Assessing bank erosion hazards along large rivers in the Anthropocene: a geospatial framework from the St. Lawrence fluvial system

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ABSTRACT
Over the past decades, riparian land-use changes coupled to the multiplication of river infrastructures have enhanced vulnerability issues for societies and ecosystems located along large rivers. Exposure to geohazards is also changing due to the ongoing climate change, underlining the need for flexible management strategies for riparian environments. In this perspective, GIS-based mapping allows integrating a wide range of environmental data. However, such datasets are often incomplete and not homogeneous over large geographical scales, which can be problematic for the implementation of regional land-use planning strategies. Using the St. Lawrence fluvial system (SLFS) (Québec, Canada) as a case study, this article reports and describes a high-resolution approach to map position, characteristics and erosion susceptibility of natural and artificial riverbanks from a combination of field-based, remote sensing and local knowledge-derived data. This approach allowed identifying erosion-prone sites and highlighting dominant erosion processes and spatially constrain them along the SLFS. The proposed geospatial framework constitutes (1) an initial portrait of the riverscape that will allow an effective implementation of future monitoring and process-based studies; and (2) a first step in supporting land-use planning stakeholders in the selection of appropriate measures to ensure a greater resilience of riparian communities and ecosystems.

1. Introduction

Erosion and flood hazards constitute major concerns for riparian communities located along large river systems. Their associated risks are often significant because lowland areas bordering rivers are generally densely populated economic corridors. Deficient management strategies associated with poor scientific knowledge and non-integrated decision-making approaches increase the exposure and vulnerability of riparian populations and sensitive ecosystems, which may result in severe damages to...
infrastructures, population displacement and riparian ecosystems degradation (Drejza et al. 2011; Rangel-Buitrago et al. 2018; Williams et al. 2018; Best 2019). The setup of integrated management policies at regional scales are now widely accepted and used to face erosion hazards (Kumar et al. 2018; Rangel-Buitrago et al. 2018; Williams et al. 2018).

Riverbank erosion results from a suite of geomorphic processes ruled by complex interactions between natural mechanisms and environmental stress factors (Couper and Maddock 2001; Henshaw et al. 2013; Chassiot et al. 2020) that are today enhanced by climate change and a increasing human pressure (Gregory 2006; Best 2019; Goudie 2020; Piégay et al. 2020; Wohl 2020). The growth of human activities in the last decades marking the Anthropocene Era (Goudie and Viles 2016; Syvitski et al. 2020) has added several stressors to river geo-ecosystems, such as ship traffic (Dauphin 2000; Gharbi et al. 2010; Houser 2010; Scarpa et al. 2019), flow regulation by dam construction (Vörösmarty et al. 2003; Nilsson et al. 2005; Lehner and Grill 2013; Wang et al. 2016; Kondolf et al. 2018), channel dredging (Jeukens and Wang 2010; van Maren et al. 2015), geo-engineering along riverbanks (Thorne et al. 2005; Gregory 2006; Mattheus et al. 2010) and the multiplication recreational infrastructures and activities (Dauphin 2000; Dauphin and Lehoux 2004; Houser 2010).

Large rivers marked by a strong seasonality are particularly exposed to climate change, which impacts both riverbank erosion (Chassiot et al. 2020) and flooding dynamics (Chen and She 2020; Moragoda and Cohen 2020; Rondeau-Genessee 2020). Among these systems, the St. Lawrence River (SL) is one of the largest and most populated ice-affected rivers worldwide (Figure 1(A)), with nearly 50% of today’s Québec population concentrated in the SL lowlands (Morneau et al. 2014) (Figure 1(B)). This densely populated SL sector is mainly vulnerable to hydrometeorological hazards such as storm surges and spring floods that enhance erosion mechanisms on riverbanks. For example, recent floods in 2017 and 2019 reached unprecedented high-water levels in the upstream part of the river that caused the degradation of mitigation structures and inhabited lands, leading to the evacuation of residents (CMM 2017) and a cost of 390 million CAD in non-insured damages to the Government of Québec.¹

Following these events along the SL, many questions regarding future large-scale management policies were raised in order to help municipalities to deal with erosion hazards. With ongoing climate change, the issue of sustaining or adapting geohazards management strategies has become even more crucial for ensuring the safety of inhabitants while limiting financial costs (Buffin-Bélanger et al. 2015). Currently, a high percentage of the decision-making process for erosion management is based on economic considerations (Cooper and McKenna 2008; Rangel-Buitrago and Anfuso 2015), local non-integrated approaches to develop solutions (Rangel-Buitrago et al. 2018) and fears of the stakeholders (Finkl 2016). These deficient strategies usually resulted from a scarcity of regional-scale knowledge and information for large rivers, which limits objective dialogue between stakeholders (Ward et al. 2001; Petts et al. 2006; Habersack et al. 2016; Piégay et al. 2020). In this perspective, the development of an accurate geospatial database on the state of riverbanks becomes necessary in order to establish a river-specific framework and a baseline for future quantitative
studies on erosion-prone sites (Currin et al. 2015; Rogers and Woodroffe 2016; Fraser et al. 2017; Marteau et al. 2017; Best 2019). With such missing information along the St. Lawrence River fluvial system (SLFS; Figure 1(B)), there is a need to setup a large-scale and qualitative mapping approach in order to support integrated management.

Figure 1. (A) Location of the St. Lawrence River (QC, Canada) and its drainage basin (pale grey). (B) Geological provinces of southern Québec, hydrographic divisions (orange lines) of the St. Lawrence River and location of the study area, the fluvial system. Average and maximum (in bold) tidal ranges are shown for some municipalities along the river. (C) The non-tidal influenced river section (RS) and (D) the tidal-influenced fluvial estuary section (FES) separated by the tidal limit (yellow dashed line). White arrows indicate flow directions.
decisions by establishing (1) the conceptual foundations of erosion hazards; and (2) a standardized riverbank positioning and classification method adapted to this specific hydrosystem.

Using the SLFS as a case study, this article proposes an adaptable GIS-based approach developed to map riverbank positions and properties from the integration of field-based, remote sensing and local knowledge geospatial information. This step-by-step method, which can be adjusted to any large river systems, provides a detailed portrait of a riverscape through maps of high-resolution (1:600 scale) and precision (<1 m). It also allows identifying riverbank erosion hotspots and geomorphological processes at work, while defining their spatial distribution along the river course. The development of such an accurate geospatial framework constitutes (1) an initial portrait of the riverscape allowing an effective implementation of the next monitoring and process-based studies; and (2) a first step in supporting land-use planning stakeholders in the selection of appropriate measures to ensure a greater resilience and an adequate long-term protection of riparian communities and ecosystems.

2. Regional settings

With a total length of about 1200 km, the SL is one of the largest ice-affected rivers of the world, flowing out of Lake Ontario and draining a catchment covering about 1.3 million km² (Figure 1(A)). From upstream to downstream of the Québec part, the SL system is divided into five major hydrographic units, which the river section (RS) and fluvial estuary section (FES) are grouped together to discern the fluvial system from the marine system downstream of Québec City (Figure 1(B)). The boundary between the RS and FES is defined by the upstream limit of tidal processes at the mouth of Lake St. Pierre, in front of the city of Trois-Rivières (Matte et al. 2017) (Figure 1(A,D)). The study area also includes the mouths of major tributaries upstream to the first anthropogenic structure encountered (i.e. dam, bridge, etc.; Figure 1(C,D)).

The mean annual discharge in the SLFS increases gradually from Cornwall (7370 m³/s) to Québec City (12,200 m³/s) (Rondeau et al. 2000; Matte et al. 2017) and flows through the St. Lawrence Platform geological province bordered to the north by the Canadian Shield and to the south by the Appalachians (Lavoie 1994) (Figure 1(B)). The modern SLFS evolves from a complex hydrosystem made of several river channels, branches, archipelagos and shallow fluvial lakes (RS) into a 1 to 5 km-wide estuary where fluvial processes formed bluffs and terraces that extend to Québec City (FES). The modern physiography and surface geology of the SL is mainly inherited from the passage and retreat of the Laurentide Ice Sheet and subsequent marine invasion in the glacio-isostatically depressed basin located in the St. Lawrence Lowlands (Occhietti et al. 2011; Dalton et al. 2020), where a sequence of glacial, paraglacial and postglacial sediments was deposited and uplifted before the onset of modern river processes (Lamarche 2005; Occhietti 2007; Normandeau et al. 2017) (Figure 1(C,D)).

The climate ruling the SLFS is humid continental, with cold winters characterized by freezing temperatures and snowfall. Spring snowmelt, in some cases associated with heavy rains, favor occasional flooding in the lowlands. However, the strong
seasonality of the region limits the possibility of compound flood events occurring, with most river discharge peaks in the spring and storm surges in the fall (Ward et al. 2018; Couasnon et al. 2020). The physiography of the SLFS directs these winds into a preferential northeast-southwest axis (Figure 1(C,D)). In addition, freezing temperatures during winter allow river ice to develop and eventually create ice-jams (Morse et al. 2003). The ice-jam hazards are, however, mitigated by the passage of icebreakers on the seaway since the beginning of the twentieth century (Ouellet and Baird 1978).

