Environmental Management

Freedom space for rivers: a sustainable management approach to enhance river resilience

--Manuscript Draft--

Manuscript Number:	EMVM-D-13-00374R1
Full Title:	Freedom space for rivers: a sustainable management approach to enhance river resilience
Article Type:	Research
Abstract:	River systems are increasingly under stress and pressure from agriculture and urbanization in riparian zones, resulting in frequent engineering interventions such as bank stabilization or flood protection. This study provides guidelines for a more sustainable approach to river management based on hydrogeomorphology (HGM) concepts applied to three contrasted rivers in Quebec (Canada). Mobility and flooding spaces are determined for the three rivers and three levels of "freedom space" are subsequently defined based on the combination of the two spaces. The first level of freedom space includes very frequently flooded and highly mobile zones over the next 50 years, as well as riparian wetlands. It provides the minimum space for both fluvial and ecological functionality of the river system and corresponds to a highly variable width, approximately 1.7 times the channel width on average, for the three studied sites. The second level includes space for floods of larger magnitude and provides for meanders to migrate freely over a longer time period. The last level of freedom space represents exceptional flood zones. We propose the freedom space concept to be implemented in current river management legislation because it promotes a sustainable way to manage river systems and it increases their resilience to climate and land use changes in comparison with traditional river management approaches which are based on frequent and spatially restricted interventions.
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Author Comments:	Dear Editor,

	Please find attached our revised manuscript. As you will see, we have made substantial change to the original manuscript based on the very thorough and stimulating comments received from the three reviewers. The detailed changes are described in the attached 27-page long letter. The most important change is that we have decided not to include the cost-benefit analysis in order to focus on better explaining the concepts and methodological issues of the freedom space approach. This is why the title of the paper has been revised to "Freedom space for rivers: a sustainable management approach to enhance river resilience". We would like to take this opportunity to thank the reviewers for their thoroughness in assessing the initial version of this paper. Their comments and suggestions prompted us to clarify our approach so that it can hopefully be applied in other regions of the world to improve resilience of river systems. We hope you will find this revised version suitable for publication in your journal. Yours sincerely, Pascale Biron

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Freedom space for rivers: a sustainable management approach to enhance river resilience

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Freedom space for rivers: a sustainable management approach to enhance river resilience

Abstract

River systems are increasingly under stress and pressure from agriculture and urbanization in riparian zones, resulting in frequent engineering interventions such as bank stabilization or flood protection. This study provides guidelines for a more sustainable approach to river management based on hydrogeomorphology (HGM) concepts applied to three contrasted rivers in Quebec (Canada). Mobility and flooding spaces are determined for the three rivers and three levels of "freedom space" are subsequently defined based on the combination of the two spaces. The first level of freedom space includes very frequently flooded and highly mobile zones over the next 50 years, as well as riparian wetlands. It provides the minimum space for both fluvial and ecological functionality of the river system and corresponds to a highly variable width, approximately 1.7 times the channel width on average, for the three studied sites. The second level includes space for floods of larger magnitude and provides for meanders to migrate freely over a longer time period. The last level of freedom space represents exceptional flood zones. We propose the freedom space concept to be implemented in current river management legislation because it promotes a sustainable way to manage river systems and it increases their resilience to climate and land use changes in comparison with traditional river management approaches which are based on frequent and spatially restricted interventions.

Keywords: hydrogeomorphology, meander migration, floodplain, river management, wetlands

1. Introduction

Several rivers across the world are located near human settlements, and are thus under stress and pressure from agriculture and urbanization in riparian zones. It is generally accepted that for purposes of navigation, power generation, water supply or protection of infrastructure, hard engineering interventions are needed in these river systems. However, since the mid-1990s, a paradigm shift from the reach-based engineering-dominated perspective to a more inclusive ecosystem-centred approach to river management has occurred (Brierley and Fryirs 2005; Hillman and Brierley 2005; Roni and Beechie 2013). There is now strong consensus in the field of hydrogeomorphology that such traditional management approaches may not be sustainable economically and ecologically everywhere along a river course (Piegay et al. 2005; Kline and Cahoon 2010; Kondolf 2011). In particular, bank stabilization, which is one of the most popular activities undertaken in the name of "river restoration programs" in North America, and flood protection measures such as levees tend to "fossilize" rivers by preventing channel migration and limiting connection with the floodplain (Kondolf 2011; Roni and Beechie 2013). They are increasingly questioned as management strategies since they require frequent maintenance (Kline and Cahoon 2010) and may be detrimental for floodplain habitat diversity (Kondolf 2011; Roni and Beechie 2013). Where possible, providing more space for rivers to migrate and flood naturally appears to be the obvious approach to sustainable management of both the quantity and quality of surface water, as well as flood and erosion risk (Piegay et al. 2005; Kondolf 2011).

The hydrogeomorphology (HGM) approach to river management emphasizes the physical and ecological integrity of living, dynamic and evolving aquatic ecosystems, with a focus on process-based restoration where the river can "heal itself" (Beechie et al. 2010; Kondolf 2011), whereas river engineering activities usually focus on empirical solutions to reach-scale issues, and are applied to maintain and protect infrastructure, navigation and flood protection networks (Brierley and Fryirs 2005; Roni and Beechie 2013). There are several documented cases where endeavors to stabilize channels through engineering practices have actually accentuated their instability and negatively affected their health (Bravard et al. 1997; Brierley and Fryirs 2005). However, in urbanized zones or where infrastructure is threatened, hard engineering approaches remain a necessity (Kondolf 2011). The HGM approach requires a broader, catchment-scale perspective, and involves skills and insights from both geomorphologists and engineers to be successful (Brierley and Fryirs 2005).

Basic concepts of river corridor management based on HGM processes have been described under a variety of names (e.g. “room for the river”, Baptist et al. 2004; “erodible corridor”, Piegay et al. 2005; “fluvial territory”, Ollero 2010; “river corridor”, Kline and Cahoon 2010).These HGM river corridor approaches typically focus on either channel mobility (by lateral channel migration or avulsion) or flooding problems. For example, mobility is the key factor determining river corridors in France, where the term “freedom space” was first used (“espace de liberté”) (Malavoi et al. 1998; Piegay et al. 2005), in Vermont (Kline and Cahoon 2010), in Spain (Ollero 2010) and in the Canadian province of Ontario (Parish Geomorphic 2004). However, the focus is more on flooding than erosion in river corridor programmes in the Netherlands (“Room for the River”), in the UK (“Making Space for Water”, Defra, 2005) and in Iowa, which also include wetland restoration (http://www.public.coe.edu/departments/Biology/SpatialEcology/ircp-index.html). These examples demonstrate that mobility, flood zones and wetlands are usually considered in isolation and are not formally integrated in a common space, despite obvious overlaps between these zones. In the Canadian province of Quebec, the HGM management approach is at this time not integrated in the river management practice. The current legislation promotes integrated watershed management with the use of protected riparian zones (“Politique nationale de l’eau” - National water policy, Québec 2002, “Politique de protection des rives, du littoral et des plaines inondables” - Policy for the protection of lakeshores, riverbanks, littoral zones and floodplains, Québec 2005, and "Loi affirmant le caractère collectif des ressources en eau et visant à renforcer leur protection" - Act to affirm the collective nature of water resources and to strengthen their protection, Québec 2009). However, in most cases, the protected riparian zone is very narrow (e.g. 3 m in agricultural zones), although it can measure up to 15 m in some cases.

The objective of this research is to develop a methodology for the delimitation of a freedom space for rivers, encompassing natural river mobility, floodplain areas and riparian wetlands based on hydrogeomorphology concepts in order to improve resilience of the fluvial system. The mapping of the freedom space was carried out for three contrasted rivers in southern Quebec (Canada).

2. Study sites

The three study sites were chosen in order to provide a contrast in river size, geomorphology and watershed land use so that the methodological tools developed would be applicable to a wide array of rivers in Quebec and elsewhere (Figure 1, Table 1). Indeed, the three rivers cover a range in grain size (from clay to gravel), in land use (including heavily agricultural, urbanized zones and pristine forests), in dynamics (from very stable to highly mobile) and in administrative units (from zones where agricultural land has the highest value in Quebec (Montérégie) to zones where sport fishing (salmonids) dominates (Gaspésie). Being located in Quebec, they are representative of a cold temperate climate and may therefore not be generalizable to all rivers.

The de la Roche River is a relatively small river located in the Montérégie region, 80 km southeast of Montreal, close to the American border and the state of Vermont. It is situated in the St. Lawrence Lowlands, except for the upstream part of the reach which is in the Appalachian Plateau (Figure 1b). The watershed is mainly agricultural, particularly in the downstream reach, with forested areas upstream (Table 1). Most of the drainage area is located in Vermont, with 55 km^2 (out of 145 km^2) located in Quebec. It is one of the main tributaries of the Missisquoi Bay in Lake Champlain. A gauging station from the Centre d'expertise hydrique du Québec (CEHQ) is located at the upstream limit of the study reach, downstream of the border with Vermont (CEHQ station 030425).

The Yamaska Sud-Est River drains an area of 411 km^2. It is also located in the Montérégie region, 90 km east-southeast of Montreal. It is a large river which drains into the Yamaska River, a tributary of the St. Lawrence River (Figure 1c). The watershed is forested upstream, in the Appalachian Piedmont zone, but predominantly agricultural as the river progresses downstream in the St. Lawrence Lowlands (Table 1). The North-Branch River, one of the tributaries of the Yamaska Sud-Est River, was also investigated in this study. There is a gauging station (CEHQ station 030314) located in Cowansville, approximately in the centre of the study reach.

The Matane River is located at the edge of the Gaspésie region, 630 km northeast of Montreal. It is the largest (catchment area of 1678 km^2) and the most dynamic of the three studied rivers. It is a salmon gravel-bed river which drains into the St. Lawrence River in the municipality of Matane (Figure 1d). It is located in the Appalachian region and is considered semi-alluvial with several bedrock outcrops through its course. The watershed is mainly forested (Table 1). There is a gauging station located near the mouth of the river (CEHQ station 021601).

3. Methodology

The hydrogeomorphology (HGM) approach requires a combination of Geographical Information System (GIS) analysis and field observations. For the de la Roche River, aerial photographs for years 1930, 1964, 1979, 1997 and 2009 were available, whereas photographs for years 1950, 1965, 1979, 1997, 2009, and years 1963, 1993, 2001 and 2009 were used for the Yamaska Sud-Est and Matane rivers, respectively. The photographs were scanned and georeferenced in ArcGIS (version 10, ESRI 2011) using between 10 and 18 control points, with an estimated root mean square error of less than 4 m. The river channel was digitized using both banks in the case of wider channels or the centreline for smaller channels.

A 10 m provincial Digital Elevation Model (DEM) was available for all the sites. In addition, for the Matane River, a LiDAR DEM with a pixel resolution of 1 m^2 was available. This high-resolution DEM proved particularly valuable for the identification of erosion and sedimentation forms and for the delimitation of terraces and valley walls (see below). In addition, the GIS tools developed by Biron et al. (2013a) were used to extract the channel water surface slope, bankfull width and bankfull discharge from LiDAR DEMs. Water surface profiles were collected during the summers of 2011 and 2012 with a DGPS (Trimble R8 GNSS, with a precision of 0.03 to 0.05 m). Bankfull width was obtained from the most recent aerial photographs on the Yamaska Sud-Est and de la Roche rivers. Bankfull discharge (Q, in m^3/s), which was considered equivalent to a 1.5-year recurrence interval event, was obtained from discharge-to-drainage area relationship:

$$Q = \alpha A^{\beta} \quad (1)$$

where α and β are the coefficients that vary between regions and watersheds. For the Yamaska Sud-Est and de la Roche rivers, a hydraulic geometry relationship for the bankfull discharge was developed from a sample of 20 gauged rivers in Vermont with drainage area (A, in km^2) ranging from 7.8 to 360 km^2, where the bankfull stage was assessed at the gauging stations from field observations (VANR 2006), resulting in a discharge-to-drainage relationship with $\alpha = 0.3376$ and $\beta = 0.9487$ ($R^2 = 0.92$). The drainage area used in this discharge-to-drainage relationship was computed for the Yamaska Sud-Est and de la Roche rivers from the 10 m DEM with ArcGIS. The bankfull discharge obtained using this relationship at the gauging station gave values of 19.2 and 54.9 m^3/s for the de la Roche and Yamaska Sud-Est rivers, respectively. These values were close to the 1.5 year recurrence flood computed from the historical record at the gauging stations (13.8 and 55.9 m^3/s for the de la Roche and Yamaska Sud-Est rivers, respectively). For the Matane River, $\alpha = 0.46$ and $\beta = 0.92$ ($R^2 = 0.54$, $p < 0.001$). These coefficient values were based on discharge estimates from measured cross-sectional area, channel slope and estimated roughness (Manning coefficient) at 18 cross-sections along the river reach.

In addition, all of the study reaches were assessed through field observation by walking or canoeing in the channel and completing field survey forms (using a handheld GPS to obtain coordinates). Recorded observations included the presence of bank stabilization structures, zones of active bank erosion, qualitative grain size estimates, the type of sediment deposits on the floodplain, vegetation changes that could help determine flood zone limits, the levels of ice scars on trees (indicating the level of flooding related to ice jams), and the presence or absence of pedogenesis.

4. Freedom space delineation

Here, a freedom space delineation method is proposed that combines two spaces related to the two main river processes: the mobility space and the flooding space. The two spaces are defined using a HGM approach.

4.1 Mobility space

The mobility of meandering rivers is related to secondary flows which will result in bank erosion on the outer bank, and sediment deposition in point bars located on the inner bank (Knighton 1998). In addition to channel migration, avulsion hazard also has to be taken into account.

The methodology involves defining two mobility spaces based on the short and long term migration patterns of a river. The determination of the two zones is based on the notion of fluvial hazard, but also on the geomorphological and ecological integrity of the river system. Both spaces are defined for homogeneous river reaches defined according to a HGM perspective - i.e. reaches where the slope, grain size, width, level of confinement, discharge, meander amplitude and sinuosity are relatively constant - as well as historical river migration from historical photographs. Homogeneous river reaches were on average 1 km, 1.7 km and 7.3 km long respectively for the de la Roche, Yamaska Sud-Est and Matane rivers.

4.1.1 The M_{50} mobility space

The first mobility space (M_{50}) represents the short-term mobility zone where there is a high risk of erosion or of avulsion (meander cut-off) over a 50-year period based on the extrapolation of migration rates calculated from historical data. It was determined from four distinct types of analysis.

Firstly, the likely lateral migration zones were obtained by measuring historical rates of erosion for the period covered by the aerial photographs for regularly-spaced transects using the software DSAS (Digital Shoreline Analysis System) (Thieler et al. 2009). This ArcGIS tool was originally conceived by the USGS to study shoreline evolution, but it can also be used to study the migration of rivers (Curran and McTeague 2011). The tool generates transects every 5 m by positioning a line at 90° to the migration direction (Figure 2). For each transect, DSAS generates linear interpolation of channel movement, including historical erosion rate, coefficient of determination (R^2) between migration distance and time, and confidence interval. Following this interpolation, extrapolation for 50 years is obtained based on the historical erosion rate in the transect direction. Only cases where R^2 was greater than 0.5 were retained for this analysis. The 5 m-spaced erosion rates, along each transect, provides an assessment of channel dynamics at a sufficiently fine scale to model meander migration. These erosion rates also reflect local conditions that affect the ground resistance to fluvial erosion, such as vegetation, soil structure or the presence of a terrace.

Secondly, for banks that are stabilized, it was assumed that these reaches would be mobile without protection and that therefore a M_{50} buffer zone was required behind these banks to represent natural mobility that would occur had it not been stabilized. The 90th percentile of historical erosion for the reach was applied over 50 years to determine the width of this buffer zone. This methodological choice takes into account the dynamics of each homogeneous reach, assuming that stabilized reaches were among the most dynamic reaches (hence the choice of the 90th percentile), but removing the extreme values which could be due to local particularities that are not necessarily applicable to the entire reach.

