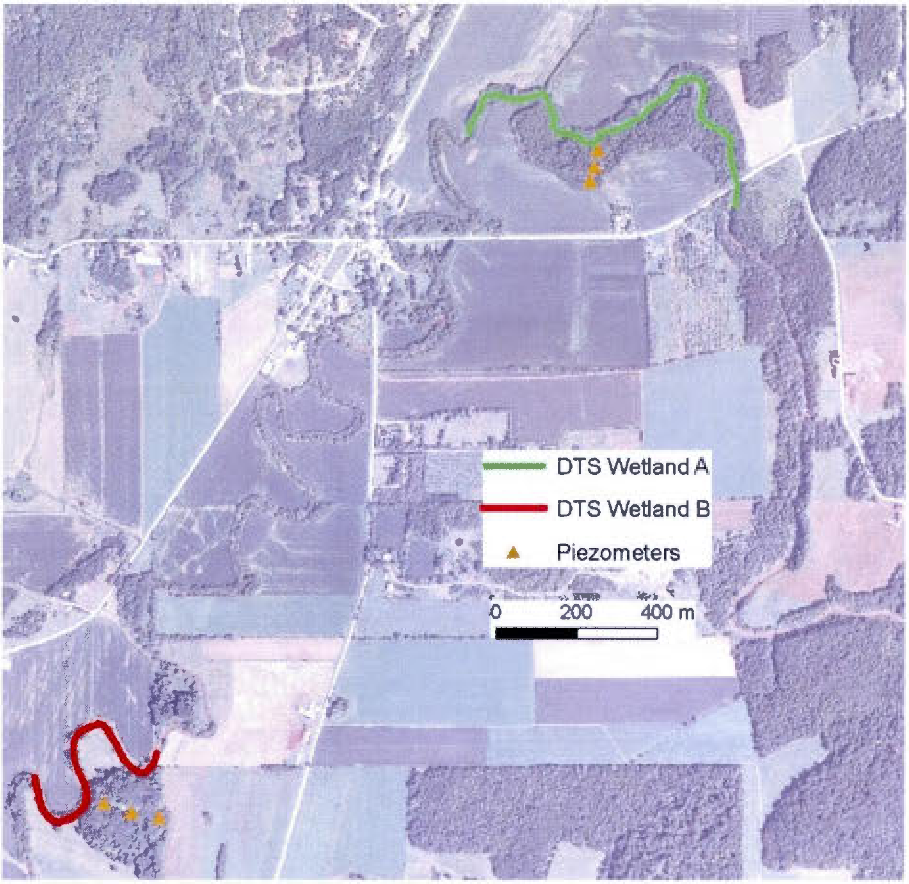

Figure 2.9 DTS cable installed near wetland A (from July 9 to 16, 2012) and wetland B (from July 29 to August 1, 2012).

2.2.3 Water levels and discharge measurements

A custom tubing setup was installed in the river adjacent to each wetland transect. Within each tube, a Solinst pressure transducer was installed to measure the water level of the river every 15 min. Water levels were measured between June 2011 and October 2012 near wetland B, and from June 2012 to October 2012 near wetland A. The exact position of the Solinst sensor was obtained with a DGPS. All time-series were corrected for barometric pressure from the Solinst Barologger.

A gauging station operated by the Centre d'Expertise Hydrique du Québec (CEHQ) measures discharge every 15 minutes since 2001 upstream of the two wetlands (station 030425; see Figure 2.1B for localization). The average daily discharge from 2001-2012 is 1.1 m^3/s

(CEHQ, 2013). However, there have been discharge peaks of more than 35 m^3/s registered during the June 2011 to October 2012 study period. Discharge was also measured six times adjacent to each wetland (see Figure 2.1B, locations LLA and LLB) during the summer 2012 using an acoustic Doppler velocimeter (ADV, Nortek Vectrino).

2.3 Water sampling

2.3.1 Stable isotopes in water

Thirty-two water samples were collected for the analysis of stable isotopes in water (^{18}O and ^{2}H) in July 2011. The samples were sealed in 30 mL polyethylene bottles devoid of air and preserved at 4°C in the refrigerator to prevent contamination and evaporation until analysis. Fifteen samples were taken directly from the river, 12 directly from the piezometers, four from the oxbow lakes, and one from the municipal well. The piezometers were purged in advance to ensure the sampled water had minimal contact with the atmosphere. The analyses were completed in February 2012 using mass spectrometer in the GEOTOP Laboratory at UQAM. The results of the analysis were corrected with a calibration curve that was constructed with three reference materials normalized on the VSMOW-SLAP scale.

2.3.2 Radon

Radon-222 is a radioactive isotope with a short half-life of 3.8 days. It is produced from the decay of Radium, ^{226}Ra, in all rocks. It accumulates in liquid form in confined and semi-confined aquifers, however once released it quickly degasses to the atmosphere. It is therefore expected that groundwater would have higher concentrations of ^{222}Rn than surface water. Thirty-two samples were collected for analysis in August 2012 during a period of low flow in the river ($Q = 0.02$ m^3/s). Fourteen samples were taken directly from the Rock River, three from its tributaries, nine from households that are sourced by wells, and six from the wetland piezometers. The piezometers were purged in advance to ensure the sampled water had minimal contact with the atmosphere. The direct method of analysis was used for these samples because they did not contain the necessary volume of water to use the extraction method. A 3.0 mL sample was collected with a syringe and inserted into 4.5 mL of Maxilight Hidex scintillation liquid contained in a 10 mL glass vial. The rest of the samples were collected in 250 mL glass bottles devoid of air to be analyzed with the extraction method in the laboratory.

Radon-222 was analyzed using a Hidex (LS 300) liquid scintillometer at UQAM using the protocol developed by Lefebvre et al. (2013).

2.4 *In situ* tests

2.4.1 Slug tests

A slug test is an *in situ* permeability test. In August 2012, two rounds of tests were completed in the shallower of the two piezometers in each nest. The pressure transducers were set to record water levels every second and approximately 150 mL of water was added to the piezometer to effect a hydraulic head change of approximately 30 cm. The rate at which the water level returned to its initial hydraulic head allowed the calculation of the hydraulic conductivity (K) using the Hvorslev method (Hvorslev, 1951).

2.4.2 Granulometry

Eight soil samples were collected by hand drilling with an auger to a maximum depth of 3.40 m near each piezometer nest. The samples were analyzed in the lab by soaking them in water, to prevent pilling of fine clay particles, and filtering with meshes ranging from >2 mm to <38 µm to determine the sediment classification. Clay is defined as particle sizes between 0 and 2 µm, fine silt between 2 and 20 µm, silt between 20 and 50 µm, fine sand between 50 and 200 µm and sand between 200 µm and 2 mm (Clément and Peltain, 1998).

2.5 Modelling and temporal analyses

2.5.1 Radinl4

Radinl4 is an Excel model that calculates the rates of groundwater inflow to streams from environmental tracers (Cook et al., 2008). In the current research, running the model required values for radon activity and electrical conductivity which were measured in different locations over the total length of the river, at the entrance of three tributaries into the main river and also in several bedrock wells. The river width, depth and discharge are also required along the entire length of the study area. Groundwater inflow to the river over the total river length is calibrated to reproduce measured discharge. The gas transfer velocity which describes the rate of loss of radon to the atmosphere through the water surface was calibrated to reproduce measured ^{222}Rn activities.

2.5.2 Cross-correlation analyses

Water level fluctuations in the river and in the piezometers were analyzed graphically through cross-correlation and autocorrelation analyses performed with the software PAST (Hammer et al., 2001). This type of analysis provides information on the causal relationship between the input and output time series, and can thus be used to determine the influence of one series on the other based on the lag time between the two series and on the intensity of the correlation. These analyses were used to determine the level of correlation and the time lag between 1) precipitation in the area and water levels in both the river and piezometers, 2) fluctuations of water level in the river and the piezometers, and 3) air temperature and water temperature in the river and piezometers.

CHAPTER III

RESULTS AND DISCUSSION

3.1 Geology and hydrogeology

3.1.1 Quaternary deposits and granulometry

The revised Quaternary deposits map (Figure 3.1) correctly constrains the river within the alluvium deposits, particularly in the downstream portion of the river. The bedrock coverage was extended to the west of the upstream portion of the river and on the hill to the northwest of Saint-Armand. An area of till blanket was added and another was extended in the central part of the map and an area of reworked till was enlarged north of the upstream portion of the river. Several other minor modifications were made based on the surveyed Quaternary deposits. Both wetlands are located in the area of alluvium surrounding the Rock River.

In wetland B, 46% of the analyzed particles are silt to fine silt (<38 μm) and 39% are in the range of 63 to 500 μm categorized as fine to coarse sand. There are no particles larger than 500 μm. In wetland A, 43% of the analyzed particles are fine to coarse sand (63 to 500 μm) and only 16 % are silt to fine silt (<38 μm). There are lesser percentages of particles in all other categories up to >2 mm. The sediment compositions in both wetlands appear to be divided between fine sand and fine silt, but in wetland B, the mix is skewed towards fine silt resulting in lower hydraulic conductivity (section 3.1.2) and a groundwater response (section 3.2) that is at times non-responsive to depth changes in the river. The opposite is true for wetland A.