The SL was a main artery for Indigenous peoples and a gateway for former European settlers in Canada (Dickason 1996; Pintal et al. 2015) and is today a major waterway for global commerce, with about 4500 cargo ships per year (SLSMC 2019). Over the past 400 years, human-induced modifications of the riverscape resulted in deforestation and concreting of riverbanks, construction of ports and flow obstacles such as dams, piers, dikes, locks, barriers and rock armors for water regulation, hydroelectricity and hazards mitigation purposes (Figure 1(A)). Since the mid-twentieth century, the dredging of the riverbed created a seaway favorable for the passage of cargo ships (Morin and Côté 2003) (Figure 1(C,D)). Meanwhile, agriculture, industrialization and urbanization in the lowlands maintained a constant pressure on the
SL, with the resulting pollution of waters and sediments (Gobeil et al. 2005; Pelletier et al. 2016; Montiel-León et al. 2019).

3. Methodology
The high diversity of geo-ecosystems in large rivers requires the implementation of a simplified method to allow consistent and comparable results along the river course. The steps leading to the positioning and the classification of the riverbanks, the assessment of erosion hazards and finally to the identification of erosion-prone sites are illustrated by a flowchart in Figure 2 with the SLFS as an example. The approach describes in the following section derives from previous work of similar nature in the SL marine system (Drejza et al. 2011, 2019; Quintin et al. 2016; Fraser et al. 2017; Sauvée et al. 2020).

3.1. Literature review
A literature review (step 1 in Figure 2) including both peer-reviewed articles and non-reviewed literature was undertaken in order to collect information on (1) current land management policies on Québec’s riparian environments; (2) former studies undertaken on the SLFS (Argus Groupe-Conseil 1996, Dauphin 2000; Rondeau et al. 2000; Dauphin and Lehoux 2004; Morneau et al. 2014; Quintin et al. 2016); (3) methods used to classify riverbanks, assess and monitor erosion dynamics in time and space (Winterbottom and Gilvear 2000; Fortin 2010; Krapesch et al. 2011; Klemas 2013; Currin et al. 2015; Gilvear and Bryant 2016; Rogers and Woodroffe 2016; Cooper and Jackson 2019); (4) erosion hazards management approaches worldwide (Biron et al. 2014; Habersack et al. 2016; Williams et al. 2018) (step 1 in Figure 2); and (5) erosion mechanisms in temperate (Lawler et al. 1997; Grove et al. 2013; Henshaw et al. 2013) and cold (Reid 1985; Boucher et al. 2009; Kessler et al. 2013; Chassiot et al. 2020; Roland et al. 2021) environments. This first step is essential to develop an appropriate erosion hazards conceptual framework and riverbank classification that will be specific to the river physiography and environmental stress factors.

3.2. Data collection
In order to delineate riverbanks with great precision, the core of the geospatial approach needed to be based on high-resolution data such as LiDAR from topographic airborne surveys and orthomosaics of digital aerial photographs (step 2 in Figure 2). LiDAR data and orthomosaics are currently the most precise and consistent geospatial information for regional-scale assessment of erosion hazards, while now commonly accessible from governmental agencies or municipalities in inhabited area as large river lowlands (Mallet et al. 2012; Tomset and Layland 2019; Williams et al. 2020). The datasets were then compiled in a geodatabase that also contained approximately 18,000 georeferenced oblique photographs and videos from boat and helicopter surveys conducted between 2017 and 2019. Data collected
during these field surveys were mainly used as a primary tool for riverbank segmentation and classification as well as to complement locations where remote sensing data could not provide quality information due to vegetation cover, flooded banks and/or poor image resolution. Boat and field surveys were also essential for documenting geomorphological processes and the state of degradation of artificial riverbanks, which were not always visible on aerial images. In addition, several participative mapping workshops were held with stakeholders to evaluate the needs
and gaps in erosion hazards management and to collect information from field actors (step 2 in Figure 2). The local knowledge-derived data acquired during these meetings provided valuable information for validating the riverbank classification results and for providing crucial information on the timing and intensity of erosion mechanisms at specific sites.

3.3. Riverbank positioning

In Anthropocene river systems, the delineation of a channel baseline must consider various artificial riverbanks, while at the same time respecting natural geomorphological limits relevant for monitoring erosion (step 3 in Figure 2) (Piégay et al. 2020). This task is complicated by the fact that large hydrosystems may present several types of geomorphological boundaries that can evolve progressively along the river course (Figure 1). The geospatial data allowed an accurate and precise (<1 m) hand delineation of the SLFS channels, a task that neither automated delineation algorithms nor satellite data (i.e. lower resolution data) can currently achieve. In some sectors, the year of acquisition between LiDAR and orthomosaics differs. In such cases, the most recent dataset was used to digitize the riverbank baseline at a scale of 1:600, which constitutes the highest resolution for riverbank mapping in the SLFS to date. Figure 3 illustrates how the hand delineation was performed using two geospatial datasets. Details of the mapping procedure according to the morphology, the influence of tidal processes and the presence or absence of artificial riverbanks are described in the following section.

The criteria used for the FES follow the method outlined in Quintin et al. (2016), Fraser et al. (2017) and Sauvé et al. (2020) for the SL marine system, with the coastline—the upper slope, if present, marking the limit of coastal processes—and the shoreline—the terrestrial limit submerged during upper high tides, above which herbaceous vegetation grows—being considered as the main geomorphological boundaries. Therefore, the coastlines correspond to all types of bluffs; the shorelines correspond to the others, namely beach terraces and tidal marshes. When a coastal segment presented both shorelines and coastlines, the choice between the two was made according to the presence or the absence of vulnerable habitats (i.e. built environment or wetlands). As a result, the first vulnerable riverbank type encountered riverward was considered as the riverbank baseline and the second one was classified as a complementary feature, which made it possible to broaden the environmental context of the area in the geospatial database (see complementary lines in Figure 3). The complementary lines were drawn to a maximum of 200 m behind the riverbank baseline.

For the RS, the bankfull discharge limit defining the minor riverbed was used to map the riverbank baseline, in agreement with previous work on Québec (Boucher et al. 2009; Fortin 2010; Biron et al. 2013, 2014; Buffin-Bélanger et al. 2015; Rousseau et al. 2018) and worldwide rivers (Lastra et al. 2008; Bizzi and Lerner 2012; Fernández et al. 2012; Schmitt et al. 2014; Heitmuller et al. 2015). Where the bankfull discharge limit was not clear or fuzzy on remote sensing data—as it is often the case for wetlands—the limit of arborescent vegetation was considered to map the baseline. In addition, the mapping of complementary lines includes, when identified, the crest and toe of bluffs.
located up to 200 m behind the riverbank baseline as well as limits of herbaceous fluvial marshes in front of it.

In both SLFS sections, field survey and remote sensing data allowed mapping artificial riverbanks that are in some cases located at the base of the riverbank slope. Most of these structures were designed to prevent erosion and/or flooding near built environment. In such cases, the positioning of the baseline was made on the top of artificial structures (Figure 3(D)). Consequently, the baseline shifts in some situations between the crest or the base of the riverbank slope, depending on the presence of artificialities downslope. This concept is illustrated in Figure 3 for a FES site, where the transition from 3A to 3B shows the shift of the baseline from the shoreline in 3C (human habitats settled downslope on a terrace at the toe of a bluff) to the coastline in 3D (crest of the bluff without habitats in front of it).

3.4. Segmentation and classification

Following riverbank positioning, a manual segmentation of the baseline was undertaken in order to assign riverbank physical attributes for each individual segment with homogeneous and continuous characteristics over a minimum length of 5 m (step 4 in Figure 2). A summary of SLFS-specific riverbank types is provided in Table 1, with the location of some types depending on the presence or absence of tidal processes. For instance, beach terraces have no equivalent in the RS due to more constant water levels that do not allow their formation. In order to simplify the reading of the results and the mapping, some terms were gathered to create six general classes: soft and rocky riverbanks, embankments, wetlands, beach terraces and canals (Table 1). The classification of artificial riverbanks was derived from field observations, analysis of remote

| Class | Definition | Type | Acronym | Short description |
|-------|------------|------|---------|-------------------|
| 1     | Soft       | High soft bluff | HS | Steep slope of unconsolidated materials; Height > 5 m |
| 1     | Soft       | Low soft bluff | LS | Steep slope of unconsolidated materials; Height < 5 m |
| 1     | Soft       | Soft      | S      | Gently sloping unconsolidated materials; no bluff |
| 2     | Rocky      | High rocky bluff | HR | Steep slope of consolidated rocks; Height > 5 m |
| 2     | Rocky      | Low rocky bluff | LR | Steep slope of consolidated rocks; Height < 5 m |
| 2     | Rocky      | Rocky     | R      | Gently sloping consolidated rocks; no bluff |
| 3     | Tidal marsh| Tidal marsh | TM | Tide-flooded ecosystem with aquatic vegetation |
| 3     | Wetland    | Swamp     | SW | Seasonally flooded ecosystem with arborescent vegetation |
| 3     | Wetland    | Fluvial marsh | FM | Flooded ecosystem with aquatic vegetation |
| 4     | Embankment | Embankment | E    | Unconsolidated deposit of anthropogenic origin |
| 5     | Beach terrace | Beach terrace | B | Gently sloping terrace of littoral sediments with an upper vegetation limit |
| 6     | Canal      | Canal     | C      | Top of a slope at the edge of an artificial watercourse |

*Only used as a complementary line in front of a baseline in the RS.
3.5. Development of the erosion index

Riverbank classification was followed by an assessment of erosion susceptibility for each segment, based on geomorphic indicators (GI) of erosion from field reports, photos, videos, local knowledge and remote sensing information (step 5 in Figure 2). Several morphologies inherited from erosion processes were used as GI of active erosion for riverbank segments: slide scars, convex-shaped bank lines, cantilevered structures, uprooted trees on steep slopes, sediment fan or rock debris at the toe of the slope. The state of the vegetation was also taken into consideration, with bare banks or those with a degraded vegetation strip band being considered more prone to erosion.