Thirdly, because extrapolation of a constant erosion rate in time along a straight line is a crude approximation of natural channel mobility in the cases of highly mobile channels, two specific procedures were applied to river reaches that display high erosion rates relatively to their meander belt width. The first method used the rate of renewal of the floodplain following O'Connor et al. (2003), Piégay et al. (2005) and Konrad (2011). For each reach, the area mobilized by the rivers between each digitalized historical channel was measured (1930-1964, 1964-1979, 1979-1997 and 1997-2009 for the de la Roche river; 1950-1965, 1965-1979, 1979-1997, and 1997-2009 for the Yamaska Sud-Est river, and 1963-1993, 1993-2001 and 2001-2009 for the Matane river). These mobilized areas were divided by the length of the reach to obtain an erosion rate for the reach. The average erosion rate, over the total observed time periods, was then divided by the area of the $M_{floodplain}$ which corresponds approximately to the meander belt area or the floodplain area (see below) to compute the floodplain renewal rate. This metric (or its reciprocal, the floodplain renewal time) provides the required measurement of the erosion rate, relative to the floodplain width, to define a threshold over which the DSAS methodology cannot be applied. Visual estimation of the past dynamism of the rivers showed that this methodology is not adequate for reaches with a renewal time of less than 200 years. Consequently, the entire $M_{floodplain}$ zone was classified as M_{50} for these highly dynamic reaches. However, the computed floodplain renewal rates may be overestimated by this method due to georeferencing errors. To prevent the classification in M_{50} of large areas with little erosional hazard, the reaches where the estimated contribution of the georeferencing error to the computed floodplain erosion rate was greater than 50 % did not have their $M_{floodplain}$ zone reclassified M_{50} even if the computed renewal times were less than 200 years. Among the 49 studied reaches, 22 reaches had a floodplain renewal time of less than 200 years, but only 13 of them had their floodplain classified as M_{50} once the error contribution threshold was considered. Despite the use of the floodplain renewal rate, some highly dynamic meanders are situated within reaches with a low average erosion rate (or with an erosion rate where the contribution of georeferencing errors is too large). For these special cases, the second method relies on an expert assessment of the likely future erosion trend, based on the observation of past erosion, to delimit the M_{50} area. However, these cases were seldom encountered in the studied rivers, and manual corrections were needed for only 8 meanders, representing only 1 % of the total length of the studied rivers.

Finally, the last zones that need to be included in M_{50} are the areas of high avulsion hazard. This step is required as the length of avulsion during meander cut-off is usually greater than the width of the predicted zone of fluvial erosion determined with DSAS. The risk of meander cut-off was assessed using two methods. First, traces of erosion were noted on aerial photographs in the floodplain (Figure 3). This step particularly allows to identify places where cuts-off were prevented by anthropic interventions. The second approach was to empirically consider that meanders with a meander neck width less than four times the channel width had a high potential of being cut off. This threshold corresponds to the average ratio for the cuts-off that occurred during the observed historical period. This was applied on the projected channel position over a 50-year period obtained with the method described above (using the DSAS tool).

The four distinct analyses leading to the delineation of M_{50} are based on a common assumption in river management: the continuity of past processes due to minimum changes in fluvial dynamics drivers (changes in climate, hydrology, and land uses). To confirm the validity of this assumption, analyses of the Matane River hydrology revealed an increase of the yearly maximum discharge between the periods 1927-1978 and 1979-2011 (t-test, $p<0.01$). Consequently, only the channel positions after 1978 were taken into account when assessing channel migration for this river. Discharge data were not available for a long enough period of time for the Yamaska Sud-Est and de la Roche rivers to compute similar analyses. However, 1930 to 2011 records of yearly maximum discharge river of the Nicolet River, a nearby river in the same geological context, do not present a change in trend. Consequently, all available historical channel positions were used to analyse the mobility of the Yamaska Sud-Est and de la Roche. Furthermore, the potential impact of climate change (discharge variability) was examined through numerical experiments (Biron et al. 2013b), and it was shown that with a 10 % increase in discharge, mobility space would only vary by less than 1 %. The two analyses support this assumption, however the potential uncertainties resulting from it and from the computations of M_{50} are considered at length in the discussion.

4.1.2 The $M_{floodplain}$ mobility space

The second mobility space ($M_{floodplain}$) is defined as the space that will be occupied by the river in the long term through meander migration (Piegay et al. 1997; 2005). The methodology to determine the $M_{floodplain}$ mobility space is largely inspired by existing methodologies developed in France by Malavoi et al. (1998), in the state of Washington by Rapp and Abbe (2003), in Vermont by the Vermont Agency of Natural Resources (Kline and Dolan 2008; Kline and Cahoon 2010) and in Ontario by Parish Geomorphic (Parish Geomorphic 2004). These methods involve delimiting a corridor around the meander axis, based on current and historic meander configuration. Here, the main meander axis was determined based on the 2009 position of the channel with, in some cases, corrections to take into account former river paths or oxbow lakes based on historic photographs.

Meander belt width was subsequently delimited for each reach centred on the meander axis according to widest meander amplitude within the reach. The $M_{floodplain}$ space thus defined was then constrained by the presence of non-erodible terraces or by valley walls. Again, historical river paths of the river were used to determine whether or not terraces were erodible, but field evidence of bank erosion on terraces were also considered. For example, on the de la Roche River, the upstream part of the channel is confined by terraces, resulting in a very narrow mobility space, whereas in the downstream part, which is not confined by terraces, the $M_{floodplain}$ space is considerably larger (Figure 4). The impact of terraces also needed to be assessed at the homogeneous reach scale for the Yamaska Sud-Est River, whereas all the terraces on the Matane River were considered as non-erodible, based on historical photograph analysis and field surveys.

4.2 Flooding space

The HGM approach focuses on the interpretation of floodplain landforms that is indicative of contemporary flood hazards. It is based on the premise that past traces of flooding activity can help anticipate future flood extents (Baker, 1994). A river floodplain is the product of ongoing long-term processes providing physical evidence of the functional limits within which flooding should be expected. This offers an opportunity to rapidly infer flood processes from HGM interpretation. Methodological guidelines are adapted to each selected floodplains. It can rely on the delineation of embedded terrace levels (Masson et al. 1996; Ballais et al. 2005; Lastra et al. 2008, Lelièvre et al. 2008), patterns and age of morpho-sedimentary unit construction (Baker 1976; Lambert and Prunet 2000) or evidence of sediment transport mechanisms during floods (Demers et al., 2014). The HGM approach is recognized as an alternative tool to hydraulic simulations because it is grounded in empirical evidence of flood activity and also because of the possibility to produce large-scale maps at low cost. For those reasons, the HGM approach has increasingly been part of flood risk assessment (Garry et al. 2002; Thompson and Clayton 2002; Bravard et al. 2008; Arnaud-Fassetta et al. 2009). However, this approach comes at the expense of sometimes evasive information on quantitative processes. Consequently, choices must be made as to how it is implemented into flood zoning and space freedom concepts. This is particularly sensitive in countries where flood legislation is essentially expressed on the basis of flood frequencies.

The first step of the HGM approach is to identify floodplain extents and define landforms that are suggestive of distinctive flood processes. A methodological framework was specifically designed for the three floodplains. It is based on the morphological imprint of past geomorphological work from flood activity and ice-drift processes (Demers et al. 2014). Field work, photo-interpretation and LiDAR image interpretation were necessary to map five types of landforms on the studied floodplains. The criteria used to delineate the different floodplain landforms as well as the riparian wetlands are summarized in Table 2. Examples of delineated landforms are illustrated in Figure 5. Erosion forms refer to isolated erosion marks as well as large surfaces reworked by competent overbank flow. Depositional landforms refer to aggrading alluvial surfaces from the deposit of fine sediments (mainly silts) resulting from low-velocity flows. Stabilized surfaces are areas of the floodplain where there is no evidence of active geomorphic processes, which are thus at the edge or outside the extent of contemporaneous flood activity. These forms often show incipient pedogenesis or other indicators of surface stability (Levish 2002). In Quebec’s southern regions, a Buntley-Westin index (Buntley and Westin 1965) higher than 10 in alluvial soils is indicative of incipient landform stability (10^2-10^3 years) (Saint-

Laurent and Lavoie 2009; Demers et al. 2014). In northern rivers such as those in Quebec where ice cover and ice-jam floods are frequent during winter, particularly in the case of the Matane River, landforms created by drift-ice can also be identified. Also, ice-jam flood levels can be determined by field evidence of scars left by drift ice on trees which, combined to a DEM, provide a flood level (Jarrett and England 2002).

Lastly, the HGM definition of a flooding space includes riparian wetlands since lateral connectivity between groundwater and surface water results in both hydrological and ecological integrity of the fluvial system. From an ecological point of view, riparian wetlands are determined on botanical and biophysical criteria (Keddy 2010). From a HGM perspective, riparian wetlands correspond to local depressions which often form as a result of river dynamics (e.g. abandoned meanders) or from the configuration of the floodplain (overflow basin on the edge of the floodplain) (Brooks et al. 2011). Here, a combination of field observations and existing wetland maps (MDDEP 2011; 2012) was used to delimit these zones. Figure 6 shows examples of floodplain areas delineated from the analysis of floodplain landforms for the three studied rivers.

The second step is to relate HGM landforms to map flooding spaces. The decision rules are summarized in Table 3. The five landforms were used to delineate three levels of flooding space with decreasing order of flood severity: F_{high}, F_{med} and F_{low}. In Quebec, flood return periods are currently used to define flood severity. F_{high} and F_{med} are respectively associated with flood frequencies of 0-20 and 20-100-year return period, whereas F_{low} is associated with a new class (> 100 year return period, yet within floodplain limits). However, floodplain landforms delineation does not necessarily coincide with defined thresholds of flood frequencies or intensities. It is an aggregate assessment from HGM interpretation and historical knowledge of flood extents.

In applying the decision rules, a distinction was made between the de la Roche and Yamaska Sud-Est Rivers on one hand and the Matane River on the other hand. The two types of floodplain are the result of different building mechanisms and floodplain construction history that lead to contrasted flooding extents. For the Matane River, floods are known to be limited in extent when compared to the active floodplain boundaries. In this river, there are methodological difficulties in isolating the active depositional landforms from otherwise incipient stabilized landforms. This has led to possible overestimation of active depositional landforms compared to the de la Roche and Yamaska Sud-Est rivers that presented well-defined floodplain boundaries over which flooding is frequent (≈ 5-10 year return period). With regards to less frequent flooding, the depositional landforms of the Matane floodplain were associated with a less severe flood space (F_{med}) than the other two floodplains (F_{high}). This highlights the necessity to remain flexible when determining flooding space zones and to take into account the various floodplain environments, methodological limits and their associated uncertainties in representing flood processes. Concerning flood intensity criteria, because erosion landforms are indicative of flood overbank flows sufficiently strong to rework the fluvial landscape, they were systematically associated with the most severe zoning class (F_{high}), irrespective of the expected flood frequency. Also, to take into account fluvial integrity preservation, the most severe zoning class (F_{high}) was given to riparian wetlands which are known to reflect close connectivity between the channel and the floodplain and ought to be preserved in a river freedom space management approach.

Figure 7 shows how the floodplain landforms presented in Figure 6 are transposed into the three flooding spaces F_{high}, F_{med} and F_{low} when applying the decision rules defined in Table 3. Note that for the de la Roche and Yamaska Sud-Est rivers, only F_{high} is used since these floodplains are confined by terraces and thus all floods occupy the same space (≈ 5-10 year return period). For the Matane River, the traditional flood zone limits of 0-20 and 20-100 years were available, and are presented in Figure 7d (for the same reach as in Figure 7c). The HGM approach has proven to be directly applicable within present flood hazard policy in Québec as it can minimally lead to the mapping of two flood zones of high and medium flood hazard that are usually respectively described by the 0-20 and 20-100 year flooding zones. The F_{high} zone in this reach corresponds approximately to the 0-20 year flooding zone, although it covers a larger area (31 % larger than the 0-20 year flooding zone). Similarly, the F_{med} zones are markedly larger than the 20-100 year zones (131 % larger than the 20-100 year flooding zone).

4.3 Freedom space

In defining freedom space zones, a methodology was required by which the two categories of mobility space and the three categories of flooding space would be combined efficiently to represent 1) different processes (erosion, flooding, wetlands), 2) different time periods (50-year horizon, floodplain renewal scale) and 3) different interests (human or infrastructure risk, ecological integrity). In addition, the methodology used to produce freedom space mapping had to take into account existing legislation (e.g. limited rights in the 20-year recurrence interval flood zone). It also had to be appropriate to the various organizations (ministries, municipalities) that would be responsible for implementing this management approach. The freedom space categorisation had to bear in mind the need to protect both public security and ecological services while also maximizing economic benefits for the society.

One option, which is called here "integral cartography", was to map all the zones, i.e. M_{50}, $M_{floodplain}$, F_{high}, F_{med} and F_{low}, without any combination, and to let river managers decide how best to use these maps in each case. This type of map has the advantage of presenting all the information, but it also has the inconvenient of being difficult to read and/or synthesize. Another option, called here "simplified cartography", is to group these zones in order to produce three freedom spaces: L_{min}, L_{func} and L_{rare}. The cartography rules must then consider cases where there is an overlap between the mobility and flooding spaces. The chosen combinations of level of flooding hazard, erosion hazard and high ecological value areas correspond more to management choices than to strict hydrogeomorphological criteria, and can consequently be modified according to the management objectives of the zonation process. The proposed combinations are based on scale-related processes as well as existing similar methodologies.

Table 4 illustrates the different possibilities and the choices made to determine L_{min}, L_{func} and L_{rare} categories, where:

- freedom space L_{min} is the union of mobility space M_{50} and flooding space F_{high};
- freedom space L_{func} is the union of mobility space $M_{floodplain}$ and flooding space F_{med}, from which freedom space L_{min} is subtracted;
- freedom space L_{rare} is the union of all mobility and flooding spaces, from which freedom space zones L_{min} and L_{func} are subtracted.

With these mapping rules, the L_{min} space is the closest to the river, and represents either zones where human occupation is most at risk or zones that are of high ecological value, such as riparian wetlands. It therefore represents the *minimal* space for a river system to operate, i.e. for HGM and ecological processes to proceed. Inclusion of the high ecological value area within a minimum functional space, as proposed by Malavoi et al. (1998), recognizes the importance of such areas. The L_{func} space represents a wider zone, and corresponds to the freedom space in its widely accepted definition in other countries (e.g. "espace de liberté" in France, Piegay et al. 2005), i.e. a corridor which is necessary for essential fluvial processes to operate or, in other words, an integrity space. The last space (L_{rare}) represents zones that may be flooded during extreme events. These zones are mapped using a distinct category since, while they should be taken into account in land use planning, they do not constitute a fluvial territory that is essential for river system operation, from a hydrogeomorphological or ecological point of view, which is represented by freedom space L_{func}. Thus, the two main freedom spaces remain L_{min} and L_{func}. Note that the L_{rare} category of freedom space only appears in the Matane River in our study, since the other two rivers do not have L_{rare} zones.

Figure 8 presents selected examples of freedom space mapping using both integral and simplified cartography, as well as how this compares with the traditional flooding zones (0-20 and 20-100 years) on the Matane River (Figure 8e). As is apparent in these examples, the freedom space area can vary considerably from one reach to the next, being in some cases limited to the immediate vicinity of the river (e.g. Figure 8a,b on the right) and in other cases being very wide, particularly in the presence of riparian wetlands. For example, on the Yamaska Sud-Est River, the width of the L_{min} space can reach up to 1000 m in a zone with a riparian wetland (Figure 9a). As this zone is currently undeveloped, there is no anticipated difficulty in its protection, particularly since it can play an important hydrological role in flood protection for the municipality of Cowansville located 10 km downstream. Flood concerns are a serious issue in this municipality where several developed zones are located within the freedom space of the river (Figure 9b).

In areas where the channel is confined by non-erodible terraces, such as in the upstream reaches of the de la Roche River, the mobility and flooding spaces are nearly identical (Figure 7a). Overall, the very frequent flood zones (F_{high}) are wider than the highly mobile zones (M_{50}), as is the case in the de la Roche River downstream (Figure 7a). For example, on the Yamaska

Sud-Est River, 84 % of the mobility zone M_{50} is included in the flood zone F_{high}. The only cases where the high mobility space extends past the flooding space are in reaches that were stabilized on terraces that limit the flooding space but that are erodible. On the other hand, it is very frequent that the $M_{floodplain}$ mobility space (which is based on meander amplitude) extends beyond the flood zones, particularly where terraces are erodible (e.g. de la Roche and Yamaska Sud-Est rivers).

When using these results for practical management applications, it is recommended that no development should be allowed in the zones classified as the first level of freedom space (L_{min}) which corresponds to the minimal space for the river natural processes to operate. This zone corresponds on average to a width of 61, 35 and 101 m on each side of the channel, or 1.2, 2.3 and 1.5 times the channel width for the de la Roche, Yamaska Sud-Est and Matane Rivers, respectively. It is somewhat wider than the traditional 0-20 year flood zone, although there are clear overlaps (compare Figure 7d and 7e). A compensation program should be initiated for farmers in order to eliminate the perceived need for any type of intervention in the river (bank stabilization, dredging, embankment). This would also allow for the preservation of riparian wetlands as they are part of the L_{min} space. The second level of freedom space (L_{func}) should be considered for both landuse planning and immunization protocols in order to analyse risk associated with both flooding and bank erosion before allowing any future development. In the case of the Matane River, L_{func} is considerably larger than the 20-100 flood zone (Figure 7d,e). The third level (L_{rare}) is useful as it highlights potentially problematic zones in cases of extreme events which could be taken into account in land use planning, but that do not constitute a fluvial territory as essential as the L_{func} space from a hydrogeomorphological or ecological perspective.