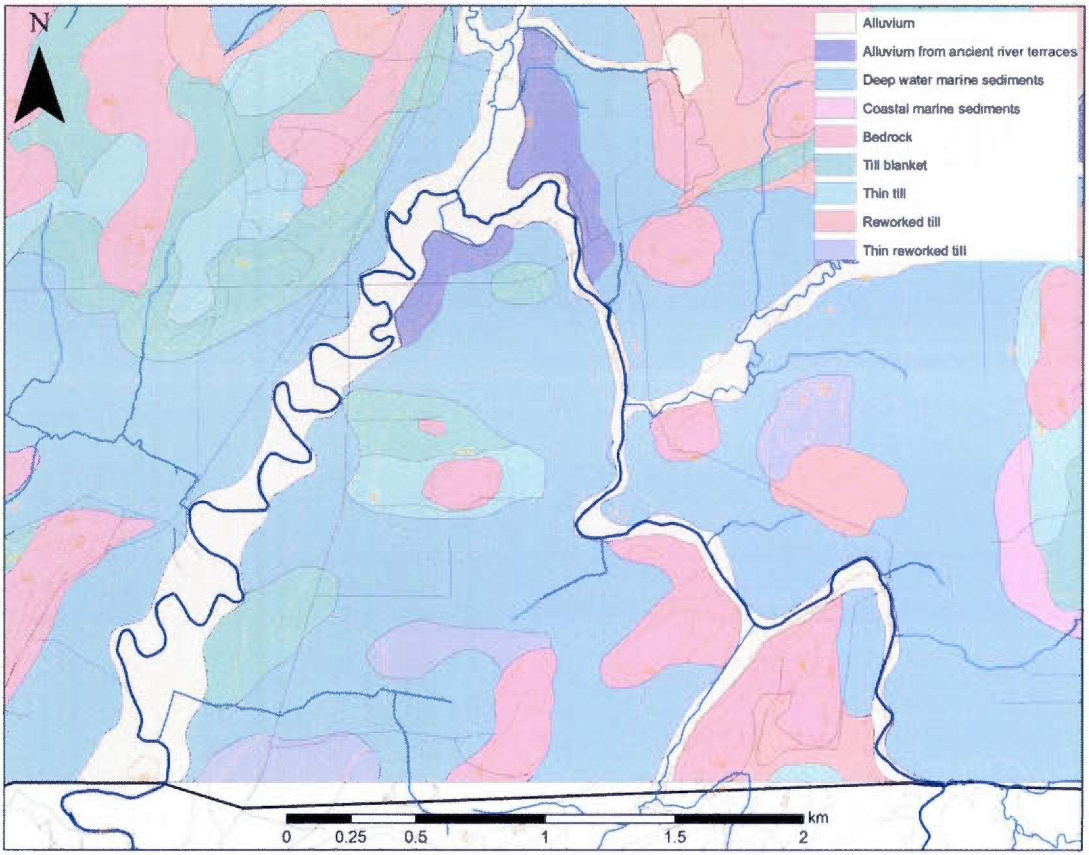

Figure 3.1 Revised Quaternary deposits map.

3.1.2 Hydraulic conductivity

Wetland B is characterized by finer sediments than wetland A, and hydraulic conductivity (K) varies from being non measurable to 5.7×10^{-7} m/s, whereas K varies between 5.3×10^{-7} and 4×10^{-6} m/s in wetland A (Figure 3.2). As a comparison, sediments with hydraulic conductivities ranging from 1 to 10^{-3} m/s are usually considered to be permeable (typically well sorted gravel and/or sand) whereas K values from 10^{-4} to 10^{-7} m/s represent semi-permeable material (very fine sand, silt, loess or loam, peat, or layered clay). For hydraulic conductivities ranging from 10^{-8} to 10^{-12} m/s, sediments are considered impervious to water (Bear, 1972). Thus, wetland A falls in the semi-permeable category, while wetland B falls on the low end of semi-permeable and also in the impervious category.

The interactions between surface and groundwater are severely impaired in wetland B with such low hydraulic conductivity values. In wetland B, the aquifer cannot reduce the impact of flooding significantly by absorbing excess surface water during a flood and slowly releasing it afterwards. Signs of flooding such as high water mark on vegetation and matted vegetation are commonly observed in wetland B after large precipitation events. In wetland A, the aquifer buffers the impact of floods more effectively with a hydraulic conductivity one order of magnitude greater than in wetland B.

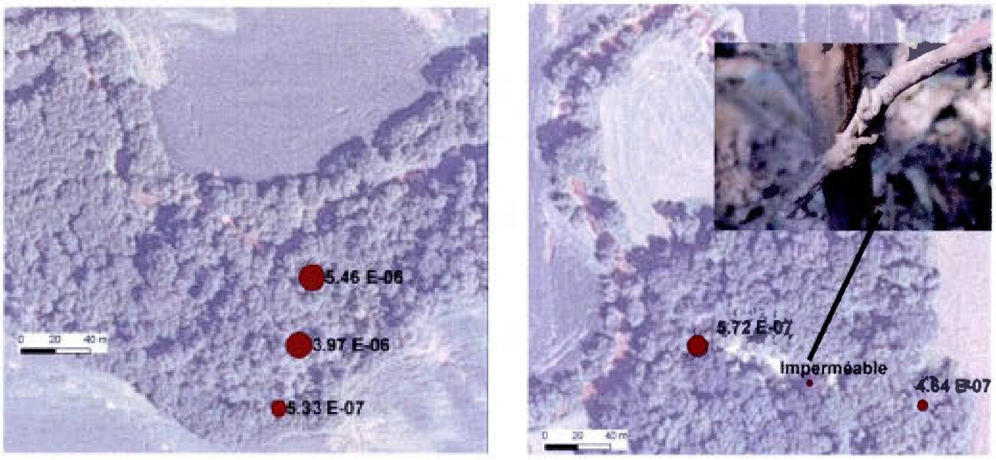

Figure 3.2 Hydraulic conductivity (K) in a) Wetland A, b) Wetland B. The photograph shows the type of fine sediments that were present at the piezometer where K was not measurable.

3.1.3 Geology, wetlands localization and the river corridor

Both wetlands exhibit very similar vegetation, are of similar size and are located in depressions close to the channel. Thus, regardless of the classification scheme that would be used, they would be considered of the same type. However, slug tests revealed marked differences in hydraulic conductivity, which will likely affect hydrologic connectivity. In terms of river corridor management and integrated floodplain management framework, these two wetlands may therefore play a different role. The fact that wetland A was in the very recent past strongly connected to the channel, prior to the cutoff which occurred sometime between 1930 and 1964, should also be taken into account in the analysis. In any case, the two wetlands are part of the "freedom space" which was determined by Biron et al. (2013) on the de la Roche

River (Figure 3.3). In the current study, it is possible that wetland B also originated from meander migration with the river corridor, but it would be at a later stage of development of the oxbow lake cycle (Gagliano and Howard, 1984).

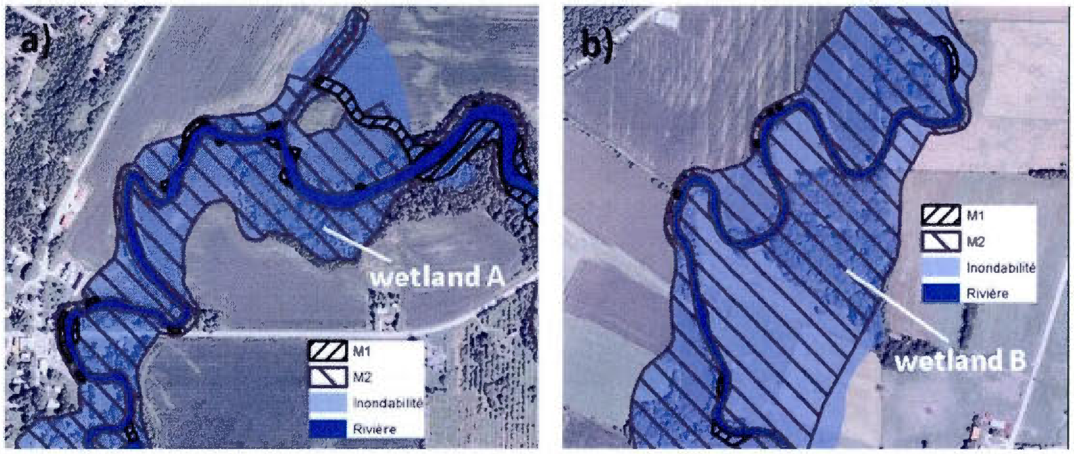

Figure 3.3 The "freedom space" of the de la Roche River near a) wetland A and b) wetland B. Both wetlands are part of the freedom space based both on flood space (blue zone) and mobility space (M2 grey diagonals), which represents mobility related to the meander characteristics (M1 zones represent mobility based on computed lateral migration rate) (Biron et al. 2013).