The state of deterioration of artificial riverbanks, when present, was then reported in the attribute table of the database. This evaluation was made using essentially oblique photographs and videos collected during boat and helicopter surveys. In total, more than 20 fieldtrips together with consultations with local stakeholders and collaborators allowed collecting up-to-date information and validating interpretations made from remote sensing data. Four state of deterioration were defined: (1) good, when no visible damage was observed over 75% of the length of the structure; (2) partially good, when degradation (cracks, collapse, rust, rotting, etc.) was observed over 25% to 50% of the length of the structure; (3) partially bad, when degradation was evidenced over 50% to 75% of the structure; and (4) bad, when damages were observed over 75% of the structure (Quintin et al. 2016).
Combining the erosion susceptibility and the state of deterioration of the artificialities allowed creating a decision tree (step 5 in Figure 2) towards a 3-level erosion index (EI) ranked from 0 (no erosion) to 2 (severe erosion). Figure 4 illustrates these levels with examples from artificial and natural riverbanks. In some rare cases, sedimentary accretion (Acc) was added on a segment when several stakeholders mentioned this trend (step 5 in Figure 2).

3.6. Identification of erosion-prone sites

Once the mapping of the EI was completed, preliminary results presented during workshops with citizens, managers and stakeholders –during which up to 100

Figure 4. Examples of EI and classification on natural and artificial riverbanks. An EI = 0 on (A) a tidal marsh showing no GI of erosion and (B) a protective wall with no alteration. An EI = 1 on (C) a beach with some intermittent GI of erosion and (D) a partially degraded rock armor with few GI of erosion. An EI = 2 on (E) a rocky sedimentary bluff with no vegetation cover and (F) an unprotected embankment highly altered. The dashed line indicates the riverbank baseline.
participants were consulted—allowed discussing and adjusting mapping results as well as characterizing erosion-prone sites highlighted by the analysis. These participatory mapping workshops and periods of discussions on local knowledge provided better guidance and information to the research team on the riverscape. Combining these inputs from the workshops and the analysis of the riverbank characterization allowed establishing a list of erosion-prone sites (step 6 in Figure 2) with a minimum length of 100 m. In some cases, two continuous segments sharing common characteristics and EI were aggregated into a single site.

3.7. Constrains and limits of the study

Despite the application of a rigorous protocol based on high-resolution mapping, the limitations of the methods used for this study should not be overlooked, as the reliability of the remote sensing data depends on several factors, such as (1) their resolution and position accuracy; (2) shading, vegetation cover density and higher-than-normal water levels at the time of shooting; and (3) subjective interpretation by different users (Winterbottom and Gilvear 2000; Provencher and Dubois 2007; Marcus and Fonsd 2008; Fortin 2010; Gilvear and Bryant 2016). In addition, due to the extent of large rivers, the spatial coverage and the resolution of geospatial data can differ from one area to another. Some of regions may have benefited from more recent geospatial data with state-of-the-art techniques providing higher resolution, allowing a better assessment of erosion susceptibility. Similarly, it should be expected that the quality and the quantity of information provided by the different contributors during workshops are greater nearby populated areas. Finally, the erosion dynamics and the processes controlling it are here based on the development of a qualitative EI, whose criteria remain subjective and difficult to homogenize over such large and diverse hydrosystems as the SLFS.

4. Results

The key physical properties of the SLFS provided by the high-resolution mapping of 3191 km of riverbanks are summarized below. The riverbank baseline is composed of 13,120 individual segments to which have been attributed specific physical and/or anthropogenic characteristics. Maps and main statistics of riverbank classification are presented for each of the two main hydrographic units (i.e. the upstream RS and the downstream FES) and for the entire SLFS. The complete geospatial database is available in open access on the St. Lawrence Global Observatory website (see Data availability).

4.1. The river section

The RS accounts for 79% (2530 km) of the SLFS riverbank baseline, where banks are half natural, half artificial (Figure 5(A)). The 1260 km of banks that are still natural correspond mainly to (1) the fluvial archipelagos (i.e. Îles-de-la-Paix, Boucherville, Varennes, Verchères, Ste. Thérèse, Contrecœur and St. Pierre) gathering several hundreds of islands; (2) the banks of Lake St. Pierre; and (3) the mouth of the
Ottawa River (Figure 5(A)). Moreover, wetlands (29%/741 km) prevail on the soft banks (21%/528 km) and very few rocky banks are observed (<1%/11 km) (Figure 5(B)).

The riparian environment is marked by the presence of the metropolitan community of Montréal, the most densely populated area in Québec, and by the various navigation structures associated with the SL seaway. Many banks have been modified and backfilled (44%/1107 km) to allow occupation of the flood-prone lowlands along the river, mostly around the city of Montréal (Figure 5(B)). In nearly half of the cases, these anthropogenic modifications on the riparian slope have been completed by the installation of protection structures (48%/613 km) to prevent the erosion...
hazards, but several bare embankments (31%/392 km), are also present (Figure 5(C)). Among artificial structures, unprotected embankments and rock armors appear to be more sensitive to erosion, as 32% (124 km) and 38% (137 km) of them, respectively, show an EI > 0 (Figures 5(C) and 6(A)).

Erosion is quite low in the RS since 72% (1829 km) of the segments show an EI = 0 (Figure 6(A)). Along the banks with an EI = 1 (19%/481 km) or 2 (8%/199 km), two erosion hotspots can be identified: (1) the mouth of the Ottawa River and (2) the archipelagos between east of Montréal and Lake St. Pierre (Figure 6(A)). These hotspots also correspond to the areas where the banks are mainly natural (Figure 5(A)). These qualitative observations combined with workshops resulted in the preliminary identification of 186 erosion-prone sites (462 km).

Figure 6. Maps showing the riverbank EI for (A) the RS and (B) the FES section. The first rank white rectangles show the main erosion hotspots for each section and the second rank rectangles are discussed in Subsection 5.2 of this article.
4.2. The fluvial estuary section

The FES is characterized by far fewer islands and channels than the upstream RS. As a result, the FES represents only 21% (661 km) of the SLFS riverbanks, but a greater diversity of riverbank types can be observed within this section (Figure 7(A)). Of the 394 km (60%) of natural banks, wetlands (31%/207 km) are the most frequent. They are concentrated in the concave parts of the river course, away from urban centers and in the channel north of Île d’Orléans (Figure 7(B)). Beach terraces (11%/70 km) and soft banks (14%/90 km) are evenly distributed throughout the sector, but the natural rocky banks (11%/75 km) are generally confined between Portneuf and Québec City. The same stretch of the river, particularly on its south riverbank, concentrates high soft/rocky bluffs (15%/102 km; Figure 7(B)).

The FES has a high proportion of artificial segments, accounting for 40% (267 km) of the riverbank delineation, where embankments prevail over 33% (218 km) (Figure 7(A,B)). Most of the artificialities are concentrated around the metropolitan community of Québec City and Trois-Rivières, the two largest cities in the FES. The artificial riverbanks are mostly protected by structures (68%/180 km). Unlike the RS, only 15% (40 km) of the embankments remain unprotected (Figure 7(C)), but much fewer major constructions (i.e. dams, canals and navigation structures) are present, except around the ports of Québec, Trois-Rivières and Bécancour (17%/42 km) (Figure 7(C)). As for the RS section, unprotected embankments and rock armors are the two most erosion-prone artificial bank types with $EI > 0$ on 54% (21 km) and 30%
Finally, 18% (49 km) of the artificialities were built on natural banks without the need of backfilling. Several riparian environments are exposed to erosion, as reflected by an EI = 1 (23%/150 km) or 2 (17%/114 km) in the FES. Two erosion hotspots are identified: the channel north of Île d’Orléans, essentially composed of marshes with soft tidal cliffs, and the Portneuf area, mainly characterized by high unconsolidated or rocky bluffs with no vegetation cover (Figure 6(B)). The latter is also characterized by the presence of some eroding beach terraces and wetlands located at the toe of anthropogenic structures (Figures 6(B) and 7(B)). The mapping and the classification, combined to information from workshops, finally, allowed identifying 65 erosion-prone sites representing 215 km of vulnerable riverbanks.

4.3. Synthesis of the St. Lawrence fluvial system

The riverbank baseline of the SLFS reaches a total length of 3191 km, of which 48% (1537 km) have been artificialized (Figure 8). Embankments are the most frequent type of riverbank (42%/1324 km), followed by wetlands (30%/948 km) and natural unconsolidated deposits (19%/618 km) inherited from the last glacial era. Embankments and natural deposits are evenly distributed along the SLFS, whereas wetlands are located around the archipelagos, Lake St. Pierre and along the north channel of Île d’Orléans (Figure 8). Among the artificial riverbanks, 52% (793 km) correspond to protection structures settled on various riverbank types and 28% (431 km) to unprotected embankments (Figure 8(A)).
the artificialities are in good condition (Figure 8(A)), although unprotected embankments and rock armors (rip-raps) appear to be the most exposed to erosive processes, representing 81% (315 km) of the structures showing signs of degradation.

