

Freedom Space for Rivers: A Sustainable Management Approach to Enhance River Resilience

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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 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. On average for the three studied

sites, this minimum space was approximately 1.7 times the channel width, but this minimum space corresponds to a highly variable width which must be determined from a thorough hydrogeomorphic assessment and cannot be predicted using a representative average. 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

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Introduction

Many rivers across the world are located near human settlements, and are thus under stress and pressure from agriculture and urbanization in riparian zones which are likely to become more frequent with the process of urbanization. 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-centered 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 (Piégay 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 (Piégay et al. 2005; Kondolf 2011).

The hydrogeomorphology 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 hydrogeomorphic 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 hydrogeomorphic processes have been described under a variety of names (e.g., “room for the river,” Baptist et al. 2004; “erodible corridor,” Piégay et al. 2005; “fluvial territory,” Ollero 2010; and “river corridor,” Kline and Cahoon 2010). These hydrogeomorphic 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; Piégay 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

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 ^a
Bed and banks	Sand-silt	Sand-silt	Gravel

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

more on flooding than erosion in river corridor programs 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 hydrogeomorphic 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 was 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).

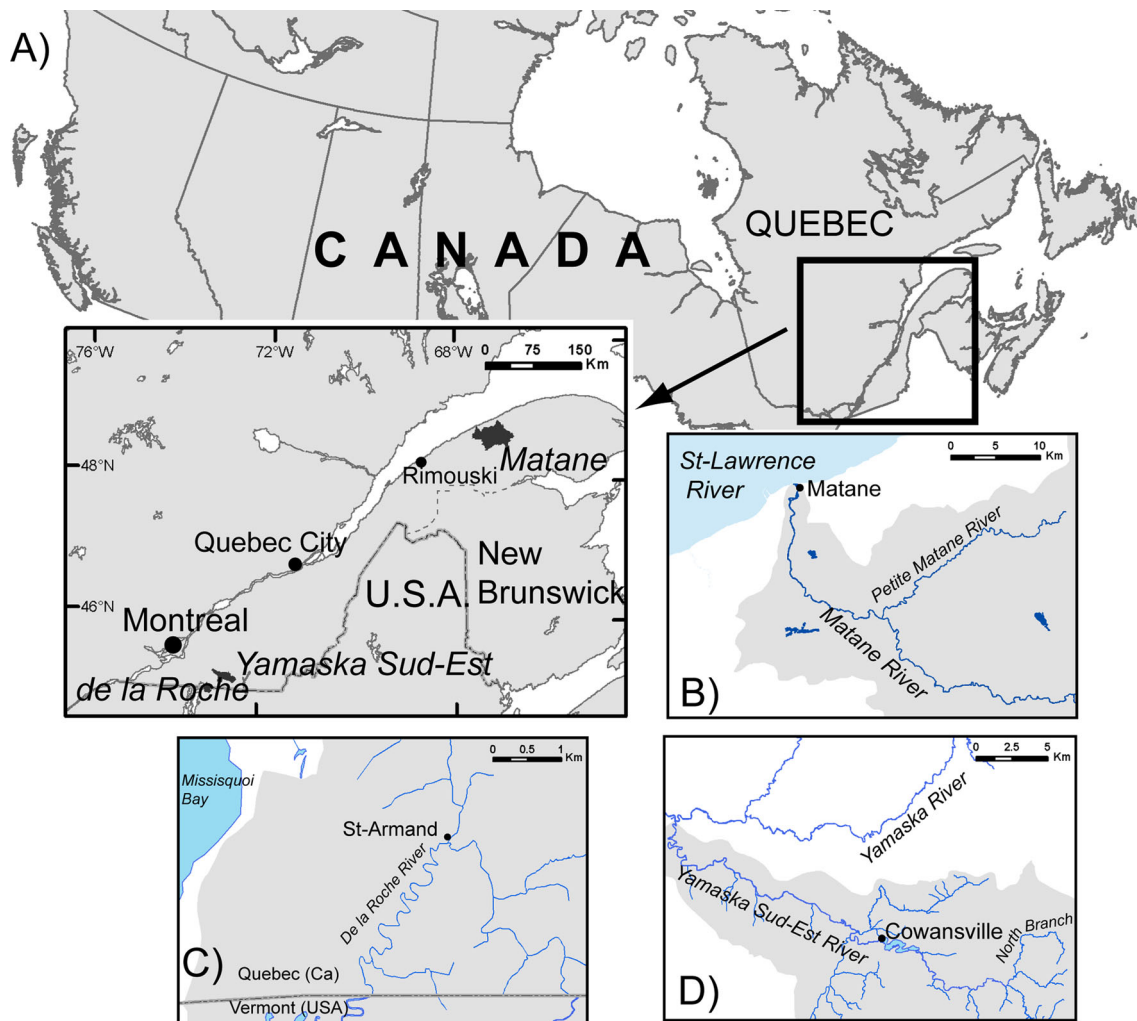


Fig. 1 **a** Location of the three study sites in Québec, Canada; **b** Matane River study reach; **c** de la Roche River study reach; **d** Yamaska Sud-Est River and North-Branch tributary study reach