5. Discussion

5.1 Uncertainties, applicability and future development

The methodology for defining the mobility and flooding spaces was inspired by existing approaches in different countries. The originality of the proposed freedom space is that it integrates two key river processes, flooding and bank erosion, into a single space. This has important advantages since it provides a thorough assessment of the contribution of different riparian zones to the integrity of the fluvial system, both from a hydrogeomorphological and an ecological perspective. A more resilient river system should emerge from river management strategies that limit development within this freedom space. This study has tested and evaluated the applicability of this methodology for case studies on three different rivers. This provides valuable insight on how to implement the method, shows that it can be used in a variety of geomorphological contexts and enhances the likelihood that it will be applied elsewhere.

There are various sources of uncertainty at all levels of the analysis in this approach, stemming from methodological decisions, premises or measurement errors. From the outset, the HGM approach involves some expert judgment and is not always easy to apply using a "Boolean approach" with crisp boundaries. For example, determining homogeneous reaches remains a somewhat subjective process. However, it should be noted that more traditional approaches such as hydraulic modelling also require a degree of expert judgment, for example to calibrate the model using the most appropriate resistance parameter (e.g. Manning *n*), and a degree of uncertainty when dealing with frequency analysis of annual discharges.

The role of human interventions such as bank or flood protection structures in the delineation of mobility zones remains to be clarified. Indeed, the HGM approach for delimiting the mobility space based on meander characteristics ($M_{floodplain}$) is not particularly well adapted to highly modified reaches or stabilized reaches associated with the presence of a road or railway, or to bridges which force rivers to remain in the same position. Bridges that are far away from the centreline of the valley are particularly likely to create enhanced erosion nearby, as was observed in this study in the village of Saint-Armand on the de la Roche River. As proposed by Malavoi et al. (1998), the $M_{floodplain}$ space can however be modified in order to exclude areas likely to always be protected from river migration, such as villages. This process, however, remains based on management choices beyond the focus of this research.

An additional source of uncertainty is that the highly mobile zone (M_{50}) may be heavily affected by georeferencing errors since it is based on extrapolation of past migration rates. In lowland rivers which are not very dynamic such as the de la Roche or Yamaska Sud-Est, this error can be significant in comparison with migration distances. For example, on the Yamaska Sud-Est River, it was estimated that only 43 % of the points used for predicting bank erosion rates exhibited a significant trend.

It is also important to be aware that this approach is based on the hypothesis that future trends can be estimated from past trends. This hypothesis might not hold true for rivers that are not in an equilibrium state or at different stages of adjustment. Climate or land use changes may have hydrological implications which, in return, could affect erosion rates or flood frequency. Meander cut-offs may follow temporal cycles (Hooke 2003) which were not taken into account in this methodology. For example, on the Matane River, wood rafting was abandoned early in the 20th century but had a major impact on the channel which is still in a disequilibrium condition. This is highlighted by the change in the maximum yearly discharge on the Matane River between 1927-1978 and 1979-2011. Thus, based on previous work on the Matane River, bank erosion rates were computed for the 1979-2009 period since this period was estimated to be more representative of the current morphological trajectory. Such a morphological trajectory analysis should ideally be conducted in all studies based on freedom space concepts, in particular in terms of land uses changes. However, it should be reminded that traditional approaches to flood mapping using hydraulic simulations also present major drawbacks. Identified flood levels rely on the assumptions of hydro-climatic equilibrium and static channel boundaries (Lane et al. 2007; Merwade et al. 2008). As a consequence, the crisp boundaries predicted from quantitative methods can be poor estimates of real flood extents. The HGM approach recognizes that rivers are dynamic and that the same flood can reach various flow stages depending on aggradation or degradation processes which may occur (e.g. Lane et al. 2007; 2008). In contrast, in the traditional approach the levels reached by floods of a certain magnitude are considered to be fixed, whereas in reality a flood of a given recurrence will reach a higher level in certain reaches if sediment deposition has occurred, or lower levels in the case of bed incision.

Overall, the freedom space delimitation remains a fairly rapid and low-cost alternative compared to hydraulic simulations and could thus contribute to a widespread application of river freedom space cartography in cases of limited funding. The methods used to delimitate the freedom space can also be adapted depending on the geomorphological context and the availability of data and funds. The application of the methodology to three rivers from different contexts and of different sizes showed the versatility of the approach. The mobility space delimitation methods appears relevant for most rivers, as the average erosion rates were respectively of 0.08 m/yr, 0.11m/yr and 0.26 m/yr for the de la Roche river, Yamaska Sud-Est river and Matane river, thus falling into the range of common values for river dynamism (Hooke 1980). However, in certain particular cases, river dynamism may not be properly assessed by the proposed methodology. This is in particular the case for highly confined dynamic rivers, where erosion rates can be high but frequently shifting direction and therefore where erosion dynamic can be masked by geopositioning errors. Small streams can present similar difficulties in assessing their dynamism, with an even larger potential error on river position in forested environments due to overhanging vegetation. As previously stated, local erosion rates cannot be used to extrapolate linearly erosion over 50 years in these cases. Floodplain erosion rate can be an alternative method if the highly dynamic part is limited to a small number of reaches, but for highly dynamic rivers at a more global scale, and in particular braided rivers, other methodologies may be more appropriate (e.g. Graf 2000; Curran and McTeague 2011).

Data required for the freedom space methodology is likely to be available to river managers or researchers in most cases. In fact, historical aerial photographs are commonly available over a 50-year timespan in North America and very often over a longer period in Europe (Rapp and Abbe 2003). If historical data are not available, the M_{50} space delimitation could be defined from an expert judgement. In this case, traces of erosion and deposition, especially point bars, observed from recent aerial pictures or field surveys, can help determine the M_{50} space. Increasing access to LiDAR data should also help to implement HGM analyses, as the availability of these data improves the accuracy of the HGM analyses while reducing their cost. Floodplain landform types and boundaries, in particular, can be assessed from LiDAR data instead of field survey. Reach delimitation can also be completed with less field work with the help of LiDAR data.

Hydrogeomorphological mapping of floodplains is a common exercise in geomorphology. However, the spread of the HGM approach for flood management and river space freedom applications is challenged by the range of floodplain characters and their related flood processes. This variability is partly represented by the floodplain classification of Nanson and Croke (1992) as well as the complex mosaic of geomorphological features and related hydrodynamics found in larger floodplains (Dunne and Aalto 2013; Lewin and Ashworth 2014). The Matane River case illustrates some methodological challenges of the HGM approach. Complexity arises mainly because the floodplain presents inherited landforms from processes acting over long periods of time. The de la Roche and Yamaska Sud-Est floodplains represent shorter time scales of floodplain construction that remain in line with contemporaneous processes and flood management horizons. In this work, using three levels of flooding space helped characterize the more complex floodplain of the Matane River, whereas a simpler classification with only one level was sufficient for the de la Roche and Yamaska Sud-Est Rivers. This contrast stresses the need to better understand the links between geomorphological boundaries and flood hydrodynamics within different floodplain environments. The real issue remains an adequate estimation of flood processes within these limits in order to implement adequate management policies. In our study, the proposed boundaries were known to match and sometimes exceed the minimal requirements of the actual policy (0-20 years and 20-100 years flood zones). Ultimately, the lack of quantification requires that geomorphologists and risk managers make concerted decisions as to how the HGM approach can best be integrated into river management to determine freedom space zones.

5.2 Implementation challenges

Although the freedom space approach is not yet implemented in Quebec, a meeting with stakeholders of Saint-Armand (de la Roche River) organized in collaboration with the municipality and the watershed agency provides useful information on public reception vis-à-vis this river management approach. Riverside property owners were notified by letter that this meeting would take place on February 11, 2013. The letter included the freedom space limits on the de la Roche River, as well as a detailed map of the freedom space at the property scale. Out of the 39 riverside property owners, 12 came to the meeting and two contacted us following the meeting. Several residential properties have very small river bank lengths while others are in wooded zones and would thus be less affected by the implementation of a freedom space approach. Attendance at this meeting is deemed representative since the agricultural owners who would be most affected by a change in legislation were present.

Before presenting the results, a quick overview of HGM concepts was provided by one of the researchers. Overall, there was an agreement that no permanent infrastructure should be allowed within the freedom space limit. There was also consensus on forbidding future bank stabilization, although riverside owners wanted to maintain the right to protect existing infrastructure. Finally, all property owners present said that they would accept an easement agreement to compensate for the loss of right to farm within the freedom space limit. The outcome of this meeting was thus positive, but extensive preparation in terms of public awareness and scientific communication about HGM concepts was required to reach such widespread acceptance. The HGM concept regarding bank erosion as a “desirable attribute of rivers” (cf. Florsheim et al. 2008) is particularly difficult to convey since farmers are repeatedly encouraged by various environmental agencies to adopt measures to limit sediment runoff from their fields to river channels so they believe that bank stabilization is an appropriate measure to improve river health.

From a political perspective, the implementation of a freedom space approach involves two options: to use the current legal framework or to create a new one. In our view the former is more likely than the latter to succeed, at least initially. In Quebec, there is no legal framework concerning mobility of channels, but the flood recurrence zones (0-20 years, 20-100 years) are mapped for the most densely populated territory. Assuming a similarity between the 0-20-year and L_{min} freedom space, and between the 20-100-year and L_{func} freedom space, new regulations could avoid infrastructures that limit flood and ice conveyance and prevent any future development within the 0-20 year zones. Limited development within the 0-100 year zones could be allowed following assessment demonstrating no significant effect on flooding processes and a very low mobility risk. Bank stabilization and other types of interventions could also be limited to the protection of existing infrastructure that are considered essential, whereas options such as moving roads away from rivers (beyond the freedom space limits) could be envisaged in the future.

6. Conclusion

A novel methodology based on hydrogeomorphology concepts is proposed to define a freedom space for rivers based on a combination of mobility and flooding spaces. The latter includes riparian wetlands, which play a significant hydrological and ecological role in fluvial systems. This approach determines two main levels of freedom space based on the notion of risk (erosion and flooding) and of ecological integrity over a 50-year period (L_{min} space) and based on an overall functional river system at a longer time scale (L_{func} space). Exceptional flood zones are also classified as L_{rare} space. By applying this methodology to three contrasted rivers in Quebec, it was possible to develop robust tools that can be applied in most rivers, at least in a temperate climate.

Acknowledgements

This project was funded by the climate change consortium Ouranos as part of the "Fonds vert" for the implementation of the Quebec Government Action Plan 2006-2012 on climate change. We thank the Ministère de la Sécurité Publique du Québec for giving us access to their LiDAR data in the Matane watershed. The help and support of Simon Lajeunesse (MRC Brome-Missisquoi) and Nathalie Martel (Ministère du Développement Durable, de l'Environnement, de la Faune et des Parcs du Québec) was much appreciated. Thanks also to the field assistants involved in this project: Diogo Barnetche, Johan Bérubé, Maxime Boivin, Larissa Holman, Ariane Lelièvre, Lecia Mancini, Jean-Philippe Marchand, William Massey, Antonin Montané, Véronic Parent, Fernanda Paulo de Oliveira, Pierre Simard, Cyril Usnik and Svenja Voss. We thank the three anonymous reviewers for their detailed and constructive comments on a previous version of this manuscript.

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Figure 9. Examples of the freedom space in the Yamaska Sud-Est River a) in an area with a riparian wetland, b) in the municipality of Cowansville, located approximately 10 km downstream of the wetland.

Table 1: Characteristics of the three studied rivers

	de la Roche	Yamaska Sud-Est	Matane
Watershed			
Area (km^2)	145	411	1 678
Agriculture (%)	41	59	10
Forest (%)	40	32	87
Average annual discharge (m^3/s)	1.1	4.6	39
Max annual discharge (m^3/s)	35	256	807
Study reach			
Length (km)	10	47	43
Elevation range (m)	30	108	78
Fluvial style	meandering	meandering	meandering/semi-alluvial*
Bed and banks	sand-silt	sand-silt	gravel

*Semi-alluvial indicates that some parts of the cross-section are bedrock, whereas other parts have alluvium on the bed.

Table 2: Floodplain landforms and alluvial wetland interpretation key.

Typology	Morphology	Grain sorting	Pedogenesis (Buntley-Westin index)	Vegetation
erosion landforms reworked by competent flow (transport mode : mixed)	• irregular land topography • flood channels • long and narrow streamwise landforms • erosion scarp	unsorted	B-W < 10	srubs and/or trees
depositional landforms deposited by slow flow (transport mode : suspension)	• rounded land topography	sorted (silt)	B-W < 10	
stable landforms	• rounded land topography	sorted (silt)	B-W > 10	
glacial landforms resulting from flow with drift ice	• *bechevnik*	unsorted		ice scars
alluvial wetlands	• paleochannels	sorted (silt)		hygrophilous species

Table 3 Decision rules used to determine flooding space

Methodological approach		Hazard interpretation: Flood frequency	Hazard interpretation: Flood power	Contribution to the integrity of the fluvial system	Flood space severity
HGM cartography	DLR and YSE Rivers				
	Erosion forms	↑	↑		F_{high}
	Sedimentation forms	↑	*		F_{high}
	Matane River				
	Erosion forms	↑	↑		F_{high}
	Sedimentation forms	*	*		F_{med}
	Stabilized forms	↓	↓		F_{low}
	Drift-ice forms	n/a	↑		F_{high}
	Alluvial fans	n/a	↑		F_{high}
	Riparian wetlands	< 2 yrs	*	storage of flood discharge and sustained low water level	F_{high}
Hydraulic models	0-20 yrs	0-20 yrs	n/a		F_{high}
	20-100 yrs	20-100 yrs	n/a		F_{med}

(↑ : high; ↓ :: low; * : variable; n/a : non-available)

Table 4 Freedom spaces L_{min}, L_{func} and L_{rare} as a function of mobility and flooding spaces. The colours correspond to the colours on the freedom space maps (Figures 8 and 9).

		Mobility		
L_{min} / L_{func} / L_{rare}		M_{50}	$M_{floodplain}$	**Outside mobility space (> $M_{floodplain}$)**
Flooding	F_{high}	L_{min}	L_{min}	L_{min}
	F_{med}	L_{min}	L_{func}	L_{func}
	F_{low}	L_{min}	L_{func}	L_{rare}
	Outside flooding space	L_{min}	L_{func}	Outside freedom space

Figure 1

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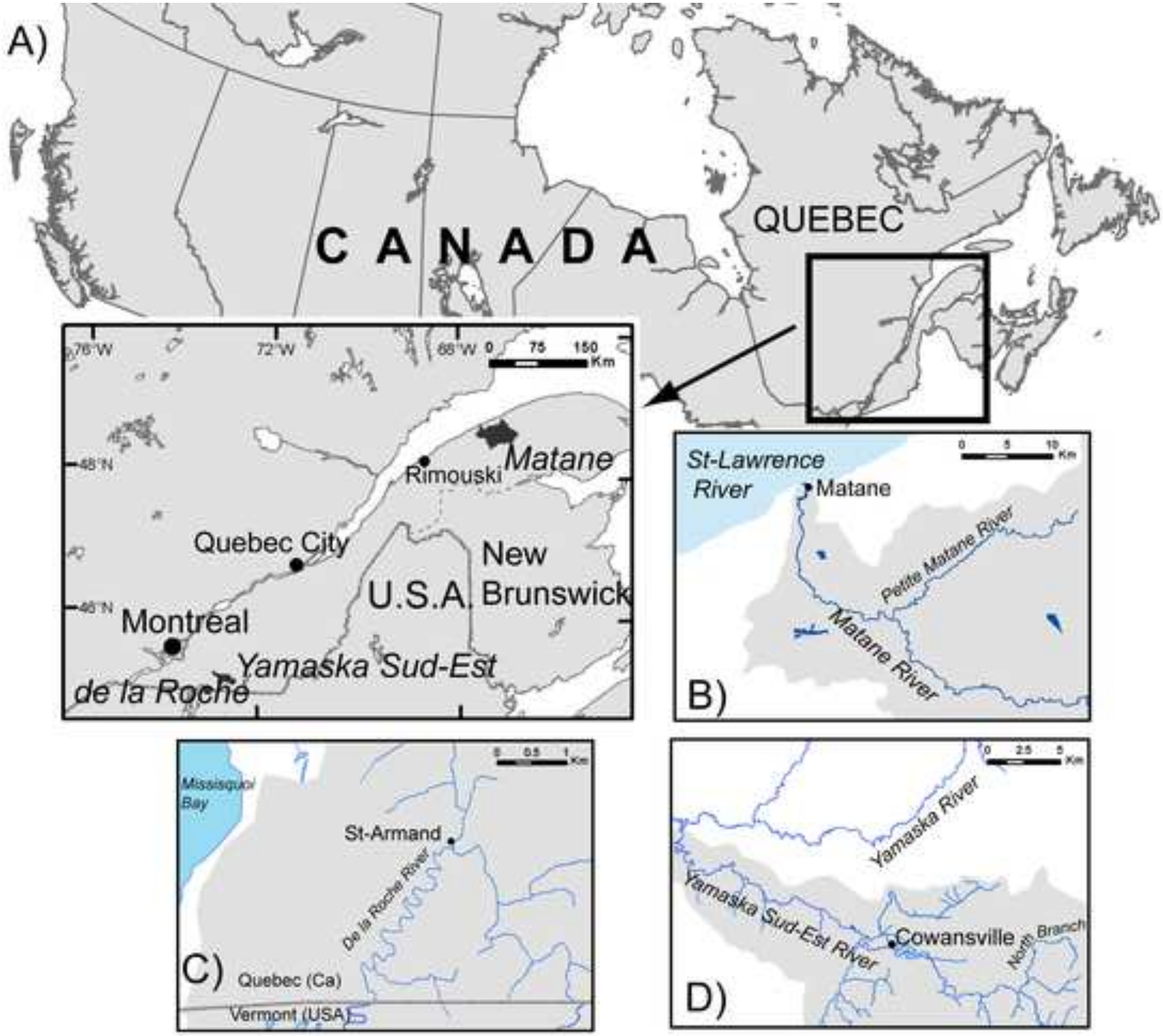