Among the entire SLFS, 70% (2225 km) of the riverbank baseline appear unaffected by erosion (EI = 0), while 30% (944 km) are submitted to active erosion processes (Figure 8), of which 10% (313 km) are considered as severely degraded (EI = 2). Natural riverbanks account for 70% (663 km) of the eroding sites (Figure 8(B)). The most sensitive riverbank types are soft banks and wetlands with 45% (278 km) and 34% (326 km) showing an EI > 0, respectively (Figure 8(B)). Finally, the combined approach of high-resolution mapping and local knowledge information allowed identifying and characterizing 251 erosion-prone sites representing a total of 677 km. Many of these sites are concentrated in four regional erosion hotspots, namely (1) the mouth of the Ottawa River; (2) the archipelagos between Montréal and Lake St. Pierre; (3) the cliffs near Portneuf; and (4) the tidal marshes in the north channel of Île d’Orléans (Figure 6).

5. Discussion

5.1. Outlooks for future monitoring studies

Despite the qualitative nature of the results, the geospatial framework provides a regional-scale portrait of an Anthropocene large river with a consistent methodology along 3191 km of riverbanks (Figure 8). The first attempt to digitize the riverbank positions in the SLFS was undertaken by Sergy (2008), but with a too low precision delineation to allow addressing erosion hazards issues (Figure 3(A,B)). A first large-scale and accurate mapping on GIS support is essential for producing subsequent reliable monitoring data addressing erosion and flood hazards issues (Figure 3(A,B)). A first large-scale and accurate mapping on GIS support is essential for producing subsequent reliable monitoring data addressing erosion and flood hazards issues, while offering an open access availability for scientists and policymakers (Lastra et al. 2008; Wheaton et al. 2009; Klemas 2013; Biron et al. 2014; Petropoulos et al. 2015; Fraser et al. 2017). Replication of this 2D approach with decadal intervals and new remote sensing data would allow precise changes to be observed and quantified. Conversely, common erosion hazards management approaches on large hydrosystem are generally based on low-resolution data such as satellite imagery or historic aerial photographs (Sergy 2008; Gilvear and Bryant 2016, Piégay et al. 2020), which limits the accuracy of the monitoring studies. A second analysis of this type would thus make it possible to (1) validate the results of this study (erosion index); (2) characterize the evolution of erosion dynamics; and (3) measure the rates of retreat at the large river extent (Winterbottom and Gilvear 2000; Bizzy et al. 2016; Best 2019).

Two-dimensional approaches are usually suitable for a first large-scale analysis, but when it comes to local erosion-prone sites, process-based approaches with short-term observations are mandatory (Roland et al. 2021). In fact, high accuracy and precision as well as a short time interval (intra-annual) between each survey are often required to determine the best management solutions (Grove et al. 2013; Smeeckaert et al. 2013; Turner et al. 2016; Scarelli et al. 2017; Piégay et al. 2020; Volpano et al. 2020). For this purpose, it is more appropriate to use easily reproducible 3D methods with
high geodetic accuracy such as GNSS, RTK/PPK UAV or terrestrial LiDAR surveys (Klemas 2013; Joyal et al. 2016; Turner et al. 2016; Piégay et al. 2020; Roland et al. 2021). For example, intra-annual topo-bathymetric surveys would isolate the impacts of episodic events from slower and more gradual retreats and provide insights on the seasonal erosion dynamics (Klemas 2013; Mandlburger et al. 2015; Roland et al. 2021). In addition, the use of monitoring stations that integrate different sensors (pressure, turbidimeter, ADCP, camera, piezometer, etc.) would allow documenting the land-river sediment continuum as well as the role of erosion mechanisms and controlling factors in erosion-prone sites (Zaggia et al. 2017; Scarpa et al. 2019; Roland et al. 2021). Conversely, short-term studies quickly become expensive and time-consuming; therefore, a preliminary identification of erosion-prone sites is important at the river scale. Dialogue between stakeholders can then be initiated to prioritize first actions to be taken at different spatial scales and to better understand land-use management issues on vulnerable sites.

Figure 9. Natural and human-induced erosion processes along natural and artificial riverbanks in an ice-affected river during summer (top) and winter (bottom).
5.2. Riverbank erosion in the SLFS hotspots

Riverbank erosion in large rivers results from a wide variety of terrestrial, fluvial and estuarine processes (Couper and Maddock 2001; Henshaw et al. 2013; Chassiot et al. 2020) that are enhanced by climate change and a growing human pressure (Gregory 2006; Best 2019; Goudie 2020; Piégay et al. 2020; Wohl 2020). Mapping results combined with field surveys and local knowledge-derived data allowed identifying a first overview of those processes with a seasonal perspective along different stretches of the SLFS (Figure 9). By providing a large quantity of geospatial data, the proposed approach can also easily allow highlighting spatial distribution and intensity of geomorphic processes at work along riverbanks (Figure 10). The conceptualization and classification of this information combined with high-resolution maps is a major step in hazards management as it can also raise awareness among decision-makers (Figures 9 and 10).

The main erosion mechanisms observed in the SLFS erosion hotspots are discussed below. These mechanisms are characterized by a geographical context combining a high anthropogenic pressure as well as seasonal and fetch-limited processes (<50 km) (Houser 2010; Nordström and Jackson 2012; Prahalad et al. 2015) (Figures 6, 9 and 10). The diversification and the intensification of human activities in the SLFS over the last century appear to have caused human-driven erosion processes to overcome those of natural origin; a trend that diminishes towards the lower reaches of the FES (Figure 10).

5.2.1. Flow regulation and flood-induced erosion in a built environment

The Moses–Saunders dam located at Cornwall plays a major role in water levels regulation and flow input in the RS, which strongly limits flood probabilities coming from Lake Ontario (Figure 1(C)). Flood-induced erosion from the main headwater is mitigated, but the involvement of tributaries to flood hazards in the SLFS remains.
Most of these tributaries are regulated by run-of-the-river structures, through which fluvial parameters are preserved to some extent. However, dam management operations such as turbine regulation or gate opening can create artificial hydrographs with hydropeaking, i.e. discontinuous and artificial flow fluctuations downstream of the dam (Greimel et al. 2018; Schmutz and Moog 2018). For example, the Ottawa River floods in 2017 and 2019 led to the opening of all the gates of the Carillon dam to discharge flows reaching more than four times the annual average value during a sustained period (ORRPB 2019). The turbulent and erosive artificial flows released by the dam during these events severely impacted downstream structures and riverbanks (Figures 7(A) and 11(A)). Nevertheless, the Ottawa River Regulation Planning Board (ORRPB) has stated that water levels at the mouth of the Ottawa River would have been nearly one meter higher and much more destructive if the river watershed had not been regulated during these floods (ORRPB 2019).

Field surveys conducted shortly after these high-water levels allowed reporting that more artificial riverbanks had an EI \(> 0\) compared to natural riverbanks, which appeared to be more resilient to shear stresses with gentler slopes and vegetation cover. Many residences and infrastructures were damaged by the turbulent waters, indicating that the protection structures were inefficient to prevent flood-induced erosion by overflows (Figures 9 and 11(A)). Flood hazards may persist despite the presence of water management and protection structures in the SLFS, particularly at the

![Figure 11. Two erosion-prone sites located in the hotspots of the RS (see Figure 6(A)). White arrows show the flow direction, and the white squares locate the adjacent picture. (A) The mouth of the Ottawa River near the Carillon dam and (B) one of the fluvial archipelagos (i.e. Verchères) near the seaway affected by the wake of cargo ships.](image-url)
mouth of the Ottawa River, which is one of the four regional erosion hotspots identified in this study (Figures 7(A) and 11(A)). In fact, these water management structures can falsely create a sense of security for riparian communities, leading them to further develop riverbanks and increase their exposure to flood-induced erosion. Backfilling operations started at the beginning of the Nineteenth century to expand residential areas in the SLFS. These operations were done especially on riparian wetlands and lowlands of the RS, as shown by the 44% (1107 km) of the riverbank baseline now associated to embankment (Jean and Létourneau 2011) (Figure 5(B)). Encroachment on the river has since regularly been carried out, in some cases over distance of up to several tens of meters. These artificial slopes, easily recognizable on LiDAR data, are generally composed of loose material of various grain sizes, ranging from silt to cobbles. In most cases, these slopes are protected by concrete walls or rock armor that are often weakly adapted to flood hazards (Jafarnejad et al. 2017) (Figures 5(C) and 11(A)). Moreover, that non-cohesive material increases the sensitivity of the artificial riverbanks to erosion by overflow, which significantly increase the vulnerability of the built environment and thereby endangering riparian populations (Gilvear and Black 1999).

5.2.2. Exposition to wake action from St. Lawrence seaway

The establishment of the SL seaway in 1959 and the increased popularity of recreational boating significantly exacerbate riverbank erosion within the RS (Department of Public Works 1968; Panasuk 1987; Argus Groupe-Conseil 1991, 1996; Lehoux et al. 1997; Dauphin 2000; Dauphin and Lehoux 2004; Gharbi et al. 2010) (Figure 1(C,D)). Major river adjustments were made between Trois-Rivières and Cornwall to adapt the SL channel for the seaway (Argus Groupe-Conseil 1991, 1996; Lehoux et al. 1997; Dauphin 2000; De Koninck 2000; Morrin and Côté 2003; Morse et al. 2003). The combination of all these anthropogenic stressors strongly alters the natural flow, sediment continuum as well as riparian ecosystems of the RS.