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 Québec and elsewhere (Fig. 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 Québec (Montérégie) to zones where sport fishing (salmonids) dominates (Gaspésie)]. Being located in Québec, 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 (Fig. 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 km² (out of 145 km²) located in Québec. It is one of the main tributaries of the Missisquoi Bay in Lake Champlain. A gaging 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 km². 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 (Fig. 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 gaging station (CEHQ station 030314) located in Cowansville, approximately in the center 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 1,678 km²) 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 (Fig. 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 gaging station located near the mouth of the river (CEHQ station 021601).

Methodology

The hydrogeomorphic 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 centerline 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 m² 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 0.03–0.05 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 m³/s), which was considered equivalent to a 1.5-year recurrence interval event, was obtained from discharge-to-drainage area relationship:

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

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 gaged rivers in Vermont with drainage area (A , in km²) ranging from 7.8 to 360 km², 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. The bankfull discharge obtained using this relationship at the gaging station gave values of 19.2 and 54.9 m³/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 gaging stations (13.8 and 55.9 m³/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.

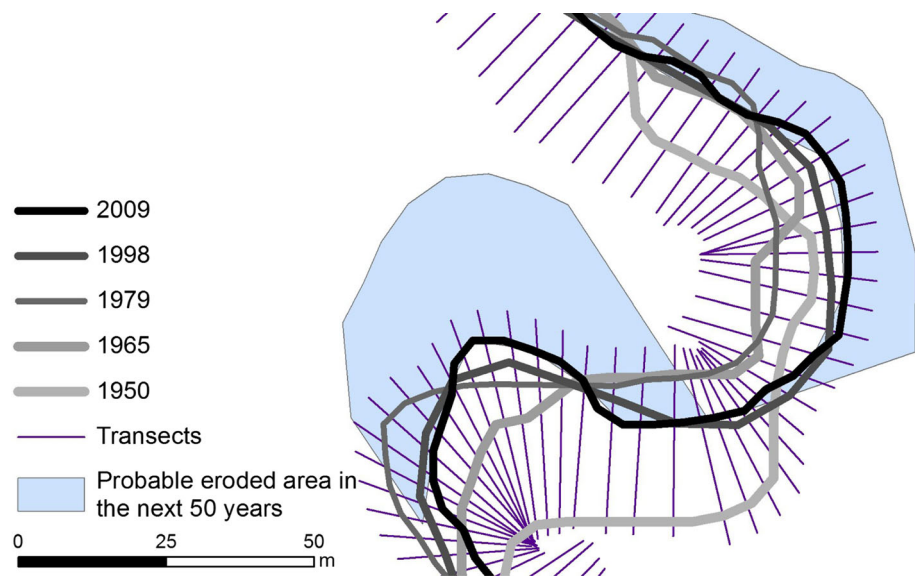
Freedom Space Delineation

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 hydrogeomorphic approach.

Mobility Space

Flow patterns in meandering rivers occur such that meanders generally migrate by outer bank erosion and inner bank deposition in point bars (Knighton 1998). In addition to the mobility of meanders through channel migration, avulsion hazard also has to be taken into account.

Fig. 2 Erosion predicted for the next 50 years by the DSAS software on the North-Branch River (tributary of the Yamaska Sud-Est River) based on past channel paths from 1950 to 2009



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 hydrogeomorphic 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, 1.7, and 7.3 km long, respectively, for the de la Roche, Yamaska Sud-Est, and Matane rivers.

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 cutoff) 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 (Fig. 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, provide 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 et al. (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 $M_{\text{floodplain}}$ 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 $M_{\text{floodplain}}$ 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 $M_{\text{floodplain}}$ 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 cutoff is usually greater than the width of the predicted zone of fluvial erosion determined with DSAS. The risk of meander cutoff was assessed using two methods. First, traces of erosion were noted on aerial photographs in the floodplain (Fig. 3). This step particularly allows to identify places where cutoffs 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 cutoff. This threshold corresponds to the average ratio for the cutoffs 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, 1930–2011 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 analyze 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.