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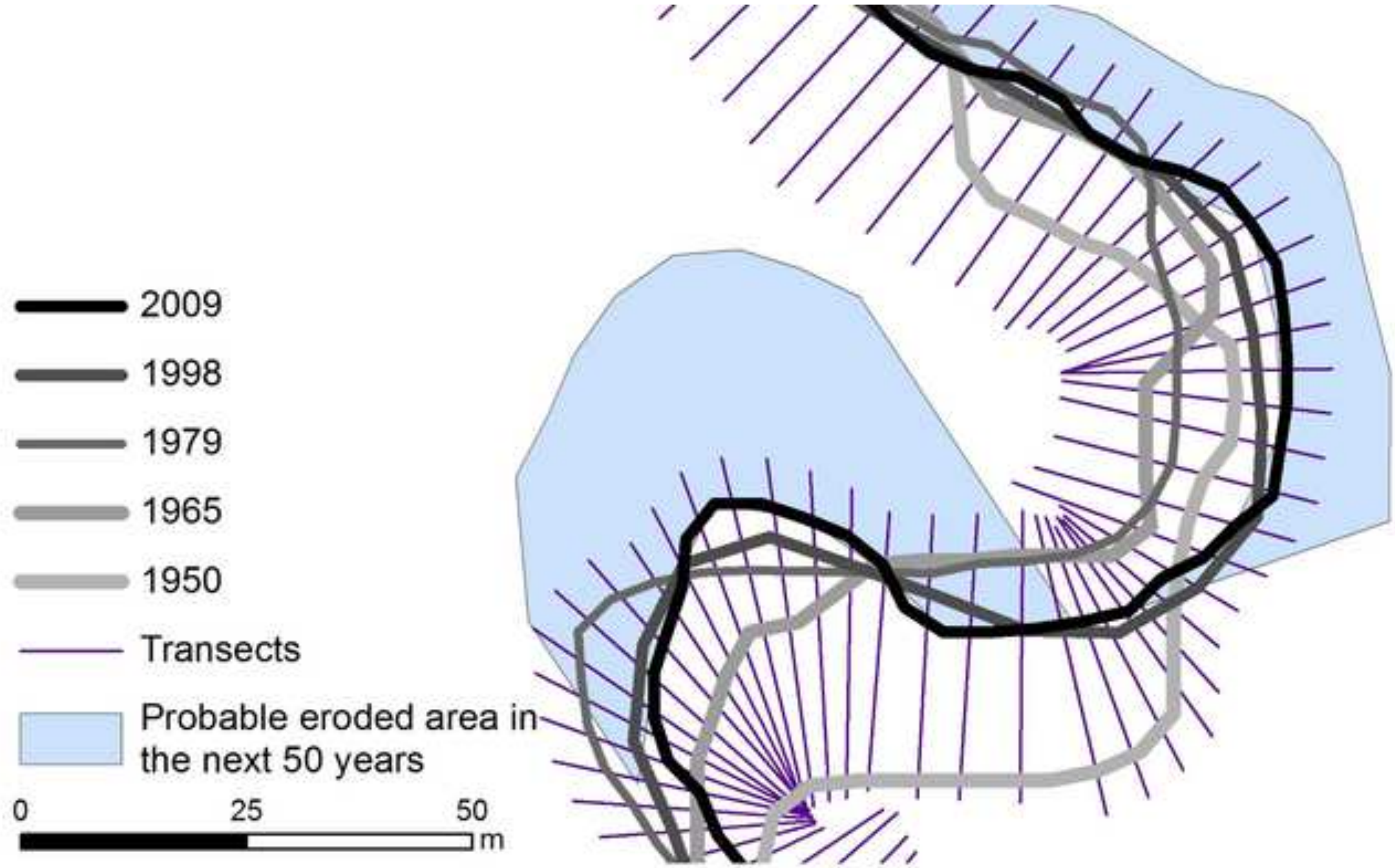

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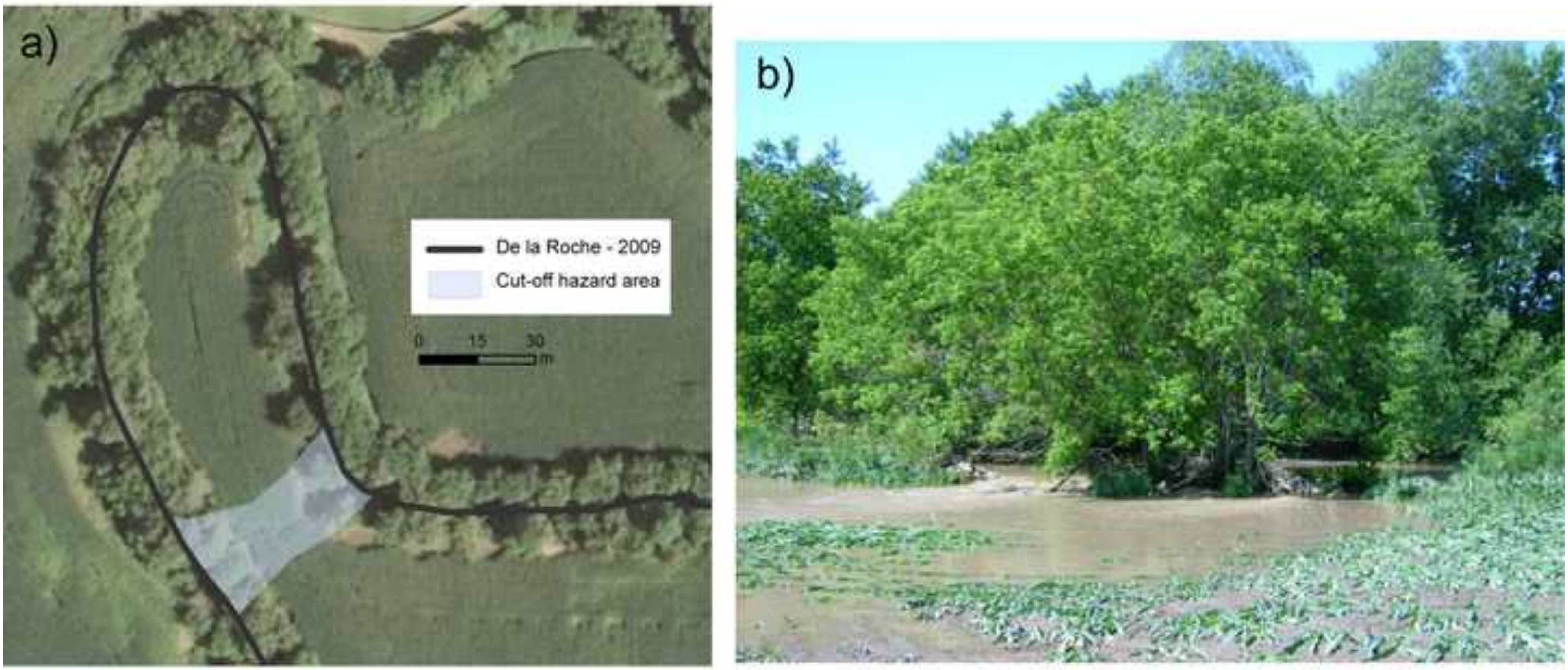

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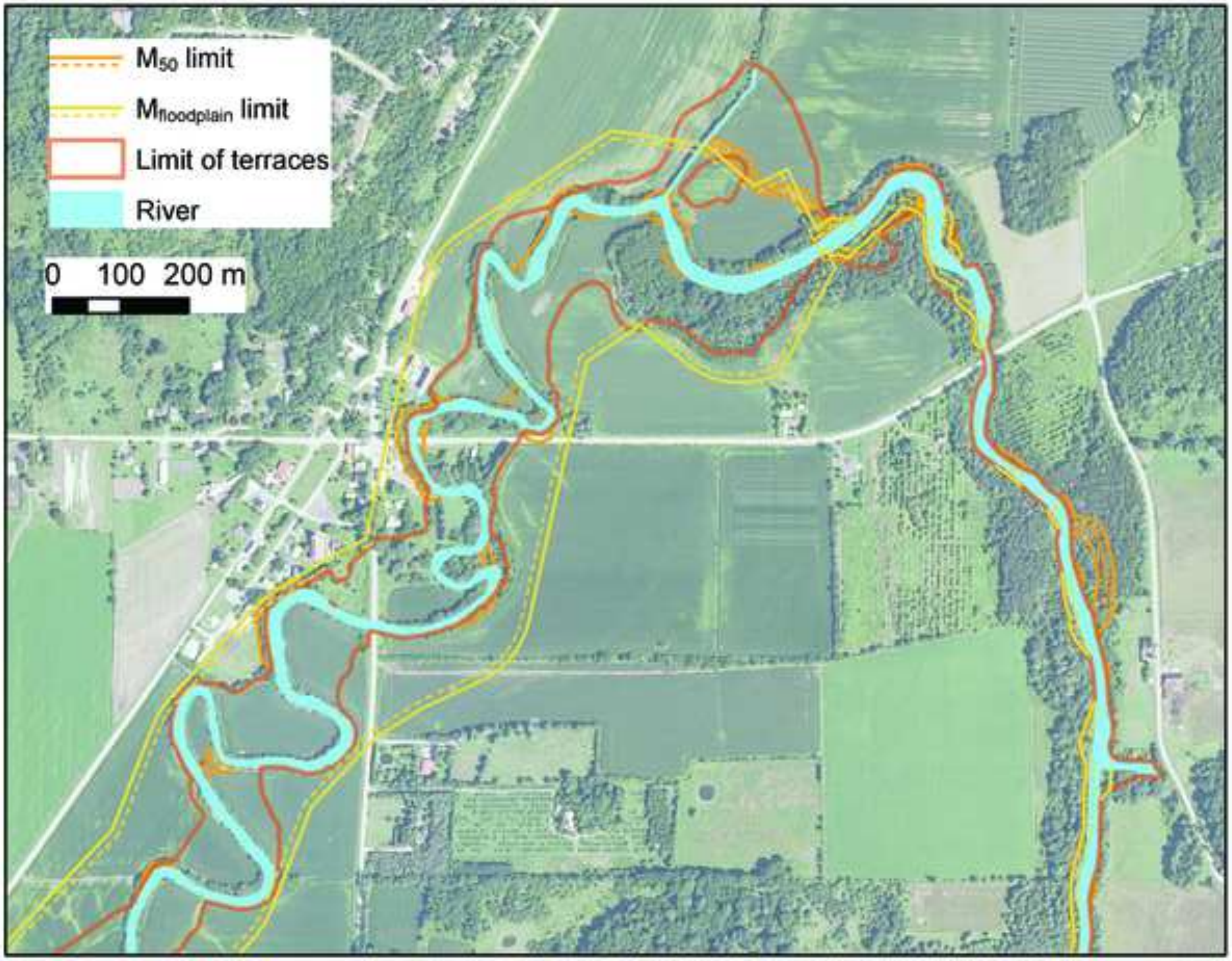

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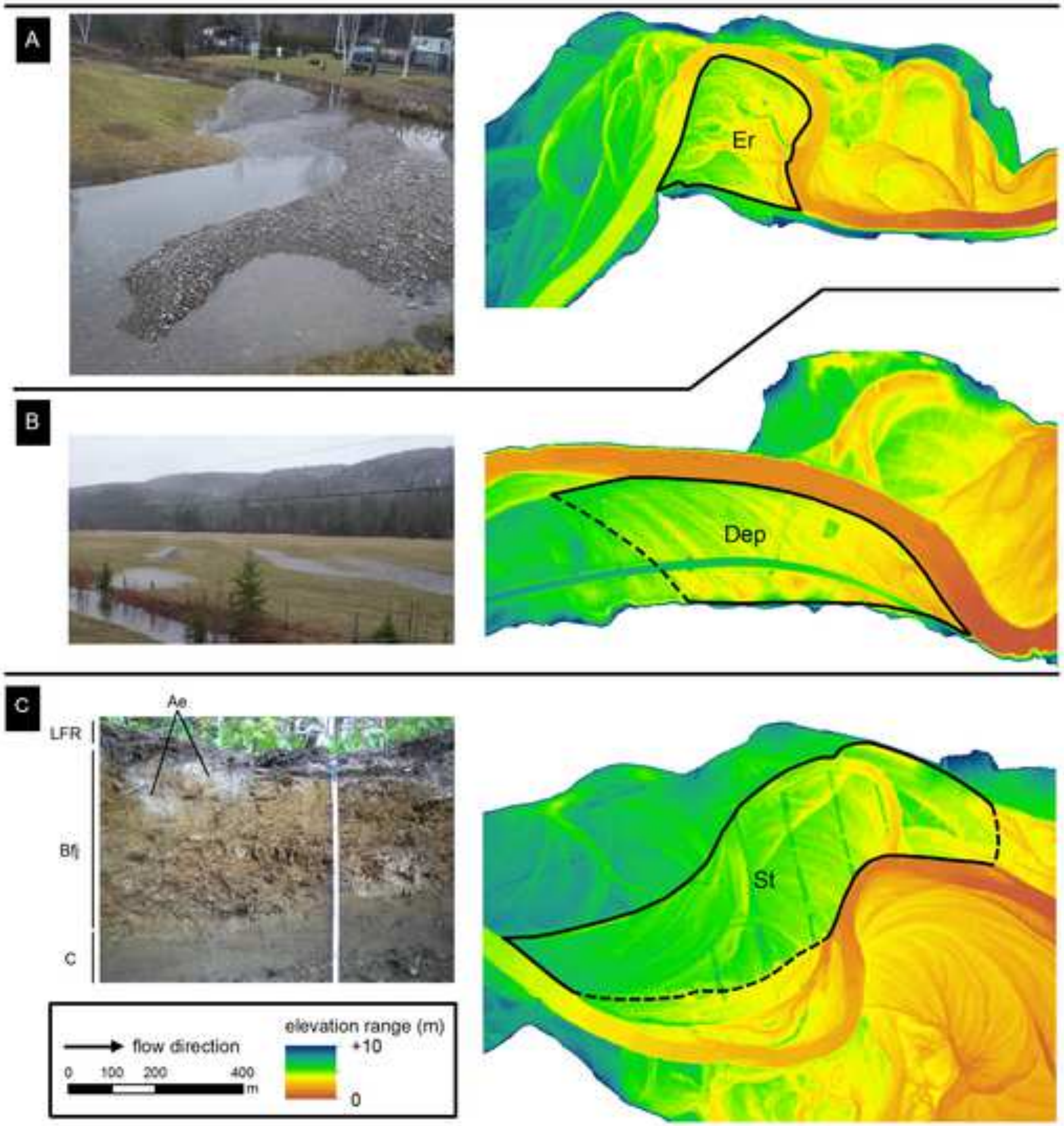