According to the riverbank classification in the RS, 37% (298 km) of the natural banks of the archipelagos (excluding Montréal, Laval, Bizard and Perrot islands) show active erosion (EI > 0), compared to 23% (361 km) for the southern and northern banks of the river (Figure 7(A)). This difference could be mainly related to the proximity of the islands to the seaway, their exposition to recreational boating and to a stabilization of the riverbanks, which are more densely populated than the archipelagos (Figure 11(B)). Several authors have also raised the issue of wake erosion in the multiple archipelagos between Montréal and Lake St. Pierre (Argus Groupe-Conseil 1991, 1996; Lehoux et al. 1997; Dauphin 2000; Dauphin and Lehoux 2004; Gharbi et al. 2010), where are located most of the remaining natural banks of the RS (Figure 5(A)). The wake generated by commercial vessels operating in the seaway could impact the shoreline at a distance of up to 800 m and more severely when initiated at less than 400 m from the shore (Dauphin 2000) (Figure 11(B)). For the SLFS, approximately 18% (584 km) of the riverbanks are within this zone of wake influence (Figure 1(C,D)). For instance, 25% (50 km) of the severely degraded riverbanks (EI = 2) in the RS are located within 800 m of the SL seaway. The ship wake impact is mainly concentrated between Montréal and Sorel, where 85% of the total erosion
attributable to commercial vessels between Cornwall and Québec City occurs. (Dauphin 2000). As a result, riverbanks are eroding under the stress of these anthropogenic changes, threatening the built environment as well as agricultural lands and natural ecosystems. However, since riverbank erosion results from a series of geomorphic and hydrologic processes, wake action is not the sole factor influencing retreat rates, even for ships travelling less than 100 m from the banks. Desiccation of fine materials, freeze-thaw or the absence of vegetation also influence bank retreat rates in this sector (Gaskin et al. 2003).

On natural riverbanks of the RS, qualitative observations indicate that the presence of wetlands, such as swamps, herbaceous marshes and aquatic grass beds, appear to limit the impacts of water level variations and waves of anthropogenic origin (Figure 11(B)). The classification conducted in the RS shows that riverbank types associated with fluvial marshes in front of the baseline (i.e. 9% with EI > 0) are less sensitive to erosion than other natural banks (i.e. 16%), supporting the conclusions of previous work on the role of fluvial wetlands in riparian protection and resilience (Murgatroyd and Ternan 1983; Thorne 1990; Simon and Collison 2002; Currin et al. 2015). According to Currin et al. (2015), shorelines consisting of marshes or swamp forests have lower rates of erosion than bare ones, particularly in high wave conditions. Even soft banks bordered by a particularly narrow band of vegetation have lower erosion rates than non-vegetated soft banks (Currin et al. 2015). Conversely, the
establishment of artificialities in these fragile environments disrupts their ecological integrity, leading to their degradation or complete disappearance (Figure 11(B)). It is necessary to ensure that these sensitive environments are capable of withstanding high-intensity waves that would otherwise not be naturally observed without the presence of the SL seaway.

5.2.3. Mass-wasting on high bluffs
The FES is characterized by the presence of high (>5 m) soft and rocky bluffs with 46% showing an EI > 0 (Figures 6(B) and 7(B)). These cliffs are generally steep and mainly composed of shales and unconsolidated materials sensitive to meteorological alteration by frost and water, which make them more vulnerable to terrestrial erosion processes than other riverbank types in this area (Figure 12(A)). Roland et al. (2021) have highlighted that strong seasonality that promotes freeze/thaw cycles events is a dominant process on bluff recession in cold riparian environments. Within the FES, 83% of the unconsolidated cliff segments are partially or completely vegetated, but field surveys suggest that they can quickly become unstable (Figure 12(A)). Erosion along soft bluffs generally results from the joint action of slow and continuous mechanisms (i.e. freeze/thaw, seepage and desiccation) with rapid and occasional mechanisms such as runoff and mass-wasting processes (Joyal et al. 2016; Chassiot et al. 2020; Volpano et al. 2020; Roland et al. 2021); one striking example is the 2019 landslide that destroyed a marina in Deschaillons-sur-Saint-Laurent, nearby Portneuf (Figure 1(B)). In addition, several slide scars, some of which are now vegetated, remain visible on LiDAR data along bluff segments. This information suggests mass-wasting is an important process of riverbank erosion within the FES. Moreover, 9% of the riverbank segments correspond to rocky cliffs along the FES (Figure 7(B)). These cliffs consist, for the most part, of friable sedimentary rocks where freeze-thaw cycles are very active, especially on about 20% of these riverbanks where an absence of vegetation is observed. Although their annual retreat rates are usually slow, rapid mass-wasting processes such as rockfalls and skinflows already occurred in the area. However, few studies have described the lithostratigraphy of these bluffs (Besré and Occhietti 2007; Occhietti 2007) but without addressing them in terms of geohazards.

5.2.4. Fetch-limited storm surges and relative sea level rise
In contrast to the RS wetlands, results show that tidal marshes are the most sensitive riverbank type of the FES, with 58% showing GI of erosion and with continuous segments up to 3.2 km with an erosive tidal cliff (Figures 6(B) and 7(B)). The majority of these segments with a high EI are located in the channel north of Île d'Orléans (Figure 12(B)). In this sector, erosion results from the joint action of storm surges, anthropogenic pressure, ice foot duration, tidal cycles and relative sea level fluctuations (Forbes and Taylor 1994; Argus Groupe-Conseil 1996; Bernatchez and Dubois 2006; Drapeau 2007; Bhiry et al. 2013). The suspension of eroded fine sediments linked with tidal range maximum close to 6 m make the northern arm of Île d'Orléans, especially Cap Tourmente mudflats, the most dynamic area of the FES (Sérides 1980). Located in a fetch-limited environment (<50 km), these marshes are less exposed to high-energy wind, but wind-generated waves remain the primary
mechanism of tidal marsh shoreline change (Houser 2010; Nordstrom and Jackson 2012; Prahalad et al. 2015). Low-energy waves could also impact marshes, especially after a storm-induced breach in the vegetation cover (Prahalad et al. 2015). Bhiry et al. (2013) monitored tidal marshes in the FES and have also observed that the height of a marsh tidal cliff greatly influences the rate of retreat, i.e. the higher the slope, the greater the rate of retreat.

Relative sea level rise is a fundamental driver influencing changes in coastal environment (Houser 2010; Nordstrom and Jackson 2012; Prahalad et al. 2015; Vousdoukas, et al. 2020a, 2020b). The anticipated rise of global sea level will test the resilience of tidal marshes and other coast types. A recent study noticed a relative sea level rise slightly lower than 2 mm/year near Île d’Orléans between 1990 and 2017 (Rondeau-Genesse 2020). Taking into account glacio-isostatic uplift and global sea level rise with the IPCC RCP8.5 scenario, James et al. (2014) predicted a relative sea level rise at Québec City between 20 and 60 cm for 2100. A continuous supply of sediment will therefore be required to keep the coasts in their current position; otherwise, they could migrate landward (Prahalad et al. 2015). As the sediment load of the SL is already low (Milliman and Meade 1983; Rondeau et al. 2000), the addition of anthropogenic disturbances in its sedimentary regime could have negative impacts on the adaptive capacity of these systems. Moreover, the expected landward migration of the riverbank position would also be greatly conditioned by the presence of obstacles (e.g. cliffs, protection structures, etc.) that could block this riparian adjustment (Nordstrom and Jackson 2012; Bernatchez and Quintin 2016). These conditions can lead to the degradation or even the disappearance of tidal marshes (Prahalad et al. 2015; Bernatchez and Quintin 2016) and sandy beaches (Nordstrom and Jackson 2012; Vousdoukas et al. 2020a, 2020b); two essential ecosystems for biodiversity, hazards mitigation, tourism and recreational activities.

6. Conclusions

The high-resolution GIS-based mapping approach reported in this article allowed identifying and spatially defining erosion hotspots and main mechanisms active in a large river that has been highly impacted by human activities. The analysis based on a high-resolution and multisource geospatial dataset covering a large geographical region coupled with field observations and local knowledge information from stakeholders allowed delineating, segmenting and classifying nearly 3200 km of riverbanks according to (1) their geomorphology; (2) the presence/absence of artificialities with their state of degradation; and (3) assessing their erosion susceptibility. These results represent a significant update from previous regional studies by providing open access GIS data to guide land management and conservation programs along the SLFS as well as a methodological guideline for other large rivers of the world.

Over the entire SLFS, riverbanks are half natural, half artificial. Embankments (42%), wetlands (30%) and soft deposits (19%) are the more represented types of riverbanks. Among artificial riverbanks, 52% are protected by structures such as rock armors or walls, 28% remain unprotected, while 16% represent various navigation structures and canals, mainly located in the upstream section around Montréal. These
structures are generally in good condition as they protect riverbanks from erosion, but 25% of them show signs of degradation. Over the entire SLFS, 70% of the riverbanks have a low erosion susceptibility, 20% show an EI = 1 and 10% present an EI = 2. These results allowed highlighting four regional erosion hotspots and 251 erosion-prone sites where future high-precision monitoring and process-based studies should be undertaken. Riverbank erosion in the SLFS is a result of the combined action of (1) human activities such as hydrological regulation by dams, wake action by ships nearby the seaway, land-use management, backfilling and encroachment on the river course that increase the erosion susceptibility and (2) natural processes such as storm surges, floods, river ice and mass-wasting, some of which are expected to intensify with ongoing climate change and future relative sea level rise.