The $M_{\text{floodplain}}$ Mobility Space

The second mobility space ($M_{\text{floodplain}}$) is defined as the space that will be occupied by the river in the long term through meander migration (Piégay et al. 1997, 2005). The methodology to determine the $M_{\text{floodplain}}$ 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 (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 centered on the meander axis according to widest meander amplitude within the reach. The $M_{\text{floodplain}}$ space thus defined was then constrained by the presence of non-erodible terraces or by valley walls. Again, historical river

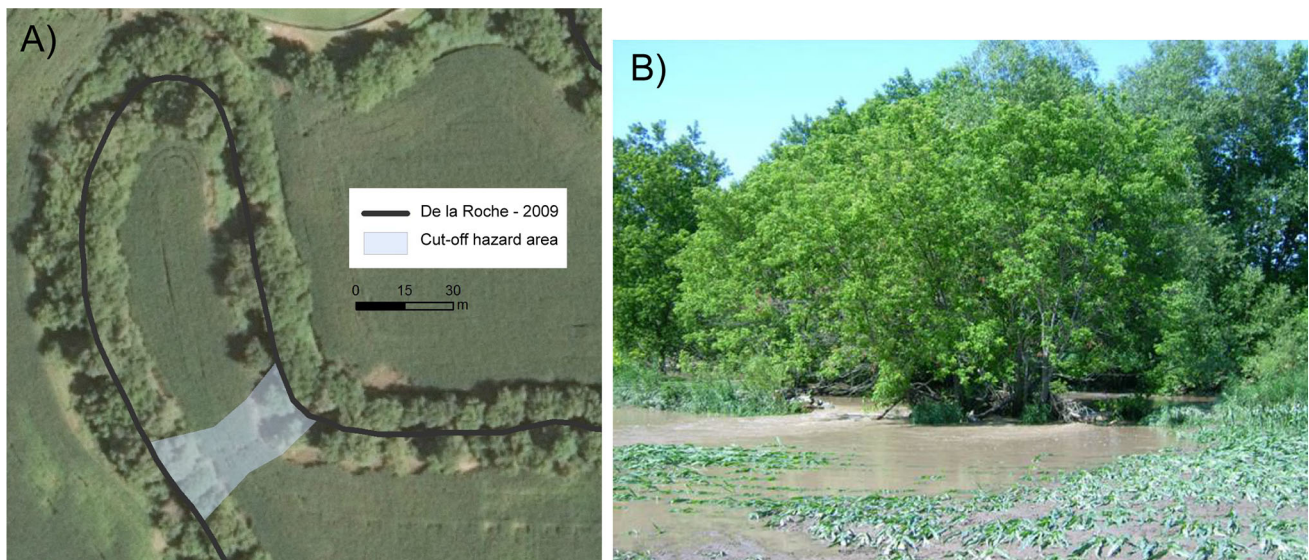


Fig. 3 a Initiation of a meander cutoff in the de la Roche River; b meander cutoff zone shown in a during a flood

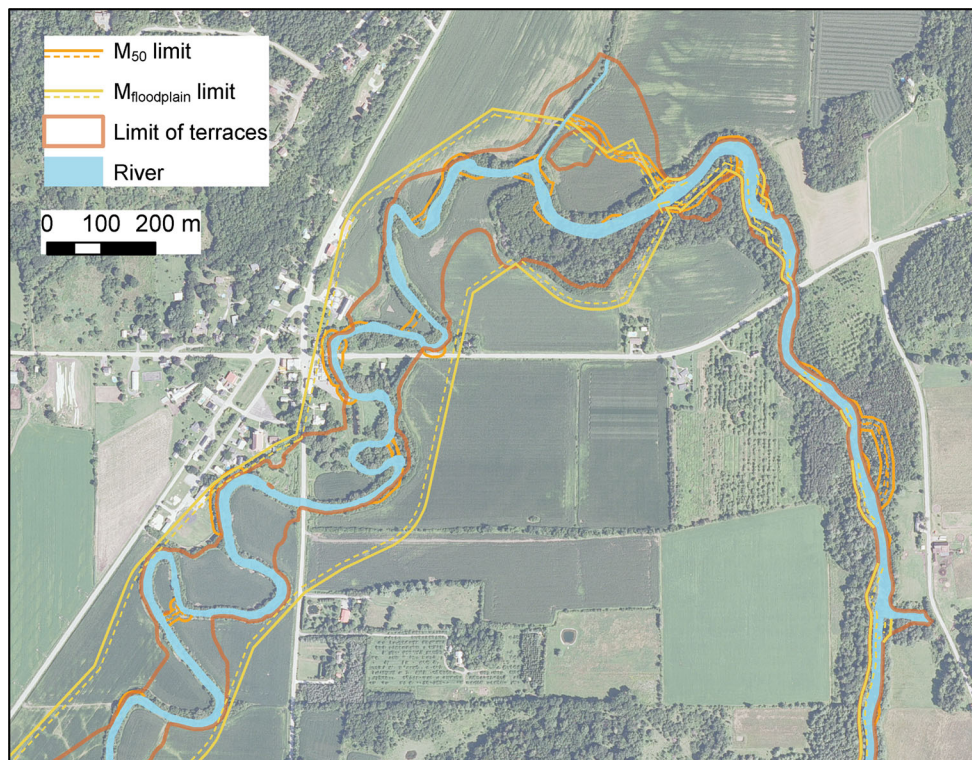


Fig. 4 Impact of erodible and non-erodible terraces on the determination of the $M_{\text{floodplain}}$ mobility space on the de la Roche River. In the downstream part (to the left on the map), terraces are erodible, and

the mobility space $M_{\text{floodplain}}$ is markedly larger than in the upstream reaches where terraces are non-erodible

paths of the river were used to determine whether or not terraces were erodible, but field evidence of bank erosion on terraces was 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 $M_{\text{floodplain}}$ space is considerably larger (Fig. 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.