Figure 3.4 shows the longitudinal profile of the river from upstream to downstream. Wetland A is located adjacent the river from approximately 4000 to 5500 m while wetland B is approximately 8000 to 8700 m downstream. There is a slope difference in the river along these two locations which visibly affects the sediment size on the riverbed. At approximately 4000 m, the majority of the riverbed consists of rocks approximately 5 to 30 cm in diameter mixed with finer sediment. Heading towards 5000 m downstream where the piezometers are located and where granulometry samples were collected, the riverbed sediment gradually turns to coarse sand. By 5500 m downstream, the riverbed is mostly fine sand and silt and remains as such for the remainder of the study area. The differences in sediment size within each wetland could be explained by this change in river slope resulting in coarser sediment being deposited in wetland A and finer sediment in wetland B when flooding over the river bank occurs.

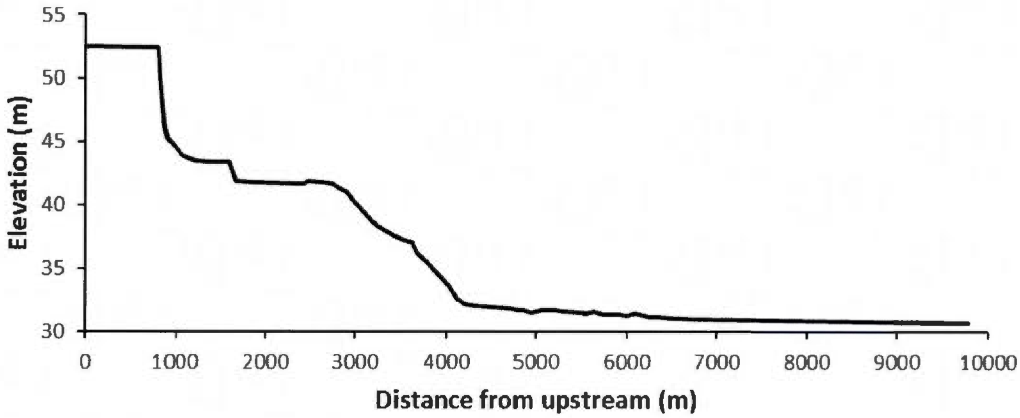

Figure 3.4 Longitudinal profile of the Rock River study area.

3.2 Water levels

3.2.1 Seasonal scale

Figure 3.5 presents data from April to October 2012. It should be noted that the levels in the river adjacent to wetland A were estimated from the measured values adjacent to wetland B before June 21, when the Solinst pressure transducer was installed (grey dashed line on Figure 3.5a). It is clear from Figure 3.5 that the water table fluctuates synchronously with the river levels near wetland A, especially for the two piezometers closest to the river (A1S and A2S; see Figure 2.8 for the position of piezometers). Starting in July, major rainfall events create a temporary increase in the level of the river beyond the elevation of the piezometers A1S and A2S. The momentary reversal of hydraulic gradients is also observed for two major events in the fall (September 5 and October 6). In wetland B, the aquifer response to changes in the river water level is much lower. The groundwater levels gradually decline throughout the summer of 2012 until the 61 mm precipitation event on September 5, which causes a sudden increase in river water level, with a rise of 1.5 m for piezometer B3S. For this event and for the 26 mm precipitation event on October 6, levels in the river temporarily exceed the levels in the three piezometers. These results indicate that the river is more dynamically connected to the riparian zone in wetland A than in wetland B.

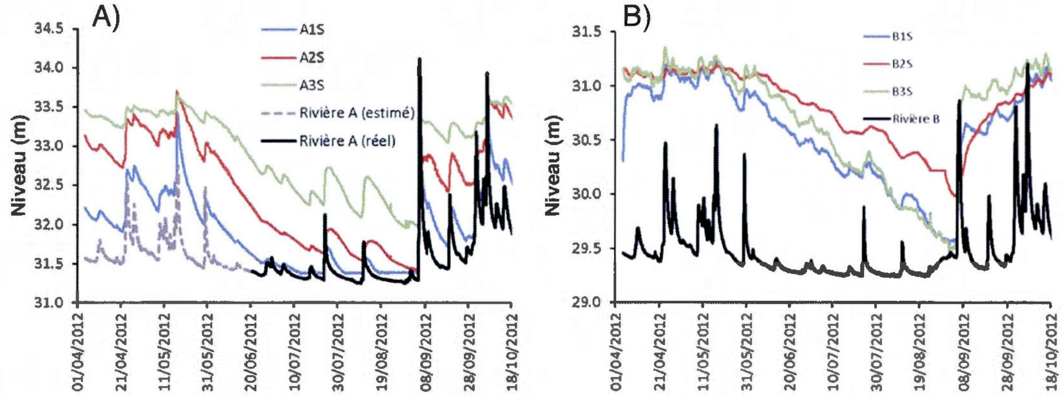

Figure 3.5 Changes in water levels (elevation above sea level) in the river (black line) and in the piezometers from April to October 2012 for A) wetland A and B) wetland B (see Figure 2.7 for piezometer locations).

3.2.2 Precipitation events scale

Four precipitation events were analyzed in more detail in 2012: July 23 (59 mm of rain), September 5 (61 mm of rain), October 6 (27 mm of rain) and October 19 (35 mm of rain) (Figure 3.6). The heavy rain in July did not result in a significant flood event (peak discharge of about 2 m^3/s), whereas the early September event, nearly identical in terms of total prescipitation, generated a peak flood of over 16 m^3/s. The two events occurring in October resulted in similar peak discharge values (10-11 m^3/s).

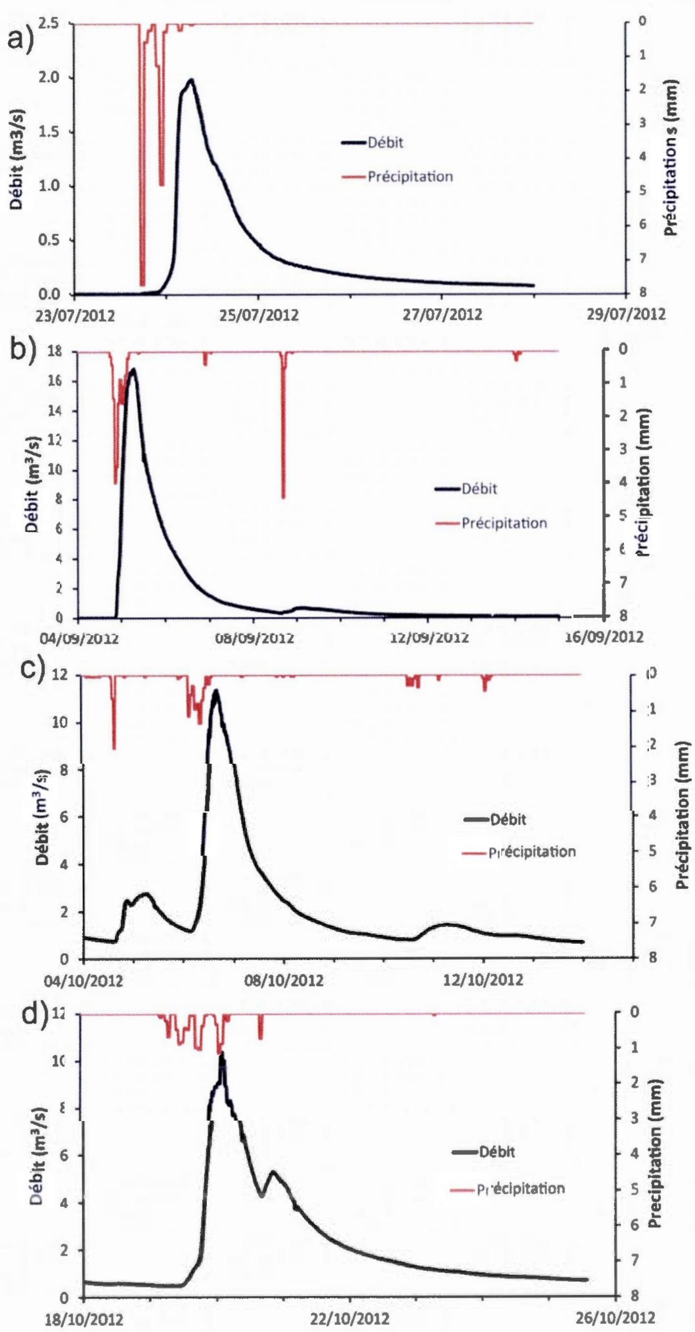

Figure 3.6 Rain and discharge (at the CEHQ gauging station) for four precipitation events in 2012: a) July 23 (59 mm), b) September 5 (61 mm), c) October 6 (27 mm) and d) October 19 (35 mm).