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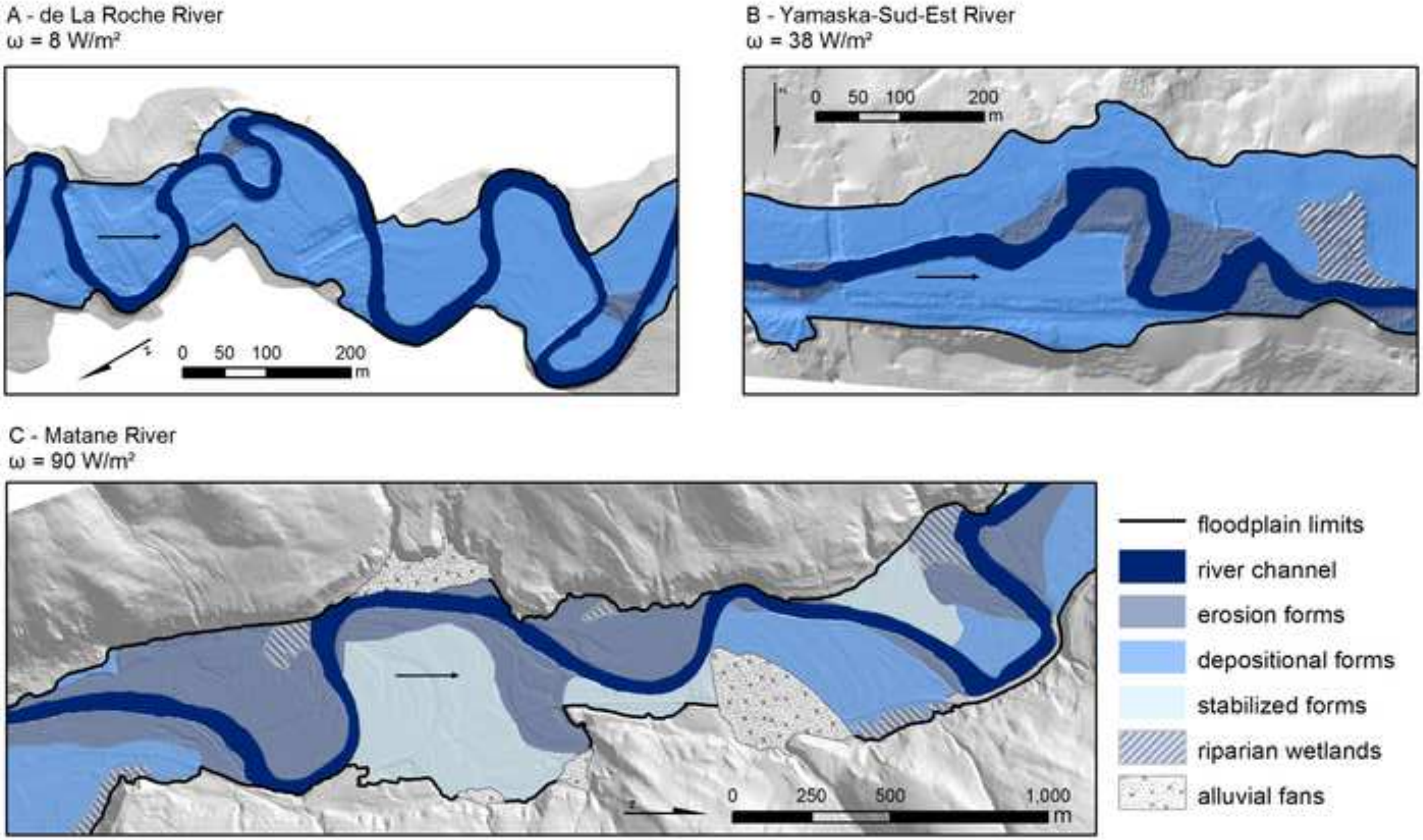

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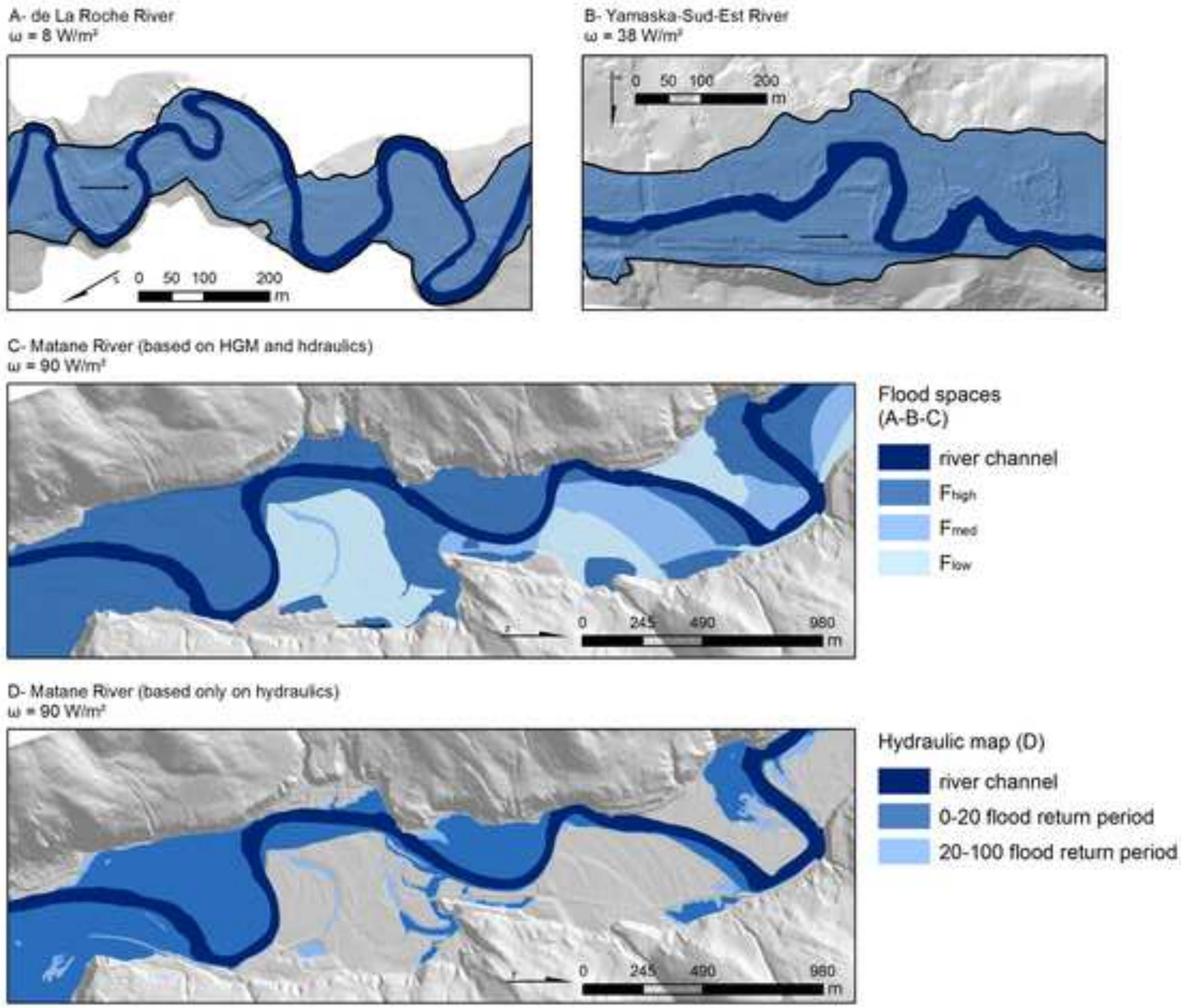

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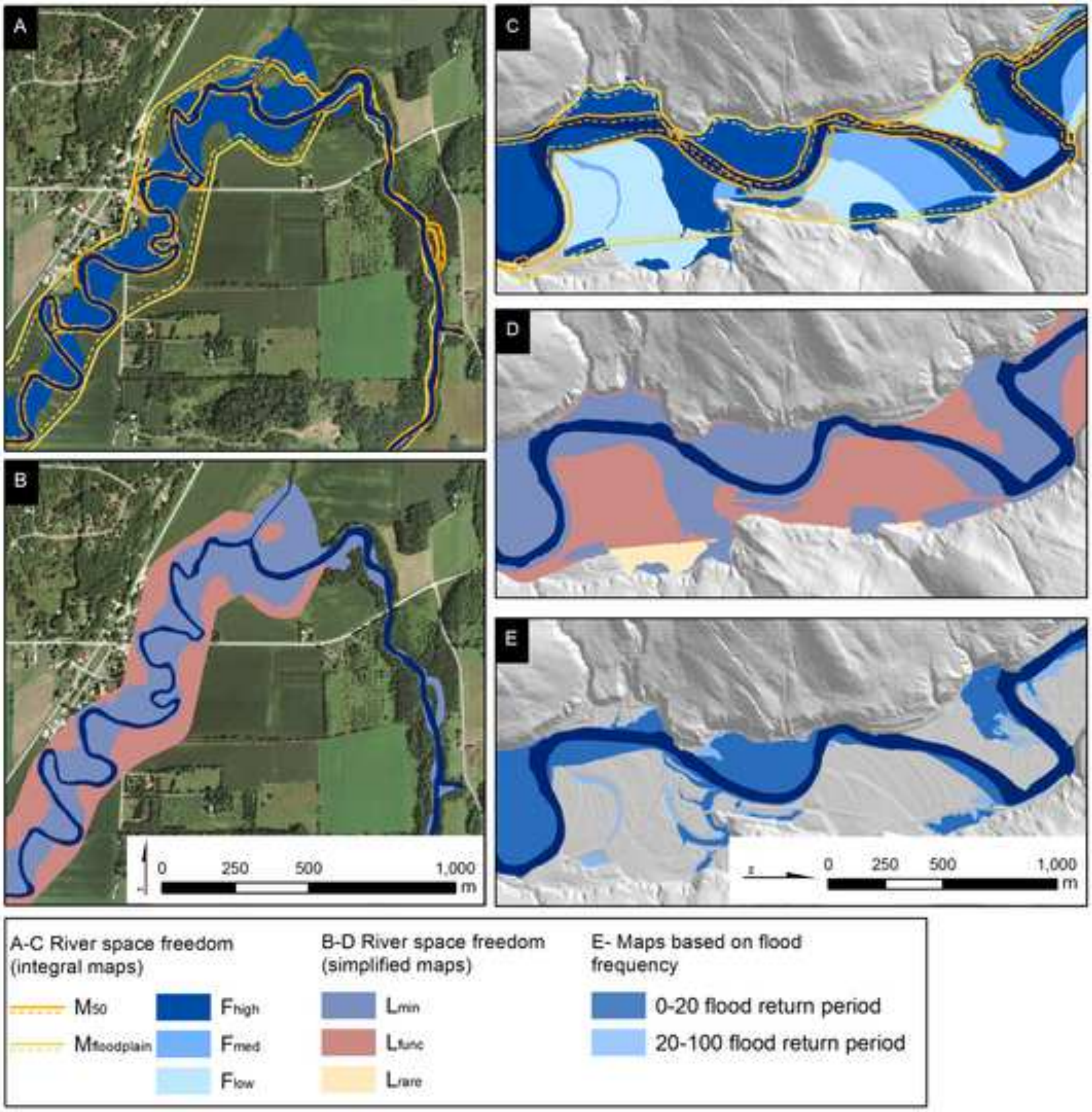

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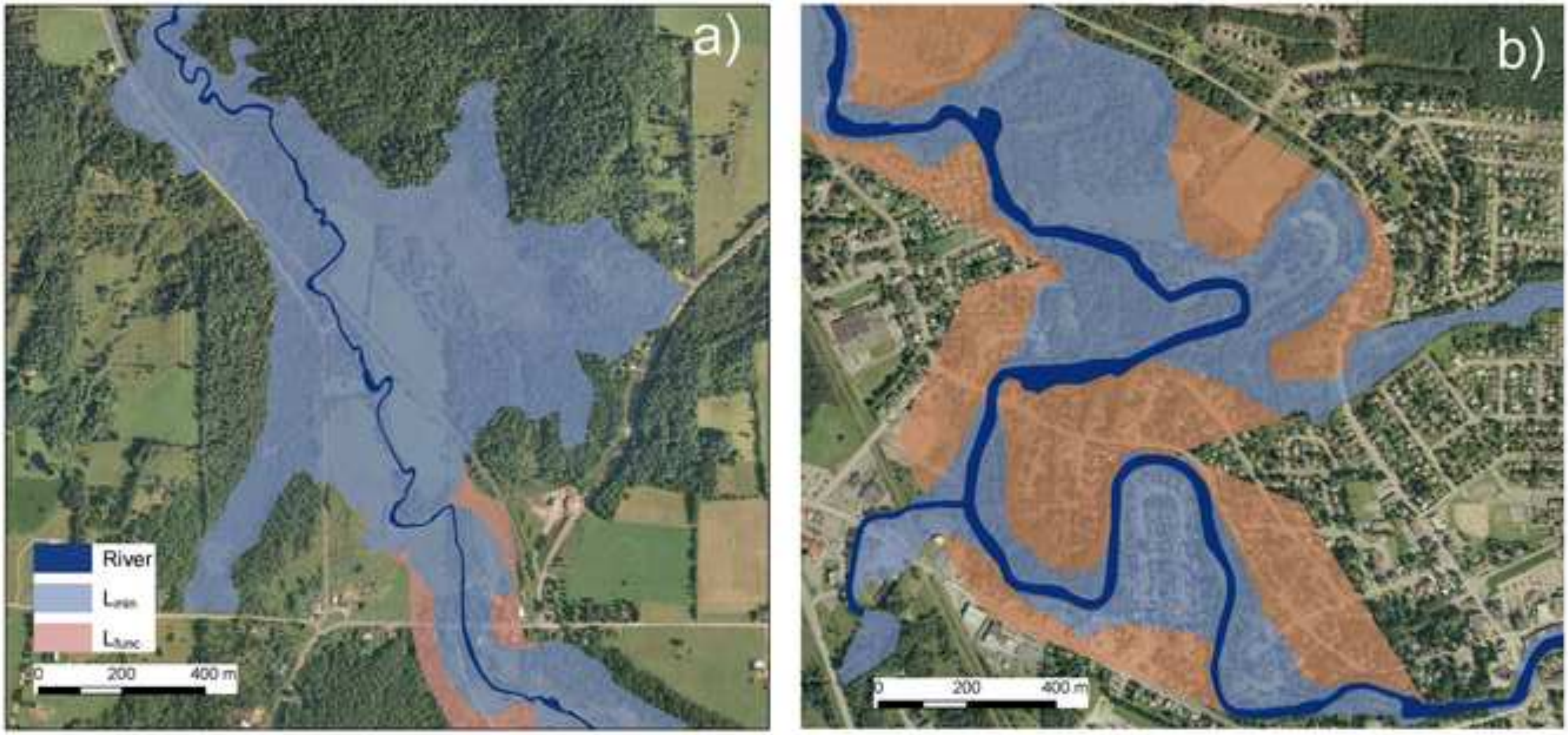

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Freedom space for rivers: a cost-effective approach to enhance river resilience: authors' response to reviews.

Review comments are in normal font; responses are indented and in italics.

Editor's comments:

The manuscript listed above has been reviewed for the journal Environmental Management and requires major revision before it can be considered further by the journal. We would like you to revise it on the basis of the comments by reviewers that appear below. We apologize for the slow review process.

Reviewers feel that it will take a considerable rewrite to get this paper to publishable quality, but they feel that if the work is done, it will be a good, novel and interesting paper on how "freedom space" can be delimited for three rivers.

Reviewers recommend

--considering additional management issue other than bank protection and flood protection

--modifying the tone so that there is not an apparent activist stance against traditional engineering approaches. for example, in 1st sentence of intro, can that be qualified? wouldn't traditional engineering approaches sometimes be sustainable, especially when used in concert with other approaches?

--better justifying the methods

--clarifying the methods (e.g., providing more information about the mobility approach, more information on methods used to designate flood space)

--considering the methods in the context of reviewer 3's comment c--ie, equilibrium and scale

--comparing these methods with other approaches

--providing more information in the cost benefit section; we see that you have submitted a separate paper to Ecol Econ on these methods, but they need to be understandable, as reviewer 3 indicates

--consider whether the benefits might have been exaggerated (see reviewer 4)

--discussion the generality of these findings--what is the applicability of the methodology to rivers across the world? can you suggest alternative methods when preferred methods don't work?

--clarifying Table 2

--improving the discussion by showing how this work is builds on and is an advance over previous work.

--Please ensure that British spellings are changed to American spellings (e.g., favourable to favorable)

Summary of the changes

The most important changes in this revised version are to 1) provide much more detailed information on the hydrogeomorphological (HGM) approach to define freedom space of rivers and 2) remove the cost-benefit analysis from this paper. The latter resulted from the former. Indeed, the paper, which was already long, was considerably lengthened by adding more information on the HGM approach, leaving us very little space to provide detailed information on the cost-benefit analysis. Consequently, we have revised the title to:

Freedom space for rivers: a sustainable management approach to enhance river resilience

Reviewers' comments:

Reviewer #2:

Reviewer #2: Overall the idea behind the paper is novel, interesting and important. However, there are some issues with its execution that make it very hard to follow. I have ticked the major revisions box above, but overall it is more like moderate revisions (this option was not available). It is really a case of clarifying what was done within this study, which as it reads now is unclear and confusing. Most of my comments are annotated on the scanned version of the manuscript (attached) but I have provided an overall summary below.

- The use of letters (L1, M1) to designate the different types and extent of migration is very confusing and hard to follow. Could the flooding notations be related back to the recurrence of the floods which inundate those areas? Also the Mobility notation could be linked back to the time period within which that area is likely to be reworked or risk such as high, medium or low. If this was clarified then the findings would be easier to follow without having to continually refer back to the paragraph in the manuscript which describes what each label (i.e. L1) means.

We have renamed the mobility zones M_{50} and $M_{floodplain}$ instead of M1 and M2. The flooding zones were renamed F_{high}, F_{med} and Fl_{ow}. We have also renamed the freedom space zones L1 as L_{min}, L2 as L_{func} and L3 as L_{rare}, where "L" stands for "liberté" (freedom in French).