Flooding Space

The hydrogeomorphic approach focuses on the interpretation of floodplain landforms that are 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 hydrogeomorphic 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 hydrogeomorphic 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 hydrogeomorphic 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 hydrogeomorphic 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 Fig. 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 hydrogeomorphic 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 hydrogeomorphic 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.

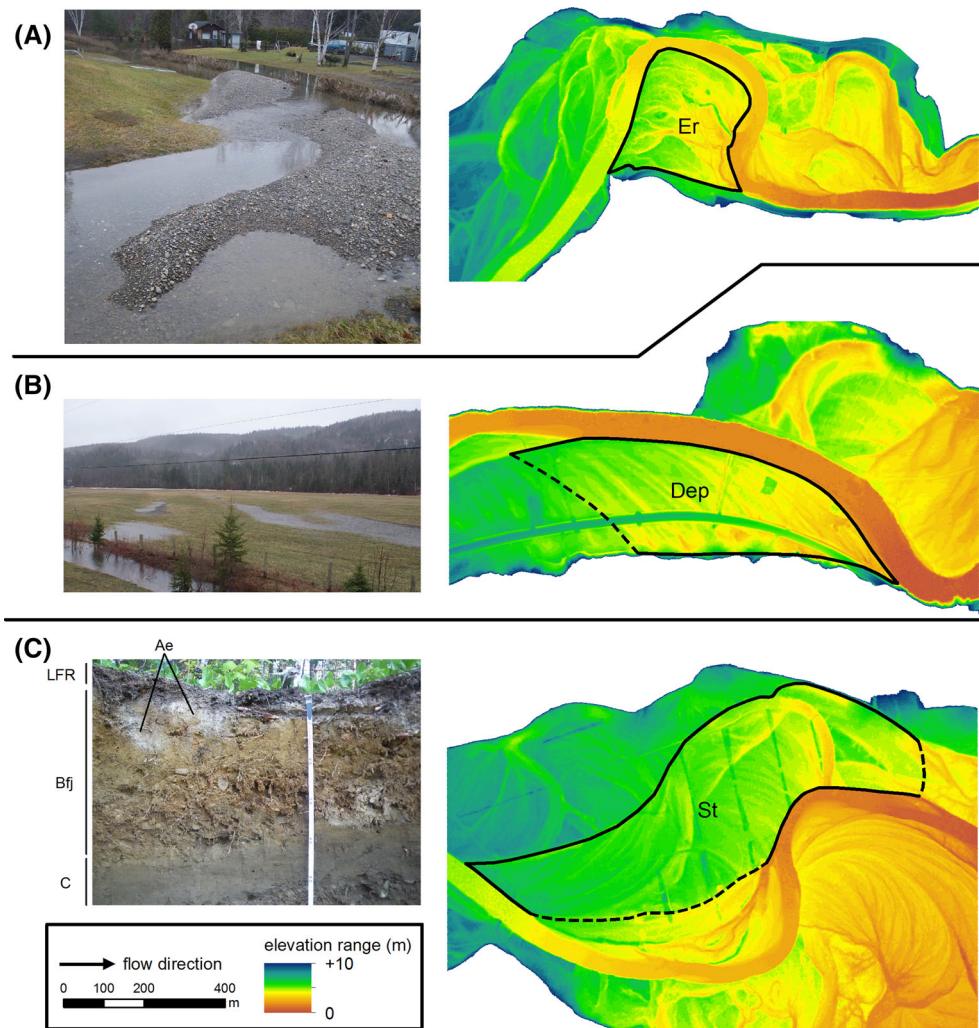
The second step is to relate hydrogeomorphic landforms to map flooding spaces. The decision rules are summarized in Table 3. The five landforms were used to delineate three levels of flooding space with decreasing order of flood severity: F_{high} , F_{med} , and F_{low} . In Quebec, flood return periods 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 hydrogeomorphic 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

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)	<ul style="list-style-type: none"> • Irregular land topography • Flood channels • Long and narrow streamwise landforms • Erosion scarp 	Unsorted	B–W <10	Shrubs and/or trees
Depositional landforms deposited by slow flow (transport mode: suspension)	<ul style="list-style-type: none"> • Rounded land topography 	Sorted (silt)	B–W <10	
Stable landforms	<ul style="list-style-type: none"> • Rounded land topography 	Sorted (silt)	B–W >10	
Glacial landforms resulting from flow with drift ice	<ul style="list-style-type: none"> • <i>Bechevnik</i> 	Unsorted		Ice scars
Alluvial wetlands	<ul style="list-style-type: none"> • Paleochannels 	Sorted (silt)		Hygrophilous species