The contrast in the response of the two wetlands is also apparent at the event scale (Figure 3.7). In July, the precipitation of 59 mm had an impact, albeit small, on water levels in the three piezometers at wetland A (Figure 3.7a). However, the change in piezometers at wetland B was negligible. In September, the water level in the wetland A piezometers rises very rapidly, by 1.5 m in 15 hours for A1, and then decreases progressively (Figure 3.7b), while the water level in the wetland B piezometers rises more gradually and continues to rise for several days after the rain. There is also a cap on the water level in wetland B indicating a spreading of the flood (hydrograph with shark fin shape, Figure 3.7b) in the swamp (this behavior is not observed in wetland A). During both floods in October, the groundwater level remains nearly constant and at the same water level for the three wetland B piezometers, while groundwater levels fluctuate with that of the river and are lower for the wetland A piezometers that are closest to the river (Figure 3.7c,d). Note that the spreading of the flood (shark fin shape hydrograph) is also observed for the October 6 event at wetland B (Figure 3.7c), although it is not as pronounced as for the September 5 event.

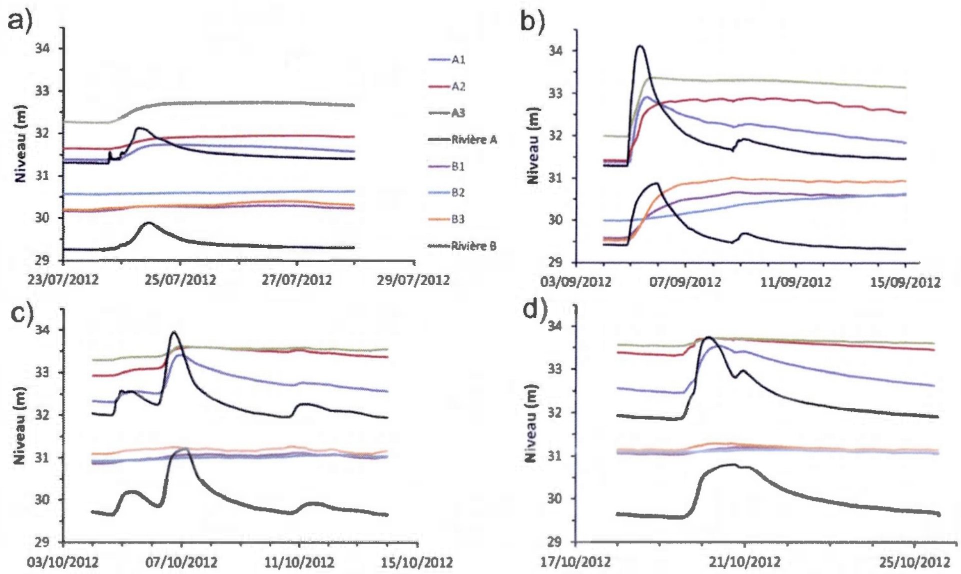

Figure 3.7 Change in water levels (elevations above sea level) in the river and in the piezometers for both wetlands to rain events occurring on a) July 23 b) September 5, c) October 6 and d) October 19 (see Figure 3.5). Note that the elevation in wetland A (located upstream) is always higher than in wetland B (downstream).

Water levels in wetlands A and B show highly contrasted responses to precipitation events. This can be linked to the geology of the surrounding areas and to the processes that led to their development. As mentioned above, wetland A has developed from an ancient meander. This probably influences the fine hydrostratigraphy of the sediments in this area and could explain its more important hydraulic connectivity. In contrast, wetland B has developed on fine sediments. It reacts slowly to precipitation events and to high river flows, but appears to store more water as a temporary surface reservoir.

3.2.3 Cross-correlation analyses

The contrast in the hydrological connectivity between wetlands also appears clearly in the cross-correlation analysis (Figure 3.8). For wetland A, the correlation is very high (from 0.90 for piezometer A1 to 0.77 for piezometer A3) and the time lag between the peak in the river and in the piezometers is low (6 to 21 hours). The maximum correlation for wetland B is 0.61, with lag times more than an order of magnitude higher, up to 330 hours (Figure 3.8). The gap is shorter in wetland A, which is explained by the coarser sediments that facilitate the transfer of the pressure wave in the riparian zone. It is expected that the lag time between the level in the river and the level in the piezometers increase as the distance between the river and a given piezometer increases, however this is not exactly the case given the granulometry of the sediments, as well as perhaps the position of the piezometers relative to hydrostratigraphic pathways that may be present in the sediments of each wetland.

The correlations between rain events and groundwater levels (Figure 3.9) are much lower than the correlations between river water levels and groundwater levels (Figure 3.8). This is explained by a significant transformation of the rain signal as it passes through the unsaturated zone. This was also highlighted by the two precipitation events of similar magnitude (July 23 and September 5, 2012) which resulted in very different responses of the water table (Figure 3.7a,b). The maximum correlations between rain events and groundwater levels are of the same order of magnitude for the two wetlands (maximum of 0.09 for wetland A and 0.05 for wetland B).

In wetland A, the time lag between river levels and groundwater levels is similar to the lag between the rain events and the river level, and shorter than the lag between the rain events and the groundwater levels. This indicates that in this wetland, the river level actually has an effect on the groundwater levels. The asymmetric shape of the cross-correlation between river levels and groundwater levels confirms that the primary function plays a direct role on the second (in the case where the two functions are simultaneously and independently influenced by precipitation, cross-correlation is symmetrical). In wetland B, the gap between the rain signal and the groundwater level is shorter than that between the river level and the groundwater level. It is therefore not possible to conclude that variations in the river level cause variations in the groundwater level.

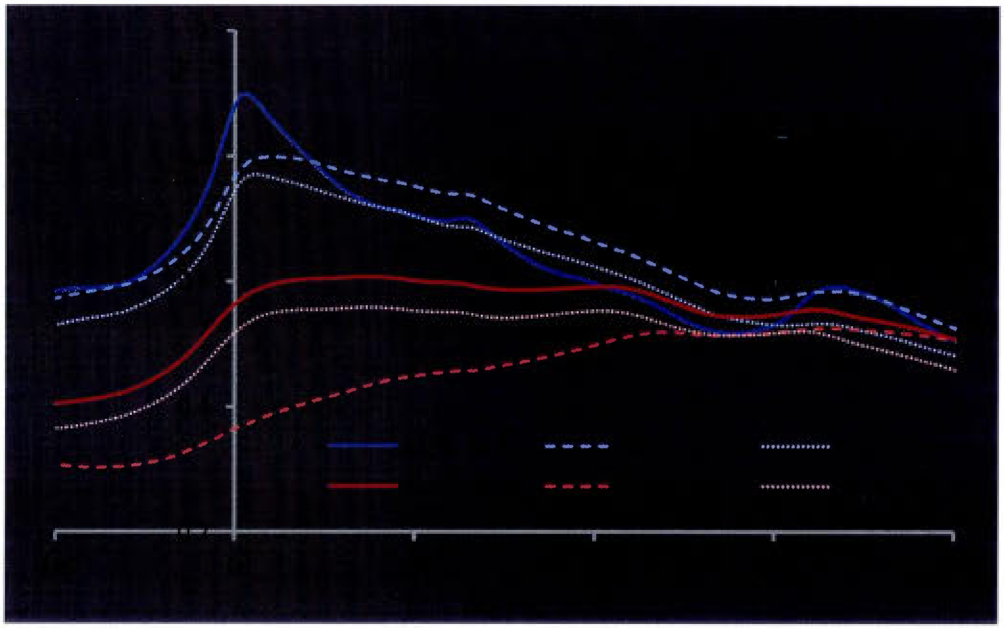

Figure 3.8 Cross-correlation between the level in the river and the level in the three piezometers for wetlands A and B in 2012.

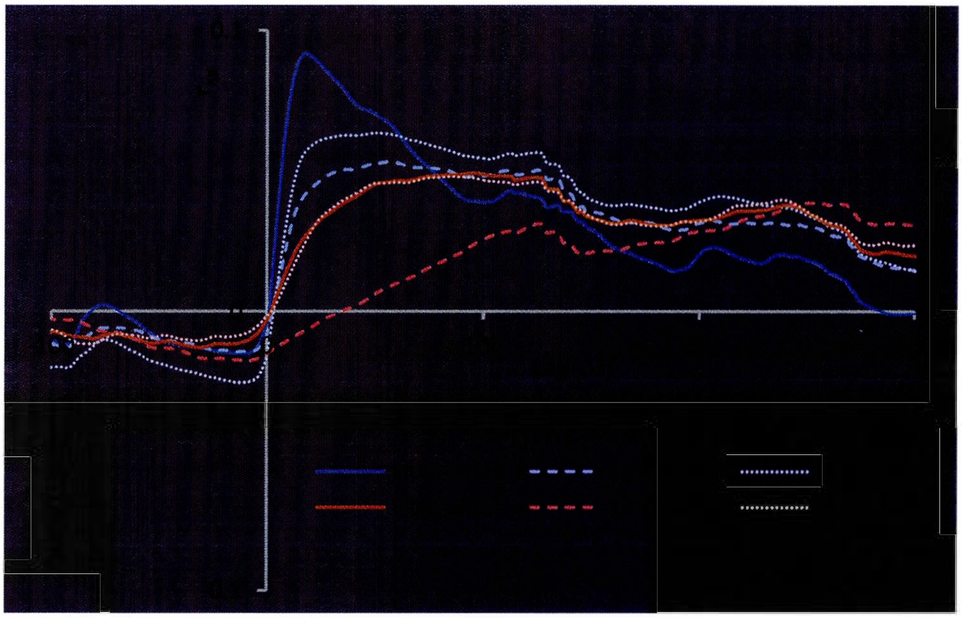

Figure 3.9 Cross-correlation between Philipsburg precipitation and the water levels in the river and in the piezometers of the two wetlands.