GIS-based scientific knowledge easily accessible to populations and policymakers is necessary for increasing the resilience of riparian communities and ecosystems to erosion hazards, while allowing improving and implementing appropriate mitigation techniques on riverbank geo-ecosystems. The proposed methodology can be established for regional mapping projects on other large rivers in order to identify erosion-prone sectors and assess hydrogeomorphological changes in both space and time. A suitable approach should then include higher-resolution monitoring (intra- and inter-annual) of the land-river continuum with topo-bathymetric surveys and hydrodynamic studies on vulnerable sites. Future projects on riverbank erosion dynamics in large rivers should be oriented at (1) providing a better understanding of the risks associated with anthropogenic processes, such as the impact of wake action, water level management and riverbank artificialization; (2) establishing an open access base of geospatial information and scientific knowledge for land-use planning choices; (3) increasing the resilience of riparian populations and ecosystems in a context of climate change; and (4) identifying sites of interest for conservation or restoration, such as artificial riverbanks with inadequate protection structures.

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Data availability

The dataset presented in this article are available through of the St. Lawrence Global Observatory (SLGO): https://catalogue.ogsl.ca/fr/dataset/448d2828-d249-4d77-ad68-563512977150

Disclosure statement

No potential conflict of interest was reported by the authors.

Note

1. https://bac-quebec.qc.ca/en/insurance-issues/flooding/

References

Argus Groupe-Conseil. 1991. Érosion des îles du Saint-Laurent: tronçon Montréal – lac Saint-Pierre. Report submitted to Canadian Wildlife Service, Environment Canada.

Argus Groupe-Conseil. 1996. Restauration naturelle des rives du Saint-Laurent entre Cornwall et l’île d’Orléans. Report submitted to Canadian Wildlife Service, Environment Canada.

Bernatchez P, Dubois J-MM. 2006. Bilan des connaissances de la dynamique de l’érosion des côtes du Québec maritime laurentien. Géogr Phys Quat. 58(1):45–71.

Bernatchez P, Quintin C. 2016. Potentiel de migration des écosystèmes côtiers meubles québécois de l’estuaire et du golfe du Saint-Laurent dans le contexte de la hausse appréhendée du niveau de la mer. Nat Can. 140(2):91–104.

Bésré F, Occhietti S. 2007. Les Varves de Deschaillons, les Rythmites du Saint-Maurice et les Rythmites de Leclercville, Pléistocène supérieur, vallée du Saint-Laurent. Géogr Phys Quat. 44(2):181–198.

Best J. 2019. Anthropogenic stresses on the world’s big rivers. Nat Geosci. 12(1):7–21.

Bhiry N, Cloutier D, Couillard L, Gervais A, Lamarre P, Normandeau M, Ousmane Dia A. 2013. Évolution des hauts marais de l’estuaire d’eau douce du Saint-Laurent et stratégies de protection des espèces en situation précaire dans une perspective de changements climatiques. Université Laval, Report submitted to consortium Ouranos.

Biron PM, Buffin-Bélanger T, Larocque M, Choné G, Cloutier C-A, Ouellet M-A, Demers S, Olsen T, Desjarlais C, Eyquem J. 2014. Freedom space for rivers: a sustainable management approach to enhance river resilience. Environ Manage. 54(5):1056–1073.

Biron PM, Choné G, Buffin-Bélanger T, Demers S, Olsen T. 2013. Improvement of streams hydro-geomorphological assessment using LiDAR DEMs. Earth Surf Process Landforms. 38(15):1808–1821.

Bizzi S, Demarchi L, Grabowski RC, Weissteiner CJ, Van de Bund W. 2016. The use of remote sensing to characterise hydromorphological properties of European rivers. Aquat Sci. 78, 57–70. https://doi.org/10.1007/s00027-015-0430-7

Bizzi S, Lerner DN. 2012. Characterizing physical habitats in rivers using map-derived drivers of fluvial geomorphic processes. Geomorphology. 169–170:64–73.

Boucher É, Bégain Y, Arseneault D. 2009. Impacts of recurring ice jams on channel geometry and geomorphology in a small high-boreal watershed. Geomorphology. 108(3–4):273–281.

Buffin-Bélanger T, Biron PM, Larocque M, Demers S, Olsen T, Choné G, Ouellet M-A, Cloutier C-A, Desjarlais C, Eyquem J. 2015. Freedom space for rivers: an economically viable river management concept in a changing climate. Geomorphology. 251:137–148.

Chassiot L, Lajeunesse P, Bernier J-F. 2020. Riverbank erosion in cold environments: review and outlook. Earth-Sci Rev. 207:103231.
Chen Y, She Y. 2020. Long-term variations of river ice breakup timing across Canada and its response to climate change. Cold Reg Sci Technol. 176:103091.

Communauté métropolitaine de Montréal (CMM). 2017. Portrait des inondations printanières de 2017 sur le territoire métropolitain, du cadre légal et des règles applicables en matière d’aménagement de développement du territoire pour les plaines inondables. Montréal, Québec: Commission de l’aménagement.

Cooper JAG, Jackson DWT. 2019. Coasts in Peril? A shoreline health perspective. Front Earth Sci. 7:260.

Cooper JAG, McKenna J. 2008. Working with natural processes: the challenge for coastal protection strategies. Geogr J. 174(4):315–331.

Couasnon A, Eilander D, Muis S, Veldkamp TIE, Haigh ID, Wahl T, Winsemius HC, Ward PJ. 2020. Measuring compound flood potential from river discharge and storm surge extremes at the global scale. Nat Hazards Earth Syst Sci. 20(2):489–504.

Couper PR, Maddock IP. 2001. Subaerial riverbank erosion processes and their interaction with other bank erosion mechanisms on the River Arrow, Warwickshire, UK. Earth Surf Process Landforms. 26(6):631–646.

Currin C, Davis J, Baron LC, Malhotra A, Fonseca M. 2015. Shoreline change in the New River Estuary, North Carolina: rates and consequences. J Coast Res. 315:1069–1077.

Dalton AS, Margold M, Stokes CR, Tarasov L, Dyke AS, Adams RS, Allard S, Arends HE, Atkinson N, Attig JW, et al. 2020. An updated radiocarbon-based ice margin chronology for the last deglaciation of the North American Ice Sheet Complex. Quat Sci Rev. 234:106223.

Dauphin D. 2000. Influence de la navigation commerciale et de la navigation de plaisance sur l’érosion des rives du Saint-Laurent dans le tronçon Cornwall–Montmagny. Final report. Québec, QC: Ministère des Transports du Québec, Service du transport maritime.

Dauphin D, Lehoux D. 2004. Bilan de la sédimentation des littoraux de l’estuaire du Saint-Laurent dulcicole (Montréal – archipel de Berthier-Sorel, incluant les Îles de la Paix) et stratégies de protections recommandées pour les rives à plus grande valeur biologique. Environnement Canada, Service canadien de la faune.

De Koninck R. 2000. Les Cent-Îles du lac Saint-Pierre: retour aux sources et nouveaux enjeux. Québec: Les Presses de l’Université Laval.

Department of Public Works. 1968. Shore erosion along waterways, navigation versus natural phenomena. Ontario, Canada.

Dickason OP. 1996. Les Premières Nations du Canada. Québec: Septentrion.

Drapeau G. 2007. Dynamique sédimentaire des littoraux de l’estuaire du Saint-Laurent. Géogr Phys Quat. 46(2):233–242.

Drejza S, Bernatchez P, Dugas C. 2011. Effectiveness of land management measures to reduce coastal georisks, eastern Québec, Canada. Ocean Coast Manage. 54(4):290–301.

Drejza S, Bernatchez P, Marie G, Friesinger S. 2019. Quantifying road vulnerability to coastal hazards: development of a synthetic index. Ocean Coast Manage. 181:104894.

Fernández D, Barquin J, Álvarez-Cabria M, Peñas FJ. 2012. Quantifying the performance of automated GIS-based geomorphological approaches for riparian zone delineation using digital elevation models. Hydrol Earth Syst Sci. 16(10):3851–3862.

Finkl CW. 2016. Retreat from a rising sea: hard choices in an age of climate change. J Coast Res. 32(6):1510.

Forbes DL, Taylor RB. 1994. Ice in the shore zone and the geomorphology of cold coasts. Prog Phys Geog. 18(1):59–89.

Fortin P-L. 2010. Développement d’un cadre d’analyse pour l’évaluation de la sensibilité des berges à l’érosion en milieu fluvial: application à la rivière Montmorency, Québec [unpublished master’s thesis]. Québec, Canada: Université du Québec.

Fraser C, Bernatchez P, Dugas S. 2017. Development of a GIS coastal land-use planning tool for coastal erosion adaptation based on the exposure of buildings and infrastructure to coastal erosion, Québec, Canada. Geomat Nat Haz Risk. 8(2):1103–1125.

Gaskin SJ, Pieterse J, Shafie AA, Lepage S. 2003. Erosion of undisturbed clay samples from the banks of the St. Lawrence River. Can. Can J Civ Eng. 30(3):585–595.
Gharbi S, Valkov G, Hamdi S, Nistor I. 2010. Numerical and field study of ship-induced waves along the St. Lawrence Waterway. Nat Hazards. 54(3):605–621.

Gilvear DJ, Black AR. 1999. Flood-induced embankment failures on the River Tay: implications of climatically induced hydrological change in Scotland. Hydrolog Sci J. 44(3):345–362.

Gilvear DJ, Bryant R. 2016. Analysis of remotely sensed data for fluvial geomorphology and river science. In: Kondolf M, Piégay H, editors. Tools in fluvial geomorphology. 2nd ed. Chichester: Wiley; p. 103–132.