- It would be useful to have more information about the mobility approach. The use of erosion rate is a very simplistic way of calculating this and it would be good to get some information about whether the mechanisms for adjustment were considered. For example, does erosion rate differ through the terrace, compared with the floodplain or with time since cut-off? Also was changes to the direction of meander migration during the time surveyed considered and how was this dealt with?

More information is provided in this revised version on the mobility approach. Section 3.1 (now 4.1) has been significantly revised to take into accounts this reviewers' comments, as well as those from Reviewer 4. The alternative method consisting in calculating a floodplain renewal rate was designed to deal with the issue of lack of temporal or spatial linearity in the erosion patterns. The paragraph describing this method has been rewritten to provide more details and now reads as follow:

"…because extrapolation of a constant erosion rate in time along a straight line is a crude approximation of natural channel mobility in the cases of highly mobile channels, two specific procedures were applied to river reaches that display high erosion rates relatively to their meander belt width. The first method used the rate of renewal of the floodplain following O'Connor et al. (2003), Piégay et al. (2005) and Konrad (2011). For each reach, the area mobilized by the rivers between each digitalized historical channel was measured (1930-1964, 1964-1979, 1979-1997 and 1997-2009 for the de la Roche river; 1950-1965, 1965-1979, 1979-1997, and 1997-2009 for the Yamaska Sud-Est river, and 1963-1993, 1993-2001 and 2001-2009 for the Matane river). These mobilized areas were divided by the length of the reach to obtain an erosion rate for the reach. The average erosion rate, over the total observed time periods, was then divided by the area of the $M_{floodplain}$ which corresponds approximately to the meander belt area or the floodplain area (see below) to compute the floodplain renewal rate. This metric (or its reciprocal, the floodplain renewal time) provides the required measurement of the erosion rate, relative to the floodplain width, to define a threshold over which the DSAS methodology cannot be applied. Visual estimation of the past dynamism of the rivers showed that this methodology is not adequate for reaches with a renewal time less than 200 years. Consequently, the entire M_{long} zone was classified as M_{50} for these highly dynamic reaches. However, the computed floodplain renewal rates may be overestimated by this method due to georeferencing errors. To prevent the classification in M_{50} of large areas with little erosional hazard, the reaches where the estimated contribution of the georeferencing error to the computed floodplain erosion rate was greater than 50 % did not have their M_{long} zone reclassified M_{50} even if the computed renewal times were less than 200 years. Among the 49 studied reaches, 22 reaches had a floodplain renewal time less than 200 years, but only 13 of them had their floodplain classified as M_{50} once the error contribution threshold was considered. Despite the use of the floodplain renewal rate, some highly dynamic meanders are situated within reaches with a low average erosion rate (or with an erosion rate where the contribution of georeferencing errors is too large). For these special cases, the second method relies on an expert assessment of the likely future erosion trend, based on the observation of past erosion, to delimit the M_{50} area. However, these cases were seldom encountered in the studied rivers, and manual corrections were needed for only 8 meanders, representing only 1 % of the total length of the studied rivers."

We also agree that erosion rate may differ though terraces compare to through floodplain. This is intrinsically taken into account in the methodology for the determination of the M_{50} mobility zone, as the erosion rate is calculated locally from the erosion displayed during the last decades. Differences in soil resistance to fluvial erosion are consequently assessed in the process, as long as the soil resistance is constant in the direction of the erosion. Precisions were added in the methodology description to highlight this:
"The 5 m-spaced erosion rates, along each transect, provides an assessment of channel dynamics at a sufficiently fine scale to model meander migration. These erosion rates also reflect local conditions that affect the ground resistance to fluvial erosion, such as vegetation, soil structure or the presence of a terrace."

- The information on Table 2 is also unclear. What do the author/s mean by risk and how does it relate back to the methods used?

Since we have now added detailed information in the text on the mobility space methodology, we no longer feel that Table 2 is necessary so it was deleted

- The methods used to designate flood space are very poorly described and unclear. For example, the concept of HGM is never properly described, and neither is the acronym.

The text describes the different types of forms but not how they are used to describe flooding space. Also there is no description of how modelling was used to define flooding space. How does HGM mapping relate back to flood zones? This would be strengthened by revisiting the information included in this section, and presenting a narrative which describes 1) what these techniques are and 2) how they are related back to flooding spaces. This confusion can be related back to the information on tables 3 and 4. They are very difficult to read and it is hard to understanding what the author is trying to get across (please see comments on each table).

The acronym HGM, which stands for hydrogeomorphology, was defined the first time it was used in the Introduction. However, we agree with the reviewer that the hydrogeomorphology approach to define flood space was not sufficiently clear in the original manuscript. The section on flooding space (section 3.2, now 4.2) was thoroughly revised to clarify what the HGM approach is, and to compare this approach with the traditional hydraulic modelling approach which is used to define the 0-20 and 20-100 flood zones. The link between geomorphological maps and flood spaces is now better introduced. We more clearly underline the idea that flood space composition is related to decisions supported from qualitatively anticipated floodplain hydrodynamics (frequency and intensity). For the frequency criteria, this is judged in line with the defined flood intervals selected for the three flood spaces (0-20 years; 20-100 years; > 100 years). This interpretation is summarized in table 3 which was also clarified. However, it is necessary to recognize that the HGM approach does not yield boundaries that coincide with fixed frequency intervals. It remains an approximate assessment based on geomorphological interpretation of flood hydrodynamics. We have also added a map showing the difference between the traditional flood zones (0-20 years, 20-100 years) and the HGM flood zones on Figure 6. Furthermore, the traditional flood zones (0-20, 20-100 years) have been added to Figures 7 and 8, so that they can be compared with the freedom space zones for a reach in the Matane River. Answers to more specific comments are on each table below.

- I am confused with how stream power was used to define flood zones. Please elaborate on how this was related back to freedom space (lines 335-336).

Because stream power is not central to the idea of flood zoning from hydrogeomorphological interpretation, this concept was excluded from the paper. Our initial intention was to find an objective way to distinguish floodplains presenting contrasted flood processes. However, work remains to be done to show if stream power is a good criterion to specify floodplain types with distinctive flood processes. This distinction is now treated on a case by case basis based on geomorphological interpretation. It is also linked to methodological difficulties in delineating the proper active limits of the floodplain. This is now more thoroughly explained in the text.

- Within the cost benefit section it would be good to have more information on which items were included, and how much they cost, particularly as the paper used as a reference is 'in review'. Perhaps even a table (or appended to either Table 6 or 7) which summarised the individual items included within the costs and benefits analysis and relative costs. For example, does it include ecosystem services, and how much do they cost? We need to know more about the methods and not just the outputs.

Since it was not possible to provide sufficient information on the cost-benefit analysis, particularly now that we have considerably increased the length of the paper by providing more detailed information on the HGM approach, we have decided to remove the cost-benefit analysis from this paper and to only briefly mention it in the Discussion section.

- Finally, the discussion concentrated mainly on limitations of the study. This could be strengthened by comparing this approach with other work published in the literature, and discussing why this approach furthered previous work done.

The discussion was thoroughly revised to address several comments made by the reviewers, including more comparison with other work published in the literature (e.g. O'Connor et al. 2003; Piégay et al. 2005; Konrad 2011) and further explaining the advantages of the freedom space approach over previous approaches.

Overall, I really liked the approach which this paper presented, and the fact that it had an obviously useful applied edge. However, the strength of the ideas behind the work were let down by the highly confusing narrative throughout, which made it very difficult to follow the procedures used. If the approaches could be clarified and substantiated, then I think this would make a very good paper, and one which is appropriate for the journal Environmental Management.

[see 3 attached files from this reviewer on the website. They are handwritten comments on the manuscript. two are rather large, apparently scanned files, so you may want to download them one by one]

Comments on the scanned version:

Line 40: Clarify mobility

In the introduction, mobility is now defined as being either lateral channel migration or avulsion. "Lateral channel migration" was preferred to "lateral channel adjustment", as the latter could be interpreted as adjustment due to instability rather than meander migration

Lines 75 and 109: Explain HGM

The term "hydrogeomorphology" has been used instead of HGM in these two sentences.

Line 81: Separate section for Study sites

We have used a separate section (section 2) for the Study sites and for the Methodology (section 3), and have renumbered the other sections accordingly.

Lines 85, 95 and 101: Catchment areas

The catchment areas are provided in Table 1. For the de la Roche River, it was already given later in this paragraph (55 km^2 of the catchment located in Quebec, out of a total catchment area of 145 km^2). The catchment areas were added in the text for the two other rivers.

Line 123: Error (DGPS)

The precision of the DGPS (from 0.03 to 0.05 m) was added.

Line 127: Clarify how this was used? What recurrence is the flood event you used? Mean annual flood or is this based on surveying the bankfull area of the channel?

We have clarified how the discharge-to-drainage relationship was computed and applied. The revised sentence is:

"Bankfull discharge (Q, in m3/s), which was considered equivalent to a 1.5-year recurrence interval event, was obtained from discharge-to-drainage area relationship:

$$Q = \alpha A^{\beta} \qquad (1)$$

where α and β are the coefficients that vary between regions and watersheds. For the Yamaska Sud-Est and de la Roche rivers, a hydraulic geometry relationship for the bankfull discharge was developed from a sample of 20 gaged rivers in Vermont with drainage area (A, in km^2) ranging from 7.8 to 360 km^2, where the bankfull stage was assessed at the gaging stations from field observations (VANR 2006), resulting in a discharge-to-drainage relationship with $\alpha = 0.3376$ and $\beta = 0.9487$ ($R^2 = 0.92$). The drainage area used in this discharge-to-drainage relationship was computed for the Yamaska Sud-Est and de la Roche rivers from the 10 m DEM with ArcGIS".

Line 147: Not published reference

We have removed this reference

Line 153: Explain what a discount rate means

This part is no longer included in the paper.

Line 162: Are the results for the sensitivity analyses presented?

No longer included in the paper.

Line 210: Average length of reaches

This information was added for each studied river in the following sentence:

"Homogeneous river reaches were on average 1 km, 1.7 km and 7.3 km long respectively for the de la Roche, Yamaska Sud-Est and Matane rivers."

Line 212: Present the elements constituting M1

A sentence explaining the elements constituting M1 (now M_{50}) was added, i.e.:

"The M_{short} mobility space represents the short-term (50-year) mobility zone, based on historical channel migration and on meander cutoff potential."

Line 218: Rivers don't migrate in a linear direction, and at a rate that can vary

and:

Lines 234 to 238: Clarifications concerning the more mobile reaches required

As previously discussed, more information has been added about the alternative methodological steps for places where river migration cannot be approximate by a linear trend.

Line 242: Justify the threshold of four times the channel width for meander cut-off.

We have added justification concerning the use of this threshold of four times the channel width. The following sentence was added:

"This threshold corresponds to the average ratio for the cuts-off that occurred during the observed historical period."

Lines 267 and 272: Clarification of the flooding space description required

The section describing the flooding space has undergone important modifications. We believe that the following description is clearer for the reader:

"The five types of floodplain landforms were used to delineate three levels of flooding space with decreasing order of flood severity: F_{high}, F_{med} and F_{low}. Flood return periods from the ongoing flood hazard policy in Québec are used as frequency criteria to define flood severity. F_{high} and F_{med} are respectively associated with flood frequencies of 0-20 and 20-100-year return period. F_{low} is associated to a new class (> 100 year return period, yet within floodplain limits)."

Lines 275 to 279: Clarification on the HGM floodplain delimitation method required

We have clarified the HGM floodplain delimitation method. It is now thoroughly explained in table 2 with examples illustrated with a new figure (5)

Line 286 to 290: Explain and clarify "active morphogenesis"

> *We have explained and clarified what we mean by "active morphogenesis". The new sentence is: 'Stabilized surfaces are areas of the floodplain where there is no evidence of active geomorphic processes wich underlines that they are at the edge or outside the extent of contemporaneous flood activity'.*

Lines 308, 311, 341 and 342: Clarify the links between recurrence intervals and N1, N2 and N3

> *We have clarified the links between recurrence intervals and N1, N2 and N3, which are now renamed F_{high}, F_{med} and F_{low}. (see revised text in answers to comments concerning lines 267 and 272).*

Line 319: Give examples of stabilized forms remnants of past flooding action

> *We now provided an example of stabilized forms in figure 5. However, stabilized surfaces of the floodplain are not apparent form surface morphology. Stratigraphic information and pedogenesis evidence have helped to identify the areas that present long-term stability. This is now explicit in table 3.*

Line 335: Clarify sentence

> *This sentence was removed in line with our decision to discard the idea of a threshold based on specific stream power. We now specify that the distinction between the different reaches is related to floodplain character and related methodological limits.*

Lines 341-344: Recurrence interval of the flood confined by terraces for de la Roche and Yamaska Sud-Est rivers

> *We have clarified the process of delimitation of HGM flood zones, and the role of terraces for the de la Roche and Yamaska Sud-Est River, which results in only one flood zone in these rivers. We now specify the range of flood frequencies necessary to fill the entire floodplain (5-10 year flood interval).*

Line 349: How was combined the different interests (human or infrastructure risk, ecological integrity) in the final map products?

> *We have explained how these different interests were combined. Precisions have been added to clarify the underlying choices associated with the two proposed mapping products (i.e. the integral cartography does not propose any combinations, whereas the simplified cartography does. These combinations are based on management choices, existing literature and scaled-related processes).The revised paragraph is:*

"One option, which is called here "integral cartography", was to map all the zones, i.e. M_{50}*,* $M_{floodplain}$*,* F_{high}*,* F_{med} *and* F_{low}*, without any combination, and to let river managers decide how best to use these maps in each case. This type of map has the advantage of presenting all the information, but it also has the inconvenient of being difficult to read and/or synthesize. Another option, called here "simplified cartography", is to group these zones in order to produce three freedom spaces:* L_{min}*,* L_{func} *and* L_{rare}*. The cartography rules must then consider cases where there is an overlap between the mobility and flooding spaces. The chosen combinations of level of flooding hazard, erosion hazard and high ecological value areas correspond more to management choices than to strict hydrogeomorphological criteria, and can consequently be modified according to the management objectives of the zonation process. The proposed combinations are based on scale-related processes as well as existing similar methodologies."*

A justification of the inclusion of high ecological value areas has also been added in the next paragraph, with the following sentence:

"Inclusion of the high ecological value area within a minimum functional space, as proposed by Malavoi et al. (1998), recognizes the importance of such areas."

Line 365: Relate L2 back to risk or recurrence interval

Comparison between 20-100 years recurrence flood and L2 space (now L_{func}*) can be done, and is shown in the new figure 9. However, the* L_{func} *space is based on HGM forms which are not directly linked with a recurrence interval or a level or risk. This is discussed in the following added paragraph:*

"The Matane River case illustrates some methodological challenges of the HGM approach. Complexity arises mainly because the floodplain present inherited landforms from processes acting over a large extent of time. The de la Roche and Yamaska Sud-Est floodplains represent shorter time scales of floodplain construction that remain in line with contemporaneous processes and flood management horizons. In our work, using three levels of flooding space helped characterize the more complex floodplain of the Matane River, whereas a simpler classification with only one level was sufficient for the de la Roche and Yamaska Sud-Est Rivers. This contrast stresses the need to better understand the links between geomorphological boundaries and flood hydrodynamics within different floodplain environments. The real issue remains an adequate estimation of flood processes within these limits in order to implement adequate management policies. In our study, the proposed boundaries were known to match and sometimes exceed the minimal requirements of the actual policy (0-20 years and 20-100 years flood zones). Ultimately, the lack of quantification requires that geomorphologists and risk managers take concerted decisions as to how the HGM approach can be best integrated into river management to determine freedom space zones."

Line 370: Clarify how the "ecological value" was determine

We have clarified that zones of high ecological value are riparian wetlands

Lines 425 to 427: Clarify

The cost-benefit analysis is no longer included in the paper.

Line 427: Explain what a discount rate is

This is no longer included in the paper.

Line 440: How are the benefits calculated? What do they include?

This is no longer included in the paper.

Line 441: Expand GHG

This is no longer included in the paper.

Line 490: Statement not limited to rivers not in an equilibrium

We have added "or at different stages of adjustment" after "not in equilibrium" in this sentence.

Line 504: Why is the HEC-RAS simulations not referred earlier?

Since the use of a hydraulic model such as HEC-RAS is very common in flood zone delineation, we didn't think it was essential to include this in the Methods section. However, we agree with the reviewer that it is somewhat confusing to bring these modelling results in this paragraph. This was initially motivated to clarify the links between the hydrogeomorphological approach and flood hydraulics. Because it would require more thorough explanations that would significantly change the main focus of the paper, we decided to withdraw these results from the paper.

Table 1: Clarification required for "Max discharge", "Elevation difference" and "Fluvial style"

We have clarified the terms max discharge (now called max annual discharge), elevation difference (now called elevation range) and fluvial style (where the term "semi-alluvial" is now defined in a note).

Table 2: Clarify "renewal rate". How can the area behind stabilized banks be at high risk?

Table 2 was removed. In the text, the paragraph explaining the renewal rate calculation and its associated methodology was extended and thoroughly revised in order to clarify these notions.