Fig. 5 Illustrated examples of floodplain landforms (*Er* Erosion, *Dep* Depositional, *St* Stable). **a** Erosion landforms reworked by overbank competent flows. The picture shows *gravel point bars* built by overbank flows, while LiDAR view shows relief resulting from similar processes. **b** Depositional landforms resulting from aggradation of fine sediments from low-velocity flows. The picture and LiDAR show ridge and scroll relief partly filled with fine sediments provided by overbank flows. **c** Stable landforms located outside the reach of contemporaneous flood extent. Picture shows well-developed pedogenesis found in alluvial soils suggestive of long-term surface stability. *Letters* refer to the Canadian system of soil classification (CSCW 1998). The LiDAR shows extent of stabilized alluvial surfaces sharing fuzzy boundaries with other erosion or depositional landforms



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

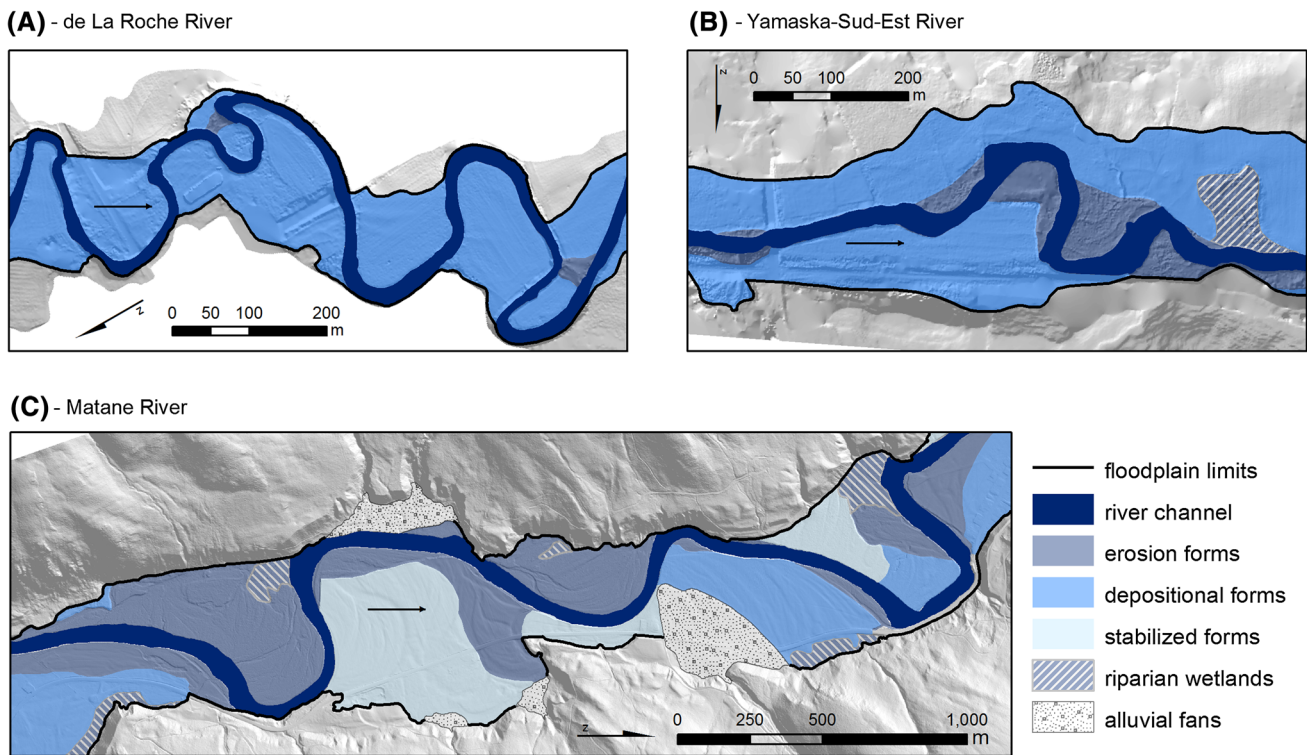


Fig. 6 Examples of hydrogeomorphic cartography of the flooding space for **a** the de la Roche River, **b** the Yamaska Sud-Est River, and **c** the Matane River

($\approx 5\text{--}10$ year return period). With regard 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 Fig. 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 ($\approx 5\text{--}10$ 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 Fig. 7d (for the same reach as in Fig. 7c). The hydrogeomorphic 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 hazards 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).