Gobeil C, Rondeau B, Beaudin L. 2005. Contribution of Municipal Effluents to Metal Fluxes in the St. Lawrence River. Environ Sci Technol. 39(2):456–464.

Goudie A. 2020. The human impact in geomorphology - 50 years of change. Geomorphology. 366:106601.

Goudie AS, Viles HA. 2016. Geomorphology in the Anthropocene. Cambridge: Cambridge University Press.

Gregory KJ. 2006. The human role in changing river channels. Geomorphology. 79(3–4):172–191.

Greimel F, Schütting L, Graf W, Bondar-Kunze E, Auer S, Zeiringer B, Hauer C. 2018. Hydropeaking Impacts and Mitigation. In: Schmutz S, Sendzimir J, editors. Riverine ecosystem management. Aquatic ecology series, Vol. 8. Cham: Springer.

Grove JR, Croke J, Thompson C. 2013. Quantifying different riverbank erosion processes during an extreme flood event. Earth Surf Proc Land. 38:1393–1406.

Habersack H, Hein T, Stanica A, Liska I, Mair R, Jäger E, Hauer C, Bradley C. 2016. Challenges of river basin management: current status of, and prospects for, the River Danube from a river engineering perspective. Sci Total Environ. 543(Pt A):828–845.

Heitmuller FT, Hudson PF, Asquith WH. 2015. Lithologic and hydrologic controls of mixed alluvial–bedrock channels in flood-prone fluvial systems: bankfull and macrochannels in the Llano River watershed, central Texas, USA. Geomorphology. 232:1–19.

Henshaw AJ, Thorne CR, Clifford NJ. 2013. Identifying causes and controls of riverbank erosion in a British upland catchment. Catena. 100:107–119.

Houser C. 2010. Relative importance of vessel-generated and wind waves to salt marsh erosion in a restricted fetch environment. J Coast Res. 262:230–240.

Jafarnejad M, Pfister M, Bruhwiler E, Schleiss AJ. 2017. Probabilistic failure analysis of riprap as riverbank protection under flood uncertainties. Stoch Environ Res Risk Assess. 31(7):1839–1851.

James TS, Henton JA, Leonard LJ, Darlington A, Forbes DL, Craymer M. 2014. Relative sea-level projections in Canada and the Adjacent Mainland United States; Geological Survey of Canada. Open File. 7737, 72 p.

Jean M, Létourneau G. 2011. Changements dans les milieux humides du fleuve Saint-Laurent de 1970 à 2002. Technical report 511. Monitoring and surveillance de la qualité de l’eau au Québec, Direction générale des sciences et de la technologie, Environnement Canada.

Jeuken MCJL, Wang ZB. 2010. Impact of dredging and dumping on the stability of ebb–flood channel systems. Coast Eng. 57:553–566.

Joyal G, Lajeunesse P, Morissette A, Bernatchez P. 2016. Influence of lithostratigraphy on the retreat of an unconsolidated sedimentary coastal cliff (St. Lawrence estuary, eastern Canada): lithostratigraphy and retreat of unconsolidated coastal cliff. Earth Surf Process Landforms. 41(8):1055–1072.

Kessler AC, Gupta SC, Brown MK. 2013. Assessment of river bank erosion in Southern Minnesota rivers post European settlement. Geomorphology. 201:312–322.

Klemas V. 2013. Airborne remote sensing of coastal features and processes: an overview. J Coast Res. 287:239–255.

Kondolf GM, Schmitt RJP, Carling P, Darby S, Arias M, Bizi S, Castelletti A, Cochrane TA, Gibson S, Kummu M, et al. 2018. Changing sediment budget of the Mekong: cumulative threats and management strategies for a large river basin. Sci Total Environ. 625:114–134.

Krapesch G, Hauer C, Habersack H. 2011. Scale orientated analysis of river width changes due to extreme flood hazards. Nat Hazards Earth Syst Sci. 11(8):2137–2147.
Kumar L, Elliot I, Nunn PD, Stul T, McLean R. 2018. An indicative index of physical susceptibility of small islands to coastal erosion induced by climate change: an application to the Pacific islands. Geomat, Nat Haz Risk. 9, 691–702. https://doi.org/10.1080/19475705.2018.1455749

Lamarche L. 2005. Histoire géologique holocène du lac Saint-Pierre et de ses ancêtres [unpublished master's thesis]. Montréal, QC: Université du Québec à Montréal.

Lastra J, Fernández E, Díez-Herrero A, Marquínez J. 2008. Flood hazard delineation combining geomorphological and hydrological methods: an example in the Northern Iberian Peninsula. Nat Hazards. 45(2):277–293.

Lavoie D. 1994. Diachronous tectonic collapse of the Ordovician continental margin, eastern Canada: comparison between the Quebec Reentrant and St. Lawrence Promontory. Can J Earth Sci. 31(8):1309–1319.

Lawler DM, Couperthwaite J, Bull LJ, Harris NM. 1997. Bank erosion events and processes in the Upper Severn basin. Hydrol Earth Syst Sci. 1(3):523–534.

Lehner B, Grill G. 2013. Global river hydrography and network routing: baseline data and new approaches to study the world’s large river systems. Hydrol Process. 27(15):2171–2186.

Lehoux D, Dauphin D, Grenier C, Melançon M, Lapointe L. 1997. Plan directeur pour la stabilisation des îles fédérales en érosion dans le tronçon Montréal-Sorel. Report submitted to Garde côtière canadienne par Environnement Canada, Service canadien de la faune.

Mallet C, Michot A. 2012. Synthèse de référence des techniques de suivi du trait de côte. Rapport BRGM/RP-60616-FR, 162 p.k.

Mandlburger G, Hauer C, Wieser M, Pfeifer N. 2015. Topo-bathymetric LiDAR for monitoring river morphodynamics and instream habitats—a case study at the Pielach River. Remote Sens. 7(5):6160–6195.

Marcus WA, Fonstad MA. 2008. Optical remote mapping of rivers at sub-meter resolutions and watershed extents. Earth Surf Process Landforms. 33(1):4–24.

Marteau B, Batalla RJ, Vericat D, Gibbins C. 2017. The importance of a small ephemeral tributary for fine sediment dynamics in a main-stem river. River Res Appl. 33(10):1564–1574.

Mattheus CR, Rodriguez AB, McKee BA, Currin CA. 2010. Impact of land-use change and hard structures on the evolution of fringing marsh shorelines. Estuar Coast Shelf S. 88(3):365–376.

Milliman JD, Meade RH. 1983. World-wide delivery of river sediment to the oceans. J Geol. 91(1):1–21.

Montiel-León JM, Munoz G, Vo Duy S, Do DT, Vaudreuil M, Goeury K, Guillemette F, Amyot M, Sauvé S. 2019. Widespread occurrence and spatial distribution of glyphosate, atrazine, and neonicotinoids pesticides in the St. Lawrence and tributary rivers. Environ Pollut. 250:29–39.

Moragoda N, Cohen S. 2020. Climate-induced trends in global riverine water discharge and suspended sediment dynamics in the 21st century. Global Planet Change. 191:103199.

Morin J, Coté J-P. 2003. Modifications anthropiques sur 150 ans au lac Saint-Pierre: une fenêtre sur les transformations de l’écosystème du Saint-Laurent. Vertigo. 4(Volume 4 Numéro 3): 1–10.

Morin J, Leclerc M. 1998. From pristine to present state: hydrology evolution of Lake Saint-François, St. Lawrence River. Can J Civ Eng. 25(5):864–879.

Morneau F, Bourque A, Larrivée C, Audet N. 2014. L’exposition des rives et des zones côtières du Saint-Laurent aux aléas hydroclimatiques. Consortium Ouranos, report submitted to Communauté métropolitaine de Québec.

Morse B, Hessami M, Bourel C. 2003. Characteristics of ice in the St. Lawrence River. Can J Civ Eng. 30(4):766–774.

Murgatroyd AL, Ternan JL. 1983. The impact of afforestation on stream bank erosion and channel form. Earth Surf Process Landforms. 8(4):357–369.
Nilsson C, Reidy CA, Dynesius M, Revenga C. 2005. Fragmentation and flow regulation of the world’s large river systems. Science. 308(5720):405–408.

Nordstrom KF, Jackson NL. 2012. Physical processes and landforms on beaches in short fetch environments in estuaries, small lakes and reservoirs: a review. Earth-Sci Rev. 111(1–2):232–247.

Normandeau A, Lajeunesse P, Trottier A-P, Poiré AG, Pienitz R. 2017. Sedimentation in isolated glaciomarine embayments during glacio-isostatically induced relative sea level fall (northern Champlain Sea basin). Can J Earth Sci. 54(10):1049–1062.

Occhietti S. 2007. Lithostratigraphie du Quaternaire de la vallée du Saint-Laurent: méthode, cadre conceptuel et séquences sédimentaires. Géogr Phys Quat. 44(2):137–145.

Occhietti S, Parent M, Lajeunesse P, Robert F, Govare E. 2011. Late Pleistocene–Early Holocene Decay of the Laurentide Ice Sheet in Québec–Labrador. In: Ehlers, J, Gibbard, PI, Hughes, PD, editors. Quaternary Glaciation - Extent and Chronology: A Closer Look. Developments in Quaternary Sciences, 15. Amsterdam: Elsevier; p. 601–630.

ORRPB. 2019. Questions and Answers – 2019 Spring Flood. Ottawa River Regulation Planning Board.