The pattern of cross-correlation observed at wetland A exhibits similarities with results from Cloutier (2013) on a riverine wetland in the Matane River (Gaspésie) with much coarser grain size, and thus much larger hydraulic conductivity values. As the Matane wetland is also located in a former meander loop, it seems to indicate that the geomorphic process which created the wetland, or the evolutionary stage it is at, considerably affects the hydrological response. In other words, riparian wetlands with a fairly wide array of sediment size can behave in a similar way if their hydrogeomorphological evolution is similar. Or perhaps this indicates that a certain threshold is reached between fine sand and clay, where hydrologic connectivity varies. Since grain size and hydrogeomorphological processes are closely correlated, it may in fact not be possible to distinguish them.

3.3 Water temperature

The study of water temperature dynamics is essential to properly characterize hydrological connectivity (Poole and Berman, 2001; Poole et al., 2008; Cabezas et al. 2011). The combination of continuous water level and temperature data measurements in this study allows for a better understanding of the river-aquifer connectivity. The presence of increased hyporheic water input is expected to dampen daily fluctuations in temperature in the channel and, in some cases to also modify the mean temperature (Cabezas et al. 2011).

3.3.1 Temperature changes in the wetland

Groundwater temperature in the three piezometers in both wetlands vary little over the course of a year, with a minimum of approximately 5°C generally occurring in April and a maximum between 13°C and 14°C at the beginning of October (Figure 3.10). Observed variations follow those of the air temperature during the year, without a marked change in relation to rainfall events (this was confirmed via cross-correlation analyses, not shown here). Groundwater temperature in the piezometers is therefore influenced by long-term variations in air temperature and is not under the influence of variations in the river level. This is contrary to what was observed by Cloutier (2013) on the Matane River where groundwater levels in the piezometers within 50 m of the river carried the influence of water levels in the river. This difference could be explained by the coarser sediments and higher hydraulic conductivities in the Matane River.

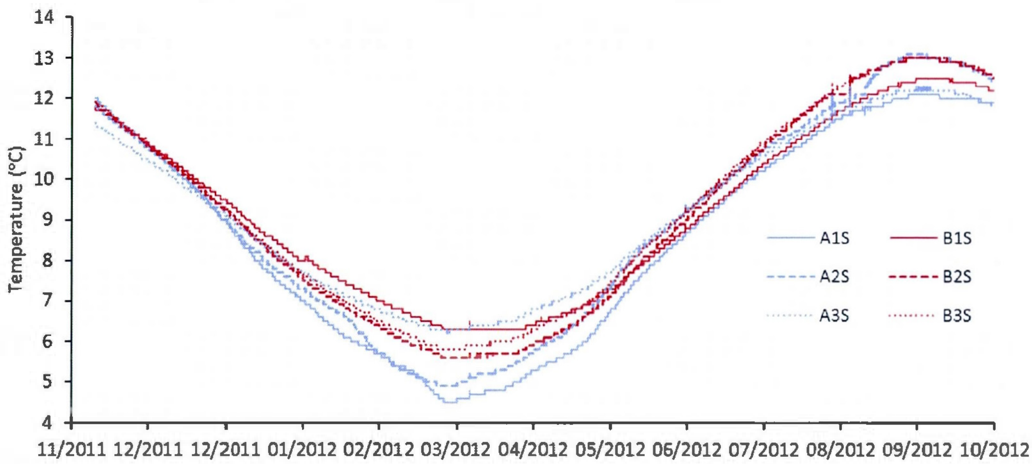

Figure 3.10 Water temperature in the piezometers in both wetlands.

At the event scale, there are marked differences in trends of river temperature between wetlands A and B following the passage of the July 23 and September 5 flood (Figure 3.11a,b). In contrast, the river temperature is almost identical for the two floods in October (Figure 3.11c,d). In July, the river temperature at wetland A follows very closely the air temperature fluctuations prior to the flood event (Figure 3.11a, green and blue lines), whereas this is less the case for wetland B (red line). Following the flood, the temperature near both wetlands follow a very similar daily pattern (distinct from the air temperature pattern) and the contrast between the two wetlands begins again after July 27. In September, the temperature rise in wetland A between September 6 and 8 occurs with diurnal cyclicality which gradually approaches that of the air temperature. During this period, temperature continues to drop in wetland B (Figure 3.11b). The contrast between the two wetlands is much smaller for the October 6 precipitation event (Figure 3.11c) and the correlation between river temperature and air temperature diurnal cycles is almost no longer apparent for the October 19 event (Figure 3.11d). The event differences between the two wetlands is thus variable in time and decreases markedly in the fall. This is illustrated by Figure 3.12 which reveals much larger amplitudes during the summer in temperature near wetland A (blue) than wetland B (red) until the September 5 event. Following this event, the river temperature near both wetlands was almost identical.

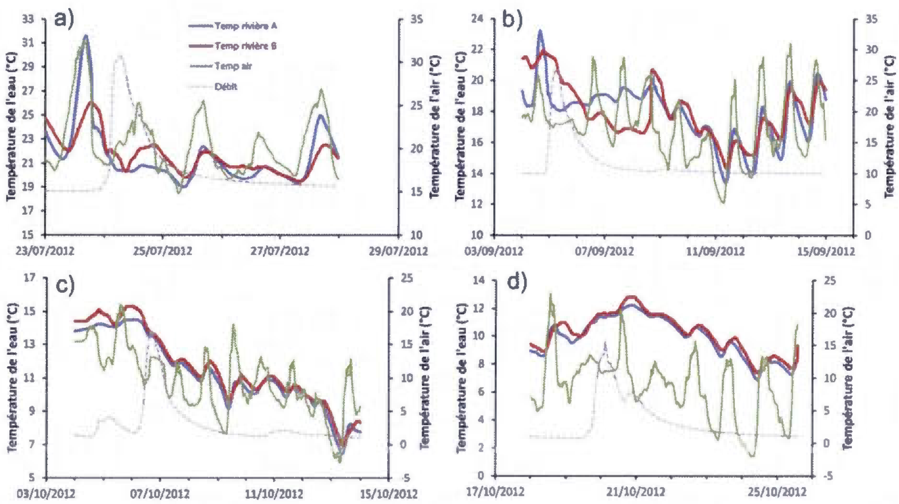

Figure 3.11 Change in air temperature (green) and water temperature in the river at wetland A (blue) and B (red) for the events of a) July 23, b) September 5, c) October 6 and d) October 19. The flood hydrograph is shown in gray (dashed line) as a guide to locate the peak discharge (discharge values do not correspond to the values on the y-axis).

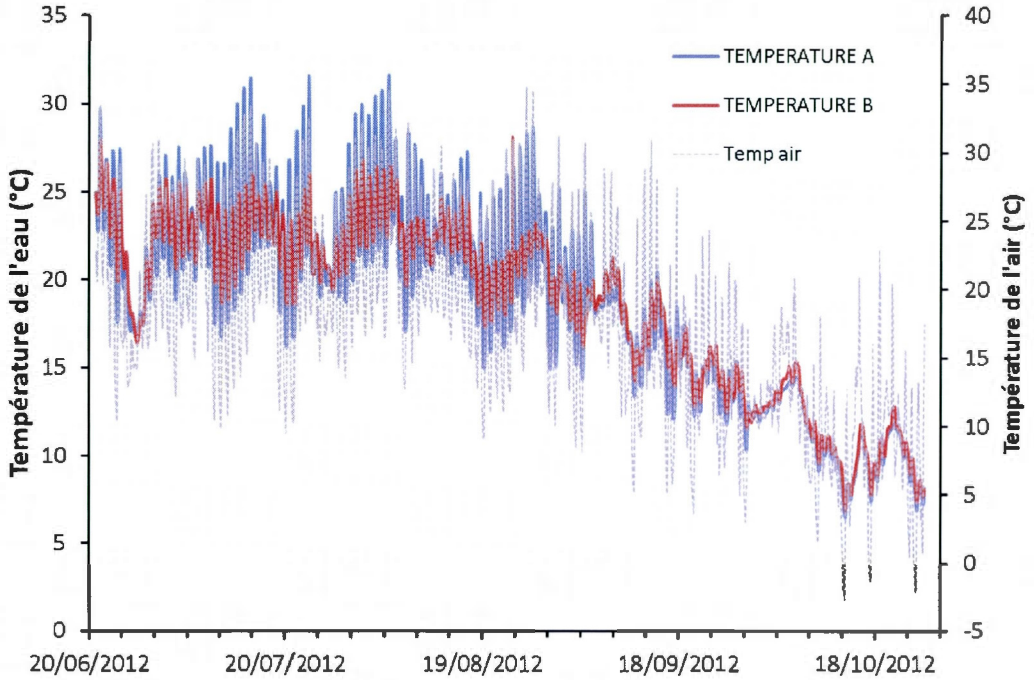

Figure 3.12 Air temperature (dotted grey line) and temperature in the river near wetland A (blue) and wetland B (red) between June and October 2012.