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, and wetlands), (2) different time periods (50-year horizon, floodplain renewal scale) and (3) different interests (human or infrastructure risk, and ecological integrity). In addition, the methodology used to produce freedom space mapping had to take into account existing legislation

Table 3 Decision rules used to determine flooding space

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

n/a non-available

↑ high, ↓ low

^a Variable

(e.g., limited rights in the 20-year recurrence interval flood zone). It also had to be appropriate to the various organizations (ministries and municipalities) that would be responsible for implementing this management approach. The freedom space categorization 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 inconvenience 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, where “L” stands for “liberté” (freedom in French): 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 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 hydrogeomorphic 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, Piégay 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 (Fig. 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. Fig. 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 1,000 m in a zone with a riparian wetland (Fig. 9a). As this zone is currently undeveloped, there is no anticipated difficulty in its protection, particularly since it can play an important

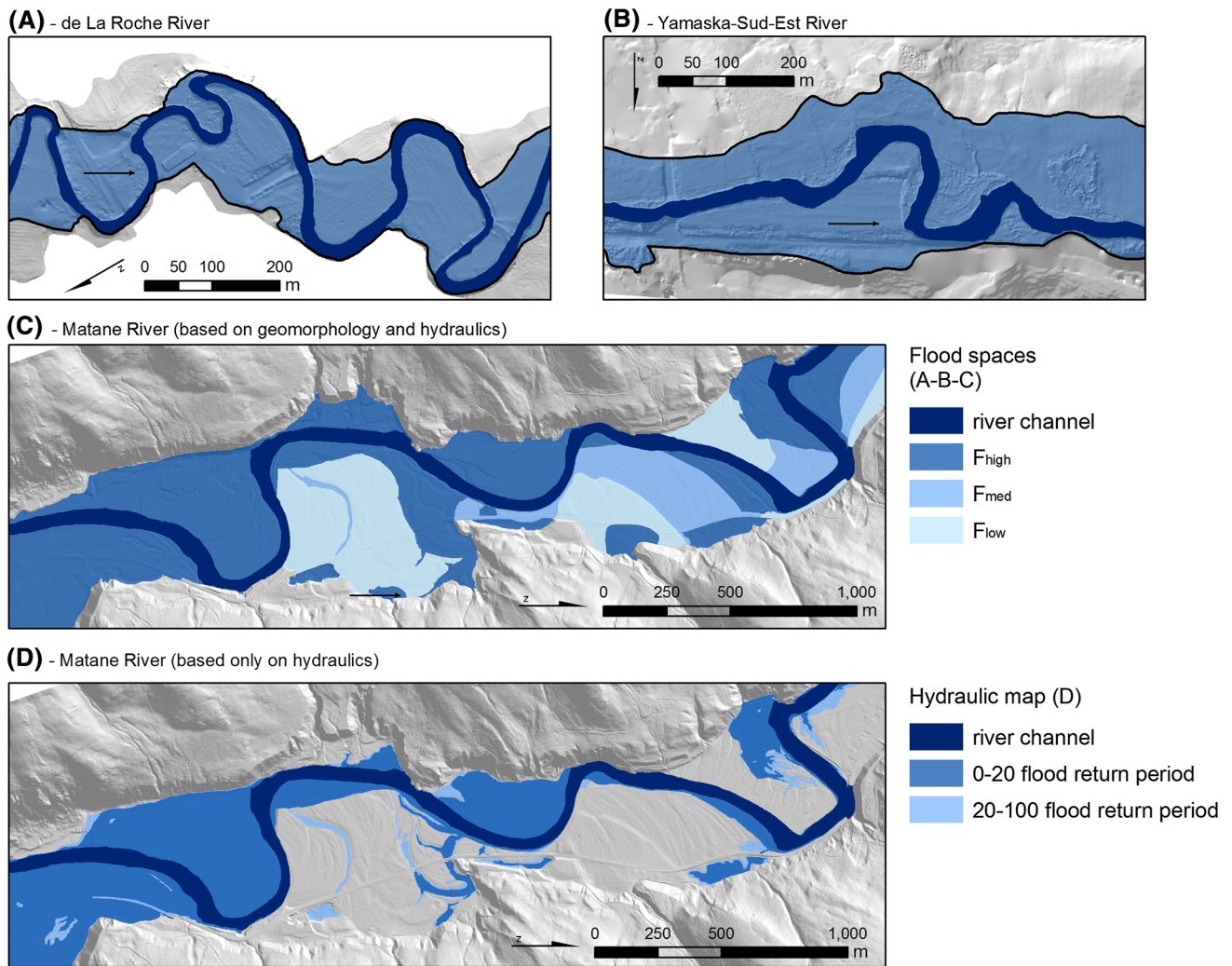


Fig. 7 Examples of the three categories for the flooding space (for the same reaches as in Fig. 6) for **a** the de la Roche River, **b** the Yamaska Sud-Est River, and **c** the Matane River. The traditional 0–20

and 20–100 year flood zones obtained from hydraulic models are also shown in **d** for the Matane River reach

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 (Fig. 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 (Fig. 7a). Overall, the very frequent flood zones (F_{high}) are wider than the highly mobile zones (M₅₀), as is the case in the de la Roche River downstream (Fig. 7a). For example, on the Yamaska Sud-Est River, 84 % of the mobility zone M₅₀ 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 Fig. 7d, e). A compensation program should be initiated for farmers in order to eliminate the perceived need for any type of intervention in the river