Table 3: How can sedimentation be in the first and in the second row? First row: Explain the link between the erosion forms and the mixed sedimentary load. Second row: Use "depositional" instead of "sedimentation". "Deposit forms associated to a suspended load" should read "Deposition form

associated with a suspended load". Third row: Is "morphogenesis" the correct term? Explain what mean "topographically consistent with the floodplain"

We have modified Table 3 (now Table 2) to make it clearer and more complete. First, 'sedimentation forms' was replaced by 'depositional forms'. The distinction with 'erosion forms' is also clarified. Erosion forms can indeed be easily confused with depositional forms since all floodplain landforms result from depositional processes. Here, the distinction lies in the transport mechanisms that contributes to the shape of landforms: erosion landform are reworked by competent flows whereas depositional form strictly refers to aggrading landforms from the deposit of fine sediments (silts) resulting from low-velocity flows. The various criteria that we used to map the different landform types are now more thoroughly presented. Illustrated examples are also provided in Figure 5.

Table 4: The message from this is unclear. What information are you trying to get across? What do the terms risk and power relate to? And how do the methods relate to the contribution to fluvial integrity?

This table represents the decisions for the delineation of flood spaces from hydrogeomorphological maps. We have modified Table 4 (now Table 3) to make it clearer. We now specify at the head of the table that this is our interpretation of floodplain landforms in terms of flood processes or support to fluvial system functions. This last criterion refers specifically to riparian wetlands. All other information was excluded from the table for clarity.

Table 5: What does "Outside mobility space" mean?

We have specified that "outside mobility space" means that it is larger than the M2 (now Ml_{ong}) limits.

Figure 1: Images are blurry. Could be useful to have a larger scale Canada map. In the situation map, add the extent of the other maps.

We have added a larger scale location map (of Canada), and improved the resolution of the other figures so Figure 1 is no longer blurry.

Figure 4: Could we also have the M1 on this map to compare?

We have added M1 (now M_{50}) limits on the map.

Figure 5: Legend: Provide a table of what the different forms are.

The different forms are now thoroughly presented in table 2 and illustrated in a new figure (Figure 5).

Figure 7: "integral and simplified cartography": unclear what this is.

Integral and simplified cartography are defined in the text. Integral cartography presents each zone of mobility and each flooding zone, so one can assess what the fluvial hazard is for a given location. Simplified cartography only presents the freedom space zones, which are easier to understand from a management point of view, and which can be related to legislation such as "no development allowed" in the L_{min} space, regardless of the reason why it is coded as L_{min} (i.e. due to high mobility or high flood hazard).

Reviewer #3:

This is a paper with some potential impact, which may be suitable for the journal with considerable revision. It relates to methods which identify medium-term behaviour of rivers and their associated morphological characteristics, which are then used to delimit 'spaces' in the river corridor which should be subject to some degree of planning constraint to reflect natural process dynamics, and which reduce the need for channel stabilisation and flood protection.

The three key issues which need to be addressed are:

a) The lack of contextualisation of the paper. Throughout, it is assumed that the principal management issue in rivers is bank protection and flood protection. In reality, these are neither the only issues, nor the major ones other than locally. There is almost an 'activist' stance taken in the paper against 'traditional' engineering-type approaches. This is a partial, and unbalanced view.

> *We have thoroughly revised the Introduction to provide better contextualisation of the paper, using several additional references, and to better explain why we focus on bank protection and flood protection, as well as to answer other comments made by reviewer. However, we are a bit surprised that the reviewer would think we are taking an 'activist' stance on this issue, when we are merely reporting the growing consensus in the geomorphological literature that the past management schemes based mostly on hard engineering interventions need to be revised (e.g. Brierley and Fryirs, 2005; Roni and Beechie, 2013). For example, Kline and Cahoon (2010), who were instrumental in developing a geomorphic river corridor management approach in Vermont, state that prior to 1999, Vermont experienced decades of disjointed river management and that: "Resolving conflicts between human investments and the dynamics of fluvial systems river largely remained an exercise of installing local engineering fixes that amounted to channel armoring" (p. 228). They also discuss a report on the impact of major floods in the 1990s. This reports highlighted "the high cost and repeated failure of common structural measures used in the attempt to protect near-stream investments and infrastructure by keeping long lengths of river permanently straightened" (p. 228).*
>
> *The revised first two paragraphs of the introduction are:*
>
> *"Several rivers across the world are located near human settlements, and are thus under stress and pressure from agriculture and urbanization in riparian zones. It is generally accepted that for purposes of navigation, power generation, water supply or protection of infrastructure, hard engineering interventions are needed in these river systems. However, since the mid-1990s, a paradigm shift from the reach-based engineering-dominated perspective to a more inclusive ecosystem-centred approach to river management has occurred (Brierley and Fryirs 2005; Hillman and Brierley 2005; Roni and Beechie 2013). there is now strong consensus in the field of hydrogeomorphology (HGM) that such traditional management approaches may not be sustainable economically and ecologically everywhere along a river course (Piegay et al. 2005; Kline and Cahoon 2010; Kondolf 2011). In particular, bank stabilization, which is one of the most*

popular activities undertaken in the name of "river restoration programs" in North America, and flood protection measures such as levees tend to "fossilize" rivers by preventing channel migration and limiting connection with the floodplain (Kondolf 2011; Roni and Beechie 2013). They are increasingly questioned as management strategies since they require frequent maintenance (Kline and Cahoon 2010) and may be detrimental for floodplain habitat diversity (Kondolf 2011; Roni and Beechie 2013). Where possible, providing more space for rivers to migrate and flood naturally appears to be the obvious approach to sustainable management of both the quantity and quality of surface water, as well as flood and erosion risk (Piegay et al. 2005; Kondolf 2011).

The HGM approach to river management emphasizes the physical and ecological integrity of living, dynamic and evolving aquatic ecosystems, with a focus on process-based restoration where the river can "heal itself" (Beechie et al. 2010; Kondolf 2011), whereas river engineering activities are usually focusing on empirical solutions to reach-scale issues, and applied to maintain and protect infrastructure, navigation and flood protection networks (Brierley and Fryirs 2005; Roni and Beechie 2013). There are several documented cases where endeavors to stabilize channels through engineering practices have actually accentuated their instability and negatively affect their health (Bravard et al. 1997; Brierley and Fryirs 2005). However, in urbanized zones or where infrastructure is threatened, hard engineering approaches remain a necessity (Kondolf 2011). The HGM approach requires a broader, catchment-scale perspective, and involves skills and insights from both geomorphologists and engineers to be successful (Brierley and Fryirs 2005)."

b) Justification of the methods and research design is poor, and is reliant either on material n figures and tables, or on methods and techniques explained in other papers.

We have improved the Methods section, particularly for the mobility and flooding spaces. In particular, we have revised the tables and explained better in the text concepts presented in the tables.

c) The authors accept that the methods are suitable for (unknown) equilibrium states in rivers. This is, perhaps, the most problematic aspect of the papers. Quasi-equilibrium is a scale-dependent phenomenon, and probably equates to periods c. 20 - 50 years on rivers such as these. The problem is that this period is close to longer-term planning time horizons as implicitly advocated in the paper: there is thus no 'independent' evidence line for the applicability or indeed, the precise calibration, of the approaches used. Although the authors discuss some of this, there is no real evaluation of the limitations imposed by it, and also, the discussion comes after the data and key findings are presented. At the very least, it makes both the techniques and the findings of questionable significance, and of questionable transferability to other sites. The issue is compounded by the lack of real data on hydrological variables and landuse change over this period.

I am not sure whether point (c) can be sufficiently addressed to render the paper scientifically robust.

The question of equilibrium is indeed a very good point raised by the reviewer and it is now addressed in the discussion section. It is indeed true that quasi-equilibrium is scale dependent, and could impact the longer-term planning. Piegay et al. (2005) have indicated that it was essential to make sure, when delimiting a mobility space for rivers (called "espace de liberté" in Piegay et al. 2005), that no significant geomorphological instabilities were present. We have added the following sentences to explain that such an analysis was conducted in our study, which is why the data from 1963 were not used in the Matane River case:

"Analyses of the Matane River hydrology revealed an increase of the yearly maximum discharge between the periods 1927-1978 and 1979-2011 (t-test, $p<0.01$). Consequently, only the channel positions after 1978 were taken into account when assessing channel migration for this river. Discharge data were not available for a long enough period for the Yamaska Sud-Est and de la Roche Rivers to compute similar analyses. However, 1930 to 2011 records of yearly maximum discharge river of the Nicolet River, a nearby river in the same geological context, do not present a change in trend. Consequently, all available historical channel positions were used to analyse the mobility of the Yamaska Sud-Est and de la Roche rivers."

However, the current traditional river management approach is one which implicitly assumes that a channel will remain static in the future, i.e. that the floods of a given recurrence will correspond to a fixed elevation which is mapped to delimit floodplain zones of 0 to 20 years, or 20 to 100 years recurrence. The HGM approach is not perfect, but it does at least recognize that rivers are dynamic. More elements have been added in the discussion to highlight these points:

"It is also important to be aware that this approach is based on the hypothesis that future trends can be estimated from past trends. This hypothesis might not hold true for rivers that are not in an equilibrium state or at different stages of adjustment. Climate or land use changes may have hydrological implications which, in return, could affect erosion rates or flood frequency. Meander cut-offs may follow temporal cycles (Hooke 2003) which were not taken into account in this methodology. For example, on the Matane River, wood rafting was abandoned early in the 20th century but had a major impact on the channel which is still in a disequilibrium condition. This is highlighted by the change in the maximum yearly discharge on the Matane River between 1927-1978 and 1979-2011. Thus, based on previous work on the Matane River, bank erosion rates were computed for the 1979-2009 period since this period was estimated to be more representative of the current morphological trajectory. Such a morphological trajectory analysis can be deepened, and in particular in terms of land uses changes. It should however be reminded that traditional approaches to flood mapping using hydraulic simulations also present major drawbacks. Identified flood levels rely on the assumptions of hydro-climatic equilibrium and static channel boundaries (Lane et al., 2007; Merwade et al., 2008). As a consequence, the crisp boundaries predicted from quantitative methods can be poor estimates of real flood extents. The HGM approach recognize that rivers are dynamic and the same flood can reach various flow stages depending on aggradation or degradation processes which may occur (e.g. Lane et al. 2007; 2008). In contrast, in the

traditional approach the levels reached by floods of a certain magnitude are considered to be fixed, whereas in reality a flood of a given recurrence will reach a higher level in certain reaches if sediment deposition had occurred, or lower levels in the case of bed incision."

Detailed points

From the Abstract and in the first lines of the Introduction, there is the assumption that intervention and management are always undertaken to prevent flooding, and largely costly and unsustainable. This is rather unbalanced: there a lots of engineering interventions in rivers which are sustainable, necessary and ongoing: navigation; power generation; siltation; some aspects of effluent disposal and also water supply.

The first sentence of the abstract was modified to remove the notion of costly maintenance. The revised sentence is:

"River systems are increasingly under stress and pressure from agriculture and urbanization in riparian zones and require frequent engineering interventions such as bank stabilization or flood protection."

Similarly, as mentioned above, the introduction was modified to remove the apparent bias against all hard engineering interventions.

Lines 36 - 72 The passages which follow on freedom space are awkward, rather staccato and insufficiently contextualised. Much more should be said to examine the various aspects of 'traditional' vs newer management; and also to introduce HGM principles in comparison with traditional approaches - including the circumstances where one might be more suited over the other.

Cost benefit approaches are hardly new, and often less than convincing: newer approaches take and eco-system goods and services approach (ESGS) - the two are, of course, potentially related, as we later see in the paper!

These paragraphs in the Introduction were considerably changed so that they would be more fluid and highlight the various aspects of 'traditional' vs newer management. We have removed the part concerning cost benefit approaches since we are no longer including this aspect of our study in this paper. The revised paragraph is:

"Basic concepts of river corridor management based on HGM processes have been described under a variety of names (e.g. "room for the river", Baptist et al. 2004; "erodible corridor", Piegay et al. 2005; "fluvial territory", Ollero 2010; "river corridor", Kline and Cahoon 2010).These HGM river corridor approaches are typically focusing on either channel mobility or flooding problems. For example, mobility is the key factor determining river corridors in France, where the term "freedom space" was first used ("espace de liberté") (Malavoi et al. 1998; Piegay et al. 2005), in Vermont (Kline and Kahoon 2010), in Spain (Ollero 2010) and in the Canadian province of Ontario (Parish Geomorphic 2004). However, the focus is more on flooding than erosion in

river corridor programmes in the Netherlands ("Room for the River"), in the UK ("Making Space for Water", Defra, 2005) and in Iowa, which also included wetland restoration (http://www.public.coe.edu/departments/Biology/SpatialEcology/ircp-index.html). These examples demonstrate that mobility, flood zones and wetlands are usually considered in isolation and are not formally integrated in a common space, despite obvious overlaps between these zones. In Quebec (Canada), the HGM management approach is at this time not integrated in the river management practice. The current legislation promotes integrated watershed management with the use of protected riparian zones ("Politique nationale de l'eau" (National water policy, Québec 2002), "Politique de protection des rives, du littoral et des plaines inondables" (Policy for the protection of lakeshores, riverbanks, littoral zones and floodplains, Québec 2005) and "Loi affirmant le caractère collectif des ressources en eau et visant à renforcer leur protection" (Act to affirm the collective nature of water resources and to strengthen their protection, Québec 2009). However, in most cases, the protected riparian zone is very narrow (e.g. 3 m in agricultural zones), although it can measure up to 15 m in some cases.

Methodology

Despite the assurance that:

The three study sites were chosen in order to provide a contrast in river size, geomorphology and watershed land use so that the developed methodological tools would be applicable to a wide array of rivers in Quebec and elsewhere, there should be some attempt to justify which rivers were chosen; and also, to place these on a spectrum or some such which places the rivers in context - to what extent are they representative of other rivers? What is the institutional/governance character, as well as the physical and biotic representativeness of these rivers? What legacy of management has there been? Again, the issue is partly one of insufficient contextualisation of the work being presented. The three rivers are presented in terms of methods but NOT in terms of research design. We cannot be left to interpret a table and figures for ourselves as readers.

The following sentences were added in the first paragraph of the Study site section:

"Indeed, the three rivers cover a range in grain size (from clay to gravel), in land use (including heavily agricultural, urbanized zones and pristine forests), in dynamics (from very stable to highly mobile) and in administrative units (from zones where agricultural land has the highest value in Quebec (Montérégie) to zones where sport fishing (salmonids) dominates (Gaspésie). Being located in Quebec, they are representative of a cold temperate climate and may therefore not be generalizable to all rivers."

The methods for ungauged catchment analysis for the Matane - to obtain bankfull Q - should quote the significance levels of the regression relationship (line 135).

We have added the significance levels (coefficient of determination, $R^2 = 0.54$) of the regression relationship.

2.2.2 Data for the cost-benefit analysis. This is really under-explained, and is a major weakness of the paper. There should be some more detail of the key elements of the analysis, in addition to what is already here, which is simply a description of the key variables which are used. The inclusion of ESGS is welcome, but again comes without explanation and justification.

We have removed the cost-benefit analysis from this paper.

Later we learn that:

The details of the sensitivity analyses on this cost-benefit analysis are not presented here (see Biron et al. in review), but even when using the least favourable values for the freedom space (e.g. doubling the value of easements for farmers, using the mean instead of median land value for constructible zones), benefits still outweigh costs.

I do not think this is an acceptable publication strategy: in the MS presented here, we have to take an enormous amount on 'faith' which is presented elsewhere. Either the CBA is integral, or it is not.

We have removed the cost-benefit analysis from this paper.

We see here that there is a clear focus on bank erosion and river migration - this is only a subset of much wider river management issues.

The focus on bank erosion (river migration) is now better explained in the Introduction. It is at the heart of the concept of "Espace de liberté" (freedom space) developed in France, which is why it holds such an important place in our analysis.

L 184 and earlier, the 'easement' scheme should be explained more clearly.

The following sentence was added to explain the easement scheme:

"Under this scheme, farmers can maintain agricultural practices outside the 15 m buffer zone, but they also need to agree to a "no-intervention policy", i.e. they are not allowed to stabilize banks, build levees, dredge or modify the river layout."

3.1 Mobility space - as a fluvial geomorphologist, I understand this, and agree with the methods etc. Would a more general readership?

The following sentence was added at the beginning of the section on mobility to ensure that a general readership would understand the mobility space:

"The mobility of meandering rivers is related to secondary flows which will result in bank erosion on the outer bank, and sediment deposition in point bars located on the inner bank (Knighton 1998)."

HOWEVER extrapolation of migration rates from historical data over c. 50 year periods deserves more comment in view of the potential uncertainties and changing drivers. Many rivers show pseudo-cyclic behaviour over this timescale, and unsteady climate/hydrology/landuse will clearly affect this. There are also assumptions in identifying previously mobile from most engineered sections etc etc. The authors do give some indication that there methods are probably conservative and follow some accepted practice BUT the evaluation could be more thorough and discuss uncertainties upfront.