3.3.2 Changes along the length of the river

Figure 3.13 compares the hourly variations measured at different temperature sensors installed along the length of the river with the hourly air temperature variations. During the month of May, and later in September and October, the water temperature is similar for all sensors. Between June and August, some sensors have cooler maximum temperatures. This is interpreted as a contribution of groundwater. Figure 3.13 has been divided into two river sections, each corresponding to a similar degree of vegetation cover, that is to say, from upstream to T05 and T06 to wetland B. In the upstream portion, the T01 sensor has a very different behavior compared to the other sensors. It is likely that it was buried under sediment. The differences observed between the other sensors can be explained by varying sunlight conditions. In the downstream portion, the highest temperatures decrease between T06 and T07, while the lowest temperatures remain constant. This could indicate a greater contribution of groundwater in this portion of the river. At T08 (immediately upstream of the wetland B), the minimum temperature drops to 15°C consistently between periods of rainfall. This indicates a significant point of groundwater arrival. Minimum temperatures then rise again at the wetland B sensor.

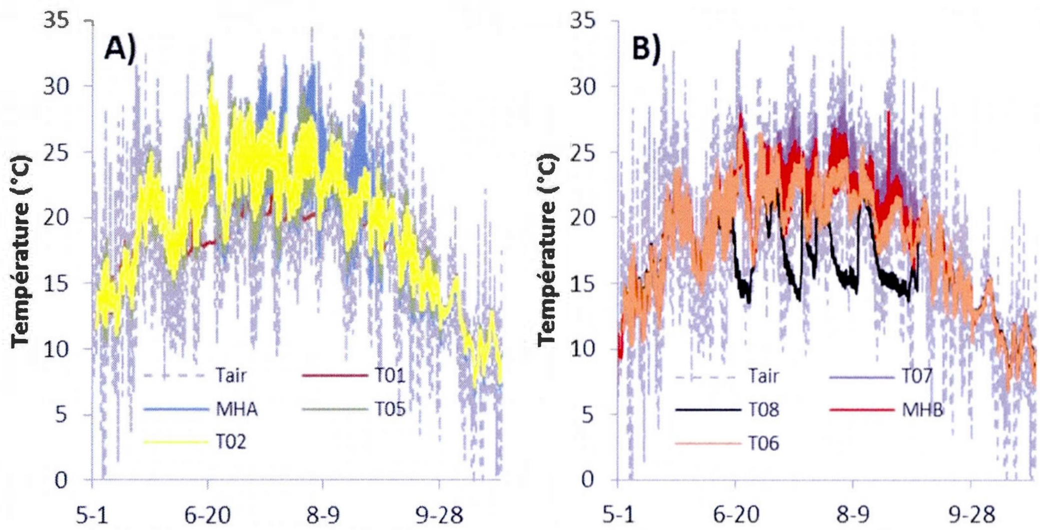

Figure 3.13 Changes in water temperature in the river from May to October 2012 A) from upstream to T05 and B) from T06 to wetland B. The air temperature is shown in gray (gray dashed line).

3.3.3 Spatial and temporal changes in water temperature using DTS

Spatial variations in temperature are also very different between the two wetlands. DTS (Distributed Temperature Sensor) data clearly show the presence of cooler and warmer areas (Figure 3.14). In wetland A, there is an area with vegetation cover in the downstream part. However, the maximum temperatures do not appear to be directly related to the shade provided by these areas as both warm areas (up to 31°C) and cool (approximately 22°C) are present (Figure 3.14A). This variability cannot be explained either by the water depth and must therefore be partly due to a contribution of groundwater that appears to be rather diffuse. The stretch of river closest to the piezometers is actually the hottest.

The maximum temperatures in wetland B show a greater spatial amplitude than in wetland A (16.6°C compared to 9.3°C) (Figure 3.14). This is due to the presence of significantly cooler water in the upstream portion of the river segment, where maximum temperatures do not exceed 10°C, even when the air temperature was 30°C. As for wetland A, the temperature variations do not appear to follow the spatial pattern of shaded areas (light green in Figure 3.14) or deeper areas, although the cooler area upstream corresponds to a relatively deep area (approximately 1.6 m).

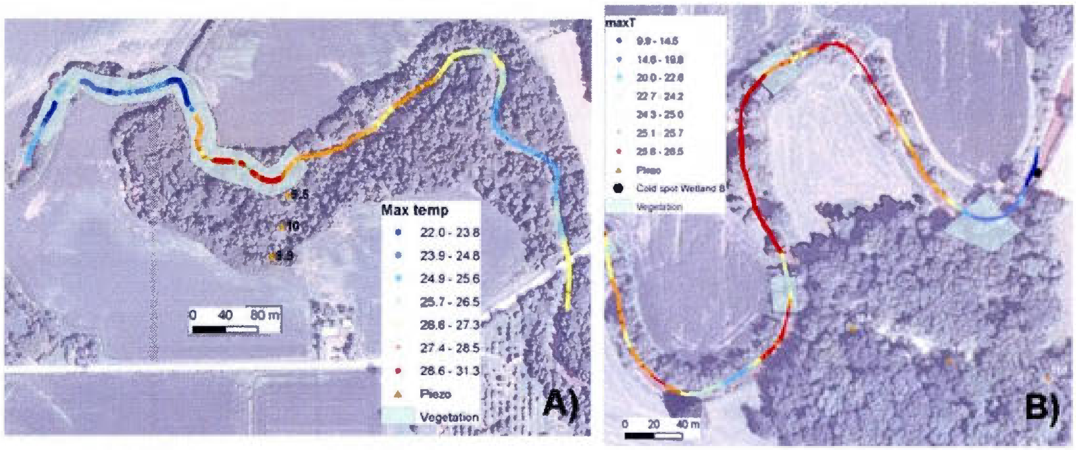

Figure 3.14 Spatial variation of the maximum temperature measured by the DTS A) wetland A and B) wet B. Note that the temperature scale is not the same in both cases.

The average water temperature at each DTS point of measurement was greater at wetland B than at wetland A, with the exception of the first 100 m, where an influx of groundwater abruptly lowers river temperature (Figure 3.15). This area is consistent with the water temperatures observed at T08. The maximum temperature in both wetlands is similar between 100 m and 400 m on the DTS line but the maximum temperature increases markedly in wetland A from 400 m onwards. It is interesting to note that reductions in average and maximum temperature are localized around wetland B. These locations can be interpreted as point-source contributions of groundwater.

The standard deviations on the measured DTS values at these locations are also lower, especially in the first 100 m, confirming that the water temperatures have a lower amplitude due to a constant supply of groundwater (Figure 3.16). In wetland A, the standard deviations are relatively small up to 700 m, probably indicating an area of diffuse groundwater supply. Thereafter, the standard deviations increase sharply.

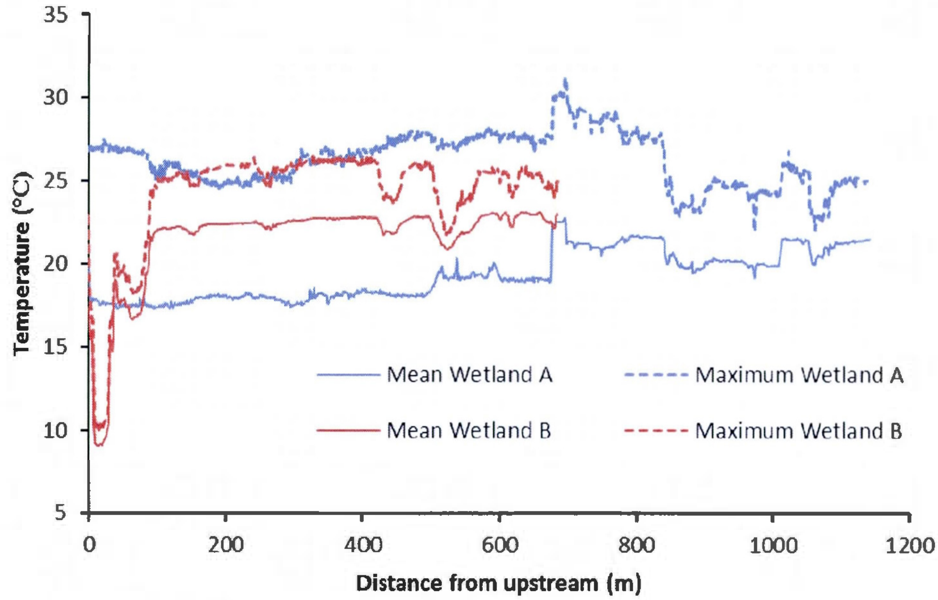

Figure 3.15 Average and maximum temperatures measured using the DTS at both wetlands.