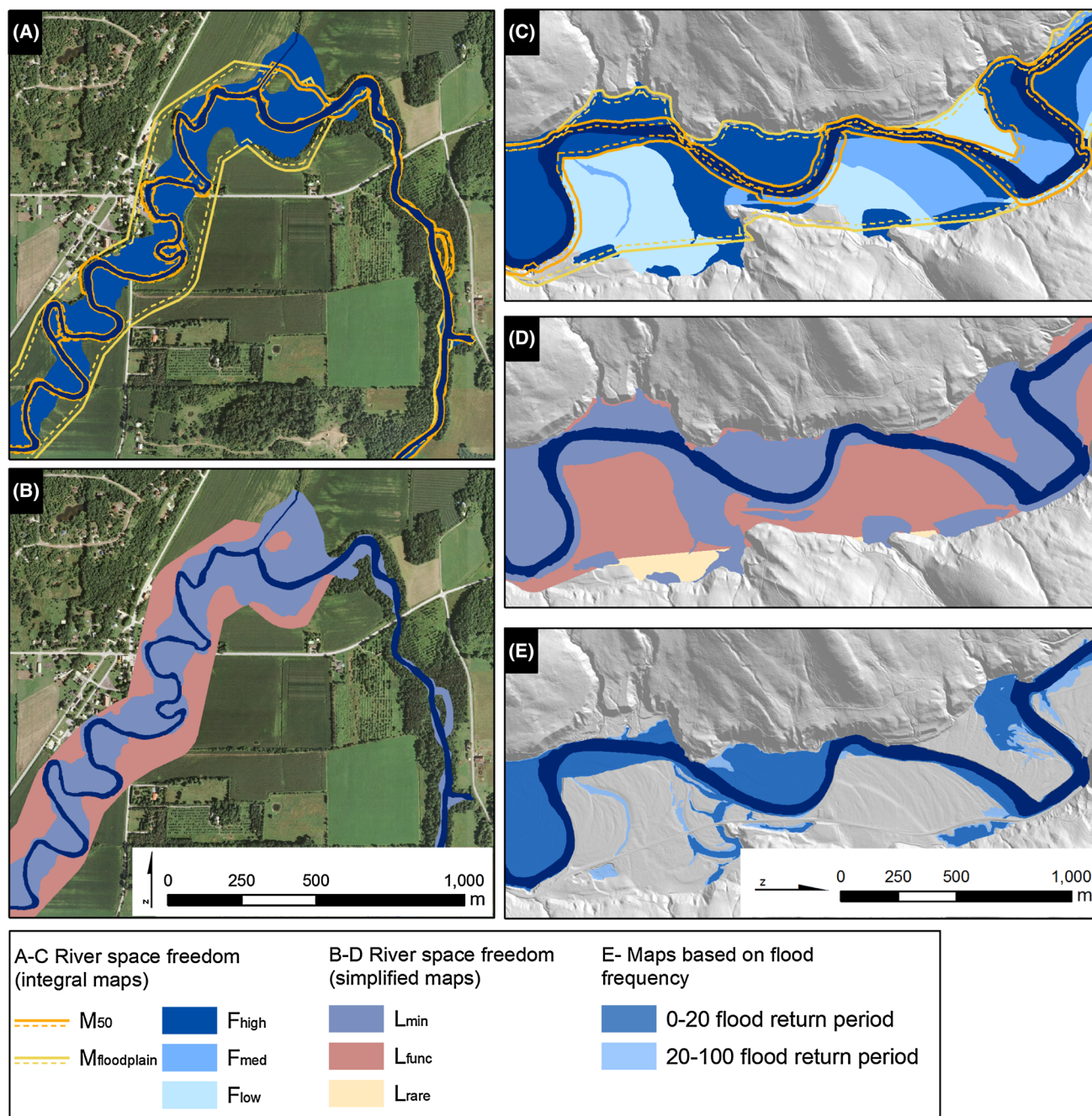


Fig. 8 Examples of the freedom space using integral (a) and simplified (b) cartography on the de la Roche River, and integral (c) and simplified (d) cartography on the Matane River. Only two levels of freedom space (L_{min} and L_{func}) are needed on the de la

Roche River, whereas the third level (L_{rare}) is required in some zones on the Matane River. The traditional 0–20 and 20–100 year flood zones from hydraulic models are also shown in e for the Matane River reach

(bank stabilization, dredging, and 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 land-use planning and immunization protocols in order to analyze 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 (Fig. 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.