It is interesting that the authors DO discuss uncertainty, but after all of the findings have been presented: 5.1 Uncertainties and future development…

Here analysis is fair and accurate, if not completely exhaustive. HOWEVER were these uncertainties to be raised BEFORE the results were obtained and presented, I suspect the paper would be severely weakened.

There are similar considerations and concerns which can be applied to the various 'space' identifications and allocations, as discussed.

> *We agree with the reviewer that there are uncertainties related to potential changes in climate (and hence discharge) and land use over the next 50 years. This project was funded by a climate change research consortium (Ouranos), so the role of climate change was considered in our overall analysis, although it is not presented in this paper due to length constraints. We have used a numerical modelling approach to assess the impact of discharge changes on both mobility and the flooding zones. Mobility was assessed using the model RVR-Meander with a 10% increase in discharge, whereas a sensitivity analysis using the hydraulic model HEC-RAS was carried out for a range of discharges. These results are presented in the Ouranos report (Biron et al. 2013, in French) and in a paper to be submitted to the journal Geomorphology (Buffin-Bélanger et al. in preparation). This analysis revealed that the mobility space limits would change by less than 1% with a 10% increase in discharge. The impact of changes in land use over the next 50 years, however, was not taken into account.*
>
> *As pointed out by the reviewer, we did discuss uncertainties in the Discussion section, which seemed to us the appropriate section to raise these issues. Uncertainties are part of any studies, and we don't believe that raising these issues before the results were presented would have severely weakened the paper. The current management scheme for rivers, at least in Quebec, doesn't consider any changes in climate or land use. By using an approach based on hydrogeomorphological concepts, we believe that river systems would become more resilient to the inevitable variability in discharge that we can anticipate in the next decades.*
>
> *The thoroughly revised section 4.1.1 (formerly section 3.1) provides detailed information on uncertainties in the approach to delimit mobility space based on past migration rates*

The Conclusions are very brief and beg all of the questions outlined above: most of the concepts and terms used are insufficiently explained and contextualised; the authors write as if bank erosion and flooding are the only or indeed, the most important, management imperatives in current 'traditional' approaches; they introduce novel analysis which is only partially explained and which is reliant on other publications; key aspects of methods and analysis are in figures - MUCH more needs to be added by way of (a) contextualisation of the issues; (b) comparison of this with other approaches; (c) research design and methodology; (d) discussion of the generality or otherwise of these findings.

Throughout, the authors seem 'too close' to their own research and research agenda - they need to think of a more general readership.

> *We have considerably revised the introduction (providing a better contextualisation of the issues), the methodology (providing more information on the methods used to define mobility and flood zones), the results (providing a comparison between the HGM and the traditional approach) and we have further discussed the generality of our findings, particularly with regards to the range of river types and the notion of equilibrium. We therefore believe that we have addressed the valid concerns raised by the reviewer in the revised manuscript.*

Reviewer #4:

I find the article "Freedom space for rivers: a cost-effective approach to enhance river resilience" to be well written and worthy of publication in Environmental Management subject to revisions. The authors demonstrate the need for space for both river migration and flooding, and demonstrate how this "freedom space" can be delimited for three rivers. I find this to be a useful concept and the authors demonstrate how delineating and protecting the freedom space can be a cost-effective strategy compared to using bank stabilization measures to stop meanders, even when loss of cultivation and development are taken into account. However, I do have some concerns with the presentation of the results as well as some questions regarding the broad applicability of the methodology used to delineate the freedom space.

First, I find that the authors have overexaggerated their cost-benefit analysis by stating in the abstract that "benefits … outweigh the cost related to losing the right to cultivate or to developing the freedom space zone". Importantly, this cost-benefit analysis only refers to the narrowest L1 zone, but based on the preceding sentence, one would think that the benefits outweigh costs for the entire freedom space. The limitations of the cost-benefit analysis to the most narrow freedom space need to be made clearer in the abstract and throughout the manuscript. This is an issue of integrity in reporting results clearly and not exaggerating. The authors should also consider giving an idea of how wide the L1 zone is (in general), so that readers have a mental picture of the space that is being set aside.

We have removed the cost-benefit analysis from the paper and have revised the abstract and the title accordingly.

We have also added an average value for the L1 zone, both in absolute (m) and relative (as a multiple of width) terms. The revised sentence is:

"It provides the minimum space for both fluvial and ecological functionality of the river system and corresponds to a highly variable width, approximately 1.7 times the channel width on average, for the three studied sites."

For the width of the L1 (now L_{min}) zone, this sentence was added in the last paragraph of section 3.3 (now section 4.3):

"When using these results for practical management applications, it is recommended that no development should be allowed in the zones classified as the first level of freedom space (L_{min}) which corresponds to the minimum functional space of the river. This zone corresponds on average to a width of 61, 35 and 101 m on each side of the channel, or 1.2, 2.3 and 1.5 times the channel width for the de la Roche, Yamaska Sud-Est and Matane Rivers, respectively."

My second major concern deals with the methodology that is used and its applicability to rivers internationally given the international scope of the journal. In general, the methods are rather complicated, require data that may not be available for all rivers, and require some alternative methods when the preferred methods don't work. First, the requirement for a series of aerial photos that can be accurately georeferenced already limits this work to those areas. This does not preclude publication but since this is a proof of concept paper, this requirement should be clearly stated in the manuscript.

Although we agree with the reviewer that the methods to delimit the freedom space may appear complicated, we do not think they require data that are that complicated to obtain in most cases. For example, historical aerial photos are relatively common, and the process of georeferencing them only requires some fairly basic GIS skills. In fact, the time coverage available for the 2 of the 3 streams was relatively limited compared to several European examples (oldest photos in 1950 for the Yamaska Sud-Est River, and in 1964 for the Matane River) and yet it was nevertheless possible to do a mobility analysis.

We have added in the discussion a few sentences on how the method can be simplified when all the data used in this study are not available. However, in cases where LiDAR data are available (which is increasingly the case), the method can actually made much simpler. Also, the access to historical aerial photographs is actually relatively common, and only basic GIS knowledge is required to georeference them.

"Data required for the freedom space methodology is likely to be available to river managers or researchers in most cases. In fact, historical aerial photographs are commonly available over a 50-year timespan in North America and very often over a longer period in Europe (Rapp et Abbe 2003). If historical data are not available, the M_{50} space delimitation could be defined from an expert judgement. In this case, traces of erosion and deposition, especially point bars, observed from recent aerial pictures or field surveys, can help determine the M_{50} space. Increasing access to LiDAR data should also help to implement HGM analyses, as the availability of these data improves the accuracy of the HGM analyses while reducing their cost. Floodplain landform types and boundaries, in particular, can be assessed from LiDAR data instead of field survey. Reach delimitation can also be completed with less field work with the help of LiDAR data."

My second question concerns the methods overviewed in lines 231 - 238. If the preferred methodology (using the DSAS tool) does not work for all reaches, is this a good methodology or should one simply use the alternative renewal rate? A comparison of the results of these two methods might help demonstrate why the DSAS tool is preferred. A related question that I have regarding how applicable the methodology is internationally is 'how mobile are the study stream reaches compared to reaches in other parts of the world (i.e., how often could the DSAS tool actually be used)?

We have rewritten this section and clarified the use of the DSAS tool.

I have two more methodological questions: (1) is it necessary to visually identify potential cutoff zones following the delineation of the M1 zone using DSAS as described in lines 239 - 243?

We have clarified the importance of identifying potential cut-off zones. The main role of this particular part of the methodology was clarified by adding the sentence:

"This step particularly allows to identify places where cuts-off were prevented by anthropic interventions."

Lines 117 - 127. (2) How does the Lidar method for calculating channel slope, bankfull width and bankfull discharge compare with using aerial photographs and the discharge-to-drainage area relationship from rivers in Vermont? (a detailed analysis for this last question is not expected but I am guessing that the authors may have used both methods on the Matane river).

The LiDAR method, as described in Biron et al. (2013b), was indeed compared to high-resolution ortho-images to extract bankfull width, and showed good agreement, although the presence of bars in the Matane River increased the level of error in width estimates (note that there is also error in estimating bankfull width from aerial photographs). The discharge-to-drainage area relationship was also used in our LiDAR method to compute unit stream power.

Related to the last notes on the methods and their applicability, I think it is necessary for the authors to compare the resulting freedom space with maps from flood frequency methods. I certainly find the freedom space in theory to be a better approach backed by HGM principles, but a comparison is in order for two reasons. First, the methodology employed in this paper will require significant data and training to expand broadly. Second, does the current legislation that protects the 20 year flood zone in Quebec include the L1 freedom space? If the L1 zone actually aligns with the area inundated by a 20 year recurrence flood, is there much benefit in delineating freedom space? The authors acknowledge that the two spaces might be similar when discussing how existing policies based on flood recurrence might be used to protect the freedom space, but do not provide a comparison. This is a key revision that should be assessed to sell the method. Regardless of the results, I think that these results can still be published to stress how the flood recurrence zoning may (or may not) protect the freedom space for these rivers. Also, based on your analysis, are there any general width rules that could be used to capture freedom space for most rivers? Specific widths are of course easier to delineate and also are less contentious since there are fewer subjective decisions that must be made (such as determining "homogenous reaches").

We have added in Figure 7d the traditional flooding zones (0-20 and 20-100 years) for a reach of the Matane River where the HGM flood zones (N1, N2 and N3, now called F_{high}, F_{med} and Fl_{ow}) are presented (Figure 7c). The traditional flooding zone limits are not available for the other two rivers. The following sentences were added at the end of section 3.2 (now section 4.2):

"For the Matane River, the traditional flood zone limits of 0-20 and 20-100 years were available, and are presented in Figure 7d (for the same reach as in Figure 6c). The F_{high} zone in this reach corresponds approximately to the 0-20 year flooding zone, although it covers a larger area. Similarly, the N2 zones are markedly larger than the 20-100 year zones."

We have also added a comparison with the freedom space zones in section 3.3 (now section 4.3) and added the figure on traditional zones as Figure 8e, with a few sentences describing the *similarities and differences between the L_{min} and 0-20 zones, and between the L_{func} and 20-100 zones.*

We have also provided some indications on the average width of the minimum freedom space zone (L1, now called L_{min}), both in absolute values and as multiple of channel width. However, we believe that one of the great advantages of the HGM approach of freedom space is precisely that it is not a fixed multiplier of the channel width, i.e. in some cases only a relatively small freedom space is needed, whereas in other zones a wider zone is required for natural fluvial processes to operate.

Regarding the cost-benefit analysis, it may be worthwhile to include the cost of delineating the freedom space and compare it to the traditional flood frequency methods. A rather simple analysis of the man hours required for the methodology and some average salary would suffice. This may not be a significant cost but would most likely be a public cost and may not be realizable due to budget issues if costs (hours of labor required) are high.

The cost of delimiting freedom space is greatly reduced when data such as LiDAR or georeferenced historical georeferenced photographs are available. For example, no LiDAR data existed for the de la Roche and Yamaska Sud-Est Rivers at the time we have conducted this research project, which forced us to use expensive ground LiDAR instrumentation both in terms of equipment and human resources. LiDAR data are now available for these regions, which greatly reduces the cost of a freedom space analysis for nearby rivers. However, as the cost-benefits analysis was excluded from the revised version of the paper, providing a value for this effort is not relevant anymore.

Other suggestions:

1. In the abstract, the minimum freedom space is related to "ecological integrity" but in the manuscript is associated with "ecological functionality" (the larger L2 is associated with "integrity"). Please correct this and be consistent.

The abstract was modified to use "ecological functionality" (see revised sentence above).

2. In the first paragraph of the introduction section, it would be very worthwhile discuss briefly in a few sentences why rivers need to be able to move and have connection to floodplain. You could focus briefly on ecology, society, and economic reasons. This would fit well between the two sentences currently in the first paragraph and convince the reader why freedom space is important. Yes, most readers may know this but a few sentences would help set the stage.

The introduction was modified (see above), and the importance of floodplain connection and river migration is now more clearly discussed.

3. Lines 58 - 59. To make this consistent and meaningful, please state what the conclusion of the study was if possible. It is not sufficient to write that they carried out a survey.

The example of Iowa was removed as the Introduction is now considerably longer than in the original manuscript.

4. Lines 54 - 63. Seems like there should also be something here about cost-benefit of not building in flood plain that incorporates flood damage and development/farming loss. A quick search pulled up quite a few results as the costs of flood damage have been relatively well studied.

The cost-benefit analysis was removed from this paper.

5. Lines 113 - 114. Should cite ArcGIS as (ESRI 20XX) and add in reference list.

We have added a reference to ESRI for ArcGIS.

6. The information in Lines 235 - 238 describing highly dynamic channels and how they are classified is a bit unclear. First, a renewal rate cannot be 200 years. I assume that you mean that the renewal time for the entire floodplain is 200 years. Second, it is not entirely clear what sentences "In these cases, the M2 classification (see below) was changed to M1. In the reaches where the positioning error could contribute to more than 50% of the floodplain renewal, the M2 classification was retained." I see later in the discussion that you mean that the M2 meander width was used in place of M1, but it is not clear here. Please try to rephrase this so that it is clear what measures were used for these mobile reaches.

We have clarified this paragraph, which was also considered unclear by reviewer #2.

7. Lines 239 - 243. If I understand correctly, the mobility space M1 is first calculated using the DSAS tool (except for mobile reaches), and then further widened to include high risk cutoffs. Is this a necessary step in the process?

Information has been added to explain, firstly, why the mapping of avulsion zone is required in addition to the DSAS process, and secondly to explain what is the relevance of using traces of erosion from aerial photos. The paragraph now reads as follow:

"The last zones that need to be included in M_{50} are the area of high avulsion hazard. This step is required as the length of avulsion during meander cut-off is usually greater than the width of the predicted zone of fluvial erosion determined with DSAS. The risk of meander cut-off was assessed using two methods. First, traces of erosion were noted on aerial photographs in the floodplain (Figure 3). This step allows in particular to identify places where cuts-off were prevented by anthropic interventions."

8. Figure 7 map legend is in French and impossible to see in print. Increase the size of fonts for both the main legend, and either get rid of the boxes with "Espace de liberte" (sorry no accents) or change to be readable.

We have modified Figure 7 (now Figure 8) so that the legend is translated in English and the font size is increased.

9. Figures 5 and 6 - A few changes. The projection information is unnecessary for this figure. There are also problems with the coordinates overlapping. I would remove the coordinates and replace with a scale bar in m or km. However, if the coordinates must be shown, please space them further apart or only put them at the edges of each box.

Figures 5 and 6 were modified to remove information on projection and replace the coordinates with a scale bar.

10. Figure 8 - increase the size of the font in the legend and scale bar. All fonts in figures should be near size 12.

The font size in the legend and the scale bar were increased in Figure 8 (now Figure 9).

11. Lines 458 - 460. Why not just say "This study has tested and evaluated the applicability of this methodology for case studies on three different rivers." Or something similar to that other than "based on three contrasting rivers, has provided multiple" since it has provided three. No reason to exaggerate to multiple as three is impressive enough for a case study and more specific.

We have modified this sentence according to the reviewer's suggestion.

12. Line 576. What is "ecological biodiversity"? I think the author(s) mean "to improve ecological health and water quality"

We have made the change in this sentence according to the reviewer's suggestion.

13. I am not sure that Table 5 is very helpful.

We agree with the reviewer that this table to do provide more information than what is already stated in the following part of the section 4.3:

" - freedom space L_{min} is the union of mobility space M_{50} and flooding space F_{high};

- freedom space L_{func} is the union of mobility space $M_{floodplain}$ and flooding space F_{med}, from which freedom space L_{min} is subtracted;

- freedom space L_{rare} is the union of all mobility and flooding spaces, from which freedom space zones L_{min} and L_{func} are subtracted. "

However, we feel that such a mathematical language can be more easily apprehended with the visual help the figure provides.

14. Can tables 6 & 7 be combined into a single table?

These tables were deleted since we no longer present the cost-benefit analysis in this paper.

15. In general the references look pretty good but I did notice a few things when looking carefully. Please edit the references to make sure that they are in the correct format. A few errors that I noticed were:

References were reviewed to make sure they complied with the required format.

a. unnecessary commas after Journal names in lines 593, 595, 598, 601, 605 etc. (for example, in line 593 the comma should be removed in "Geomorphology, 10: 39-159.

b. A period is needed after "and Values" in line 590

c. "DOI" should be doi in line 605 (and the comma should be deleted)

d. The two period should be deleted after the (2008) in line 622

e. The format of the Levish (2002) reference in line 667 is incorrect. Please change to "Levish DR (2002) Paleohydrologich bounds: non-exceedance information for flood hazard assessment. In: House PK, Webb RH, Levish VR (eds.) Ancient floods, modern hazards: principles and applications of paleoflood hydrology, Edition. Publisher, City, 175-190.

f. The font of the reference in lines 701 - 704 appears different.

g. Add the date that you accessed all online references and remove the hyperlinks, as some are in blue and underlined while others are not.