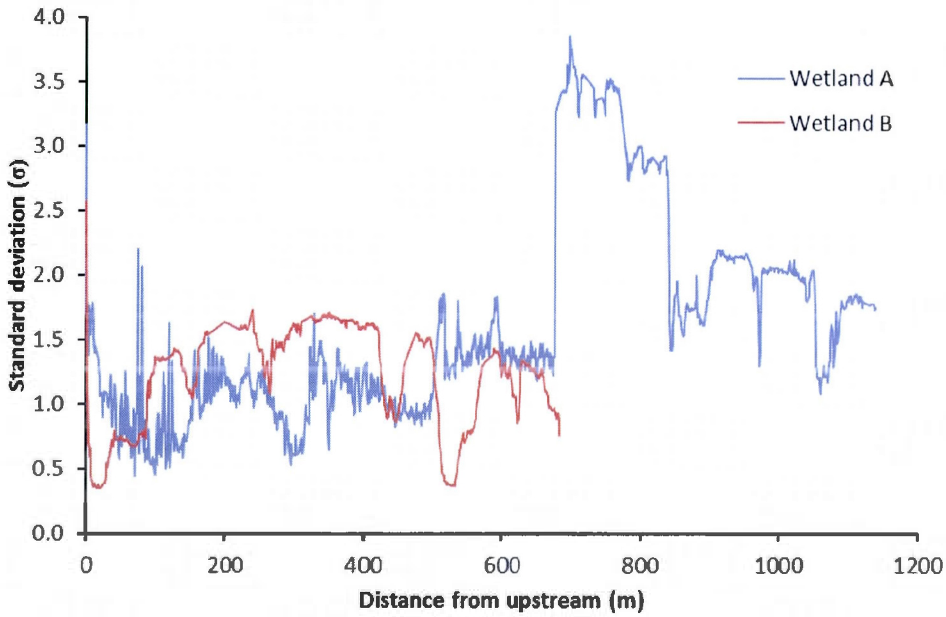

Figure 3.16 Standard deviation of the measured temperatures using the DTS at both wetlands.

The results from high spatial resolution measurements of temperature using DTS highlight how water temperature can vary markedly over short distances. It also illustrates again the contrast between the two wetlands, with much higher maximum temperatures measured in wetland A (Figure 3.14). This is better seen when plotting temperature using the same colour scheme (Figure 3.17). The maximum temperature pattern alone would seem to indicate stronger hydrological connectivity between wetland B and the river than between wetland A and the river, which is in contrast to an interpretation based on water levels. As these temperature measurements were taken at very low flow, it may indicate that the river-aquifer dynamics varies with flow stage. At very low flow, baseflow contribution at wetland A, despite an overall higher hydrological connectivity, may be smaller than at wetland B, therefore allowing for rapid warming of the water in the channel. In wetland B, the influx of groundwater observed with water temperature sensor T08 and with the DTS probably provides a cool input to the river even during low flows. These results therefore support the hypothesis that groundwater contribution in wetland A is more diffuse than in wetland B (see section 3.4.2 below).

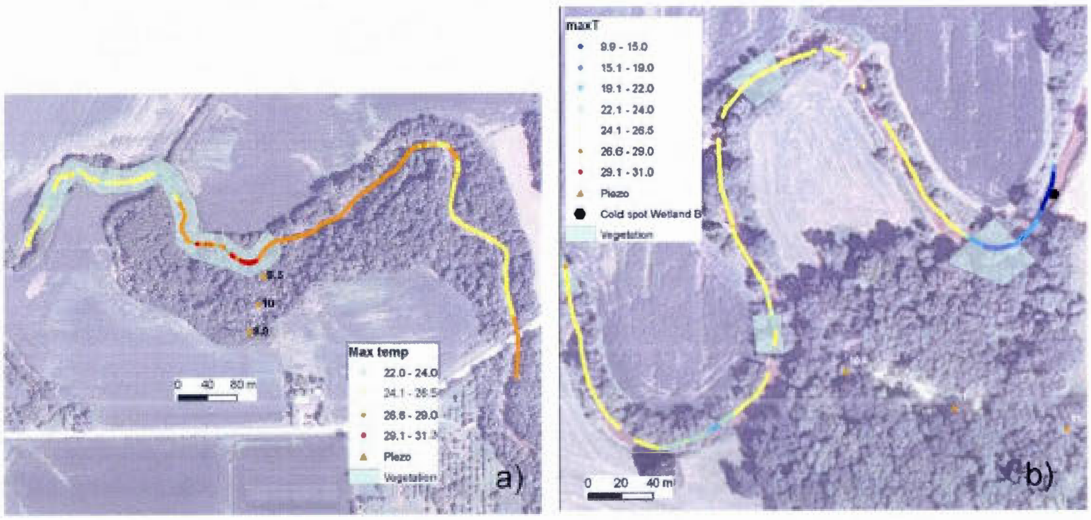

Figure 3.17 Maximum temperature data obtained from DTS measurements from Figure 3.15 for a) wetland A and b) wetland B, here presented using the same colour legend.

3.4 Isotopes

3.4.1 Stable water isotopes

Local rainfall data are not available, therefore the local meteoric water line was generated for the study area (Bowen, 2013). The range of values shown reflects annual rainfall variability corresponding to an altitude of 40 m (Figure 3.18). The waters samples analyzed for this study fall immediately below this line. Water from the aquifer (i.e. municipal well tapping the bedrock aquifer) is the most depleted, reflecting the spring recharge of the groundwater. The river water is more enriched than the aquifer, but more depleted than the June and July precipitation. This reflects a mixing of inputs from rainfall and groundwater inflow. The isotopic signature taken from the surface water of the two wetlands diverges away from the global meteoric water line, indicating the presence of evaporation. Water from piezometers A1S, A2S, A3S, A3L and B3L has a similar isotopic composition to the aquifer while the water from piezometers B1S, B1L and B2S is similar to that of the river. The surface deposits located near the latter are less permeable than elsewhere on the piezometric profiles and precipitation is likely to infiltrate more slowly. Other piezometers (A1L, A2L, B2L and B3S) have an isotopic composition between that of the river and aquifer. This indicates that all piezometers are influenced by groundwater, but to varying degrees.

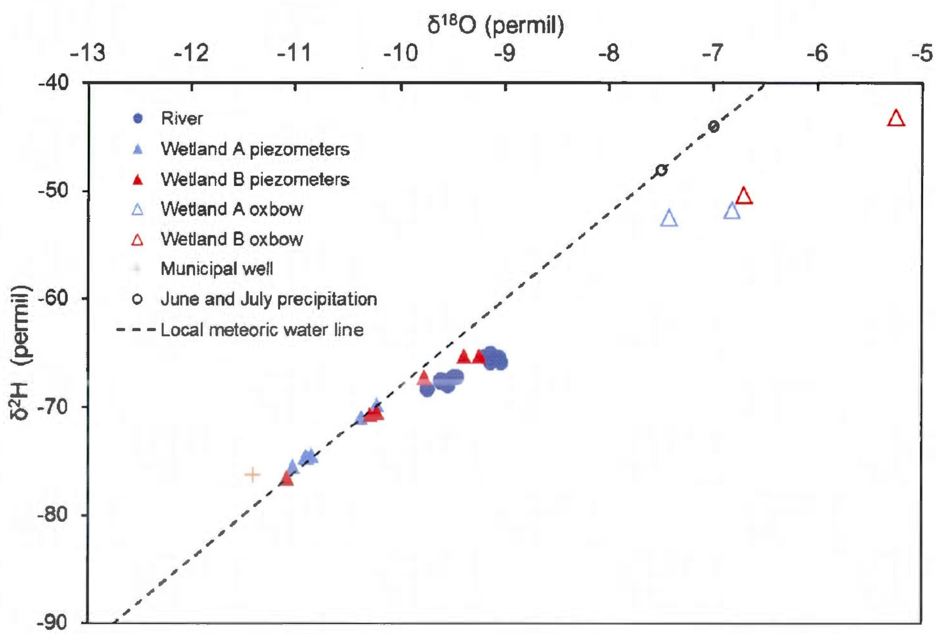

Figure 3.18 Stable water isotope samples analyzed from the River Rock.