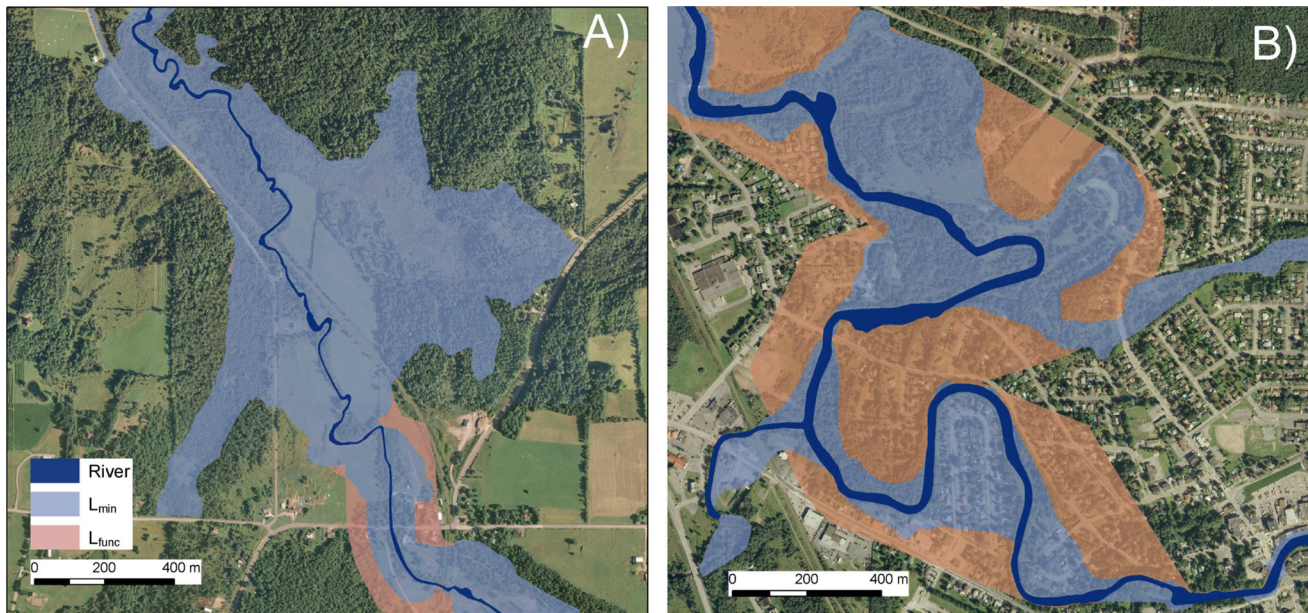


Fig. 9 Examples of the freedom space in the Yamaska Sud-Est River **a** in an area with a riparian wetland, **b** in the municipality of Cowansville, located approximately 10 km downstream of the wetland

Discussion

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 hydrogeomorphic 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 modeling 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 hydrogeomorphic approach for delimiting the mobility space based on meander characteristics ($M_{\text{floodplain}}$) 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 centerline 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 $M_{\text{floodplain}}$ 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 cutoffs 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 twentieth 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 hydroclimatic 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 hydrogeomorphic 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 delimit 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 appear relevant for most rivers, as the average erosion rates were, respectively, of 0.08, 0.11, and 0.26 m/year 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, highly dynamic rivers may not be properly assessed

by the proposed methodology since high erosion rates can be masked by frequently shifting direction. 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, making it impossible to extrapolate local erosion rates 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, in particular braided rivers with high sediment transport rate or rivers in arid or semi-arid climates characterized by flash floods, other methodologies may be more appropriate (e.g., Graf 2000; Curran and McTeague 2011).

Data required for the freedom space methodology are 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 judgment. 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 implement hydrogeomorphic analyses, as the availability of these data improves the accuracy of the analyses while reducing their cost. Floodplain landform types and boundaries, in particular, can be accessed 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 hydrogeomorphic 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 hydrogeomorphic 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 and 20–100 years flood zones). Ultimately, the lack of quantification requires that geomorphologists and risk managers make concerted decisions as to how the hydrogeomorphic approach can best be integrated into river management to determine freedom space zones.

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 2 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 hydrogeomorphic 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 hydrogeomorphic concepts was required to reach such widespread acceptance. The hydrogeomorphic 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. They are led to believe that bank stabilization is an appropriate measure

to improve river health, both in terms of water quality and physical habitat.

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, 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, which are considered essential, whereas options such as moving roads away from rivers (beyond the freedom space limits) could be envisaged in the future.

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. Specific methodologies were presented to delineate the mobility and flooding spaces for three contrasted rivers of southern Québec. Other methodologies could be more appropriate in other conditions such as highly dynamic rivers (e.g., braided) or fluvial systems characterized by flash floods such as in arid or semi-arid climate. Here, a freedom space methodology to combine the mobility and flooding spaces was proposed and applied to three rivers in Quebec. The method 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. It was shown that this approach has the potential to be useful in most rivers, at least in a temperate climate. Several challenges remain for the implementation of the method. However, consultations with the public and stakeholder for one of the rivers suggest that freedom space for river concept crystallize objectively several representations and knowledge that the community has on the river and on the way it should be

managed. This recognition represents a strong support to develop and promote the freedom space concept.

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