3.4.2 Radioactive isotope ^{222}Rn

Radon activity (^{222}Rn) measured in wells ranged from 2.79 to 159.32 Bq/L and are shown in Figure 3.19. The highest values are observed in the upstream portion of the study area, but it is difficult to identify a spatial pattern. This reflects the high spatial variability of radon production in the aquifer. In the river, ^{222}Rn activity is relatively stable, except immediately upstream from wetland B where it increases rapidly. The area with much cooler temperatures upstream (Figure 3.14B) corresponds very clearly with higher radon concentrations at this location (Figure 3.19). In the portion of the river that runs past wetland A, the concentrations are about half those past wetland B (between 0.22 and 0.30 Bq/L), but they vary less spatially, which may reflect a more diffuse contribution of groundwater very similar to what is present in the rest of the river. The spatial variation of radon concentrations reveals that, despite greater hydrological connectivity in wetland A, the contribution of groundwater is more important in wetland B. In the wetland A piezometers, ^{222}Rn activity varies from 4.57 to 7.39 Bq/L while in wetland B, it ranges from 1.42 to 8.89 Bq/L. These results confirm that the piezometers in both wetlands are influenced by groundwater.

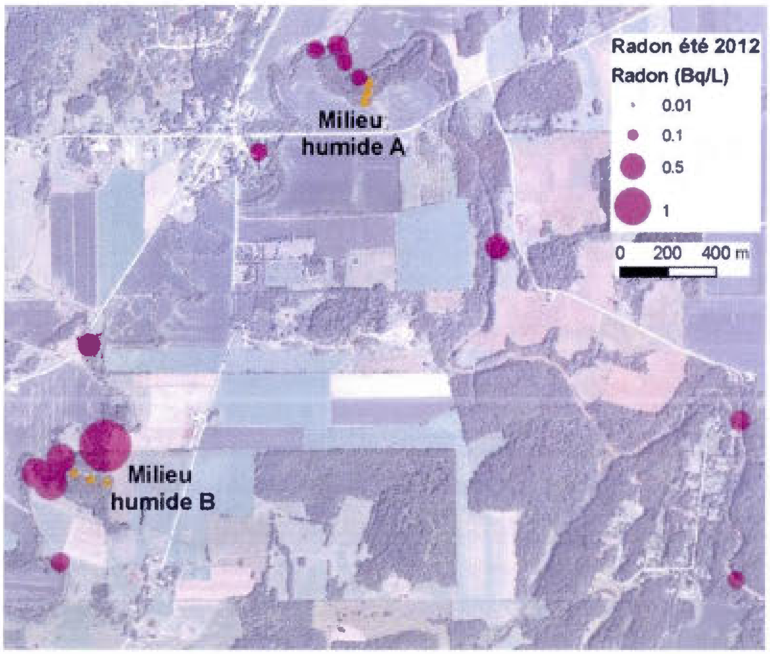

Figure 3.19 Radon concentration variability along the Rock River during the sampling conducted in the month of August 2012.

In the calibrated Radin14 model (Cook et al., 2008), groundwater inflows are similar up to 7.5 km from upstream (range from 0.1 to 0.2 $m^3/d/m$). They increase significantly when approaching wetland B, reaching 2.8 $m^3/d/m$ immediately upstream of the wetland (in the area of point-source groundwater inflow identified above), and dropping to 0.3 $m^3/d/m$ downstream of the wetland. Available measurements of river discharge did not confirm that the groundwater inflows are actually more important between T05 and T08 (downstream half of the river). The total contribution of groundwater to the river in the study area is 3.09 m^3/d. This contribution corresponds to 100% of the increase in discharge from upstream to downstream for the study area, which is quite plausible since the sampling was conducted during a low flow period (no direct or hypodermic runoff) and the tributaries have a negligible contribution (approximately 150 m^3/d).

Figure 3.20 shows the total measured and simulated river discharge, as well as the measured and simulated ^{222}Rn activity. These results confirm that the area surrounding wetland B is an area of significant groundwater inflow, despite the presence of fine sediments in this portion of the river. The groundwater contribution in the area surrounding wetland A is marginally higher than further up the river. Given the very different behavior of the two relatively similar wetlands in most respects, the aquifer contribution in the area surrounding wetland B cannot be directly linked to the presence of the wetland.

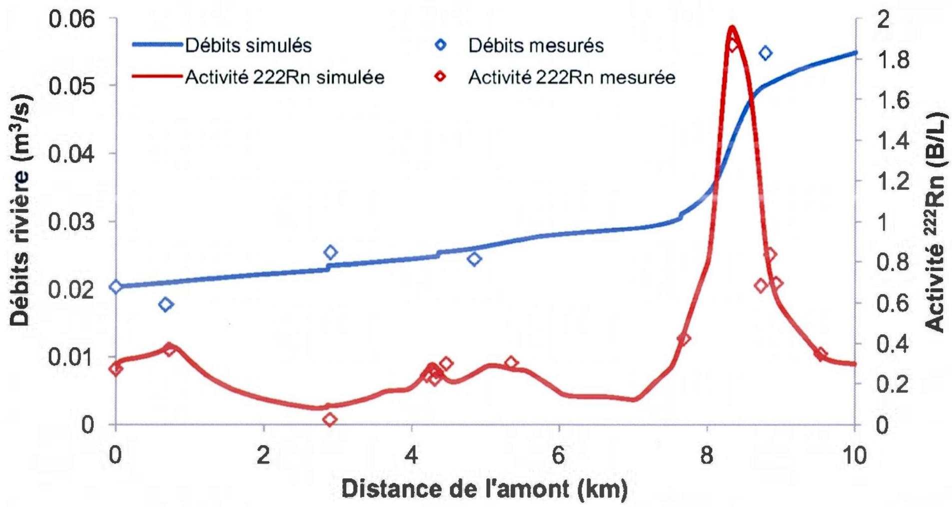

Figure 3.20 Measured and simulated total discharge and ^{222}Rn activity.

CHAPTER IV

CONCLUSION

The objective of the project was to increase our understanding of the interactions between a river (the Rock River), two wetlands located within the freedom space of this river, and the aquifer in the Monteregie region of Quebec. Although the beneficial hydrological functions of riparian wetlands are generally recognized by scientists and practitioners, these interactions remain poorly understood. Hence, fundamental knowledge on hydrological connectivity in these environments, such as provided in this research, is highly valuable for sustainable river corridor management.

The main finding of this research is that aquifer-river connectivity varies significantly in space. The two riparian wetlands which were studied in detail in the Rock River watershed exhibited many similarities in terms of size, vegetation and proximity to the channel. Despite this, significant differences were noted in the relationship between water table and river channel levels fluctuations between wetland A, which is located in the former path of the channel in a zone where meander cutoff occurred somewhere between 1930 and 1964, and wetland B where the river channel has remained in the same position for at least 83 years. Differences in hydrogeomorphology and geology are probably responsible for the distinct hydrological response at these two wetlands.

In addition to the analysis of water level fluctuations between the two studied wetlands and the river, interactions between the river and wetlands was assessed through detailed measurements of water temperatures (DTS) and ^{222}Rn activity, which both carry considerable information on aquifer-river connectivity. Groundwater inflow to the river is apparently diffuse over most of the study area with the exception of a spot just upstream of wetland B, where a significant groundwater inflow was evident from both temperature data records and radon activity. Given the very different behavior of the two relatively similar wetlands in most respects, the aquifer contribution in the surrounding wetland B cannot be directly linked to the presence of the wetland.

Increasingly, riparian wetlands are seen as a key component of successful floodplain restoration projects as they can play an important role in attenuating of floods and low flow, in limiting the duration and spatial extent of high temperature episodes during the summer which may enhance algal blooms (e.g. cyanobacteria) and in improving water quality, particularly in agricultural watersheds where diffuse pollution linked to nitrate and phosphorus accumulation is important. The role of riparian wetlands is also believed to become even more important in future with larger risk of heat waves and extreme events due to climate change, combined with ever-growing anthropogenic pressure associated with agricultural productivity. The results from this study highlight the important connectivity between riparian wetlands and river channels, but the marked variability between the two studied wetlands suggests that caution is required when grouping all riparian wetlands together: their hydrological impact may be more variable than assumed in most river management schemes.

Many similarities were observed between wetland A, located in the former meander loop of the channel, and a riparian wetland in a gravel-bed river (Matane River; Cloutier, 2013) where hydraulic conductivity is several orders of magnitude larger than in the Rock River, and which is also located in a former meander bend. The similarities between these two environments thus seems highly related to hydrogeomorphology, and suggest that conducting a hydrogeomorphological assessment of a study zone would help better understand the variability in riparian wetland hydrological connectivity.

It is evident that quantifying aquifer-wetland-river interactions is a process which requires various data sources to decrypt its complexity. The results obtained here could be extended to other studies interested in river-aquifer connectivity through wetlands. However, a variety of aquifer, wetland and river characteristics should be studied as the impact of wetlands on the aquifer-river connectivity can apparently vary significantly in space. More studies of hydrologic connectivity relying on the idea that river systems have a constantly evolving river corridor would be beneficial to furthering our understanding of these complex processes.

It may also be useful to use numerical modelling tools to better assess controlling factors in the variability of hydrological responses of riparian wetlands. The extensive field dataset collected in the Rock River could be used to calibrate and validate a groundwater model such as MODFLOW to test different hypotheses on interactions between a river, riparian wetlands and the aquifer.

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