Ouellet Y, Baird W. 1978. L’érosion des rives dans le Saint-Laurent. Can J Civ Eng. 5(3):311–323.

Panasuk S. 1987. L’érosion actuelle et récente des îles de Varennes dans la région de Montréal. Report submitted to Université du Québec à Montréal.

Pelletier M, El-Fityani T, Graham A, Rutter A, Michelutti N, Zeng DM, Sivarajah B, Smol JP, Hodson PV. 2016. Tracking pesticide use in the Saint Lawrence River and its ecological impacts during the World Exposition of 1967 in Montreal, Canada. Sci Total Environ. 572:498–507.

Petropoulos GP, Kalivas DP, Griffiths HM, Dimou PP. 2015. Remote sensing and GIS analysis for mapping spatio-temporal changes of erosion and deposition of two Mediterranean river deltas: the case of the Axios and Aliakmonas rivers, Greece. Int J Appl Earth Obs. 35:217–228.

Pelletier M, El-Fityani T, Graham A, Rutter A, Michelutti N, Zeng DM, Sivarajah B, Smol JP, Hodson PV. 2016. Tracking pesticide use in the Saint Lawrence River and its ecological impacts during the World Exposition of 1967 in Montreal, Canada. Sci Total Environ. 572:498–507.

Petropoulos GP, Kalivas DP, Griffiths HM, Dimou PP. 2015. Remote sensing and GIS analysis for mapping spatio-temporal changes of erosion and deposition of two Mediterranean river deltas: the case of the Axios and Aliakmonas rivers, Greece. Int J Appl Earth Obs. 35:217–228.

Pettis GE, Nestler J, Kennedy R. 2006. Advancing science for water resources management. Hydrobiologia. 565(1):277–288.

Piégay H, Arnaud F, Belletti B, Bertrand M, Bizzi S, Carbonneau P, Dufour S, Liébault F, Ruiz-Villanueva V, Slater L. 2020. Remotely sensed rivers in the Anthropocene: state of the art and prospects. Earth Surf Process Landforms. 45(1):157–188.

Pintal JY, Provencher J, Piéraluge G. 2015. AIR: Territoire et peuplement - Archéologie du Québec. Montréal: Les Éditions de l’Homme.

Prahala V, Sharples C, Kirkpatrick J, Mount R. 2015. Is wind-wave fetch exposure related to soft shoreline change in swell-sheltered situations with low terrestrial sediment input? J Coast Conserv. 19(1):23–33.

Provencher L, Dubois JMM. 2007. Précis de télédétection. Presses de L’Université du Québec. 4(4):359–402.

Quintin C,Arsenault E, Bernatchez P. 2016. Caractérisation côtière du territoire de la Table de concertation régionale, zone de Québec. Laboratoire de dynamique et de gestion intégrée des zones côtières, Université du Québec à Rimouski. Report submitted to Communauté Métropolitaine du Québec (CMQ).

Rangel-Buitrago N, Anfuso G. 2015. Risk assessment of storms in coastal zones: case studies from Cartagena (Colombia) and Cadiz (Spain). In: SpringerBriefs in Earth Sciences. Cham: Springer International Publishing.

Rangel-Buitrago N, de Jonge VN, Neal W. 2018. How to make Integrated Coastal Erosion Management a reality. Ocean Coast Manage. 156:290–299.

Reid JR. 1985. Bank-erosion processes in a cool-temperate environment, Orwell Lake, Minnesota. Geol Soc America Bull. 96(6):781–792.

Rogers K, Woodroffe CD. 2016. Geomorphology as an indicator of the biophysical vulnerability of estuaries to coastal and flood hazards in a changing climate. J Coast Conserv. 20(2):127–144.
Roland CJ, Zoet LK, Rawling JE, Cardiff M. 2021. Seasonality in cold coast bluff erosion processes. Geomorphology. 374:107520.

Rondeau B, Cossa D, Gagnon P, Bilodeau L. 2000. Budget and sources of suspended sediment transported in the St. Lawrence River, Canada. Hydrol Process. 14(1):21–36.

Rondeau-Genesse G. 2020. Impact des changements climatiques sur les facteurs hydroclimatiques influençant les inondations et les processus d’érosion des berges du tronçon fluvial du Saint-Laurent. Report submitted by Ouranos. Montréal.

Rousséau Y, Biron P, Van de Wiel M. 2018. Comparing the sensitivity of bank retreat to changes in biophysical conditions between two contrasting river reaches using a coupled morphodynamic model. Water. 10(4):518.

Sauvé P, Bernatchez P, Glaus M. 2020. The role of the decision-making process on shoreline armoring: a case study in Quebec, Canada. Ocean Coast Manage. 198:105358.

Scarelli FM, Sistilli F, Fabbri S, Cantelli L, Barboza EG, Gabbianelli G. 2017. Seasonal dune and beach monitoring using photogrammetry from UAV surveys to apply in the ICZM on the Ravenna coast (Emilia-Romagna, Italy). Remote Sens Appl: Soc Environ. 7:27–39.

Scarpa GM, Zaggia L, Manfè G, Lorenzetti G, Parnell K, Soomere T, Rapaglia J, Molinaroli E. 2019. The effects of ship wakes in the Venice Lagoon and implications for the sustainability of shipping in coastal waters. Sci Rep. 9(1):19014.

Schmitt R, Bizzi S, Castelletti A. 2014. Characterizing fluvial systems at basin scale by fuzzy signatures of hydromorphological drivers in data scarce environments. Geomorphology. 214:69–83.

Schmutz S, Moog O. 2018. Dams: ecological impacts and management. In: Schmutz S, Sendzimir J, editors. Riverine ecosystem management. Aquatic Ecology Series, Vol. 8. Cham: Springer.

Sergy G. 2008. The Shoreline Classification Scheme for SCAT and Oil Spill Response in Canada. Proceedings of the 31st Arctic and Marine Oil Spill Program Technical Seminar. Ottawa, ON: Environment Canada. p. 811–819.

Sérodès J-B. 1980. Étude de la sédimentation intertidale de l’estuaire moyen du Saint-Laurent. Report 05D79-00117, Inland Waters Directorate. Québec Region: Environment Canada.

Simon A, Collison AJC. 2002. Quantifying the mechanical and hydrologic effects of vegetation on streambank stability. Earth Surf Process Landforms. 27(5):527–546.

Smeeckaert J, Mallet C, David N, Chehata N, Ferraz A. 2013. Large-scale classification of water areas using airborne topographic lidar data. Remote Sens. Environ. 138:134–148.

Syvitski J, Waters CN, Day J, Milliman JD, Summerhayes C, Steffen W, Zalasiewicz J, Cearreta A, Gályuszka A, Hajdas I, et al. 2020. Extraordinary human energy consumption and resultant geological impacts beginning around 1950 CE initiated the proposed Anthropocene Epoch. Commun Earth Environ. 1:32.

The St. Lawrence Seaway Management Corporation (SLSMC). 2019. Traffic report for the 2019 navigation season. Canada: Great Lakes St. Lawrence Seaway System.

Thorne C, Hey R, Newson M. 2005. Applied fluvial geomorphology for river engineering and management. New York: Wiley.

Thorne CR. 1990. Effects of vegetation on river bank erosion and stability. In: Thorne J, editor. Vegetation and erosion: processes and environments. New York: Wiley; p. 125–144.

Tomsett C, Leyland J. 2019. Remote sensing of river corridors: A review of current trends and future directions. River Res Appl. 35: 779–803. https://doi.org/10.1002/rra.3479

Turner IL, Harley MD, Drummond CD. 2016. UAVs for coastal surveying. Coast Eng. 114:19–24.

van Maren DS, van Kessel T, Cronin K, Sittoni L. 2015. The impact of channel deepening and dredging on estuarine sediment concentration. Cont. Shelf Res. 95:1–14.

Volpano CA, Zoet LK, Rawling JE, Theuerkauf EJ, Krueger R. 2020. Three-dimensional bluff evolution in response to seasonal fluctuations in Great Lakes water levels. J Great Lakes Res. 46(6):1533–1543.
Vörösmarty CJ, Meybeck M, Fekete B, Sharma K, Green P, Syvitski JPM. 2003. Anthropogenic sediment retention: major global impact from registered river impoundments. Global Planet. Change. 39(1–2):169–190.

Vousdoukas MI, Ranasinghe R, Mentaschi L, Plomaritis TA, Athanasiou P, Luijendijk A, Feyen L. 2020a. Sandy coastlines under threat of erosion. Nat Clim Chang. 10(3):260–263.

Vousdoukas MI, Ranasinghe R, Mentaschi L, Plomaritis TA, Athanasiou P, Luijendijk A, Feyen L. 2020b. Reply to: sandy beaches can survive sea-level rise. Nat Clim Chang. 10(11):996–997.

Wang Y, Rhoads BL, Wang D. 2016. Assessment of the flow regime alterations in the middle reach of the Yangtze River associated with dam construction: potential ecological implications: Assessment of Flow Regime Alterations in the Yangtze River. Hydrol. Process. 30, 3949–3966. https://doi.org/10.1002/hyp.10921

Ward JV, Tockner K, Uehlinger U, Malard F. 2001. Understanding natural patterns and processes in river corridors as the basis for effective river restoration. Regul Rivers: Res Mgmt. 17(4–5):311–323.

Ward PJ, Couasnon A, Eilander D, Haigh ID, Hendry A, Muis S, Veldkamp TIE, Winseumis HC, Wahl T. 2018. Dependence between high sea-level and high river discharge increases flood hazard in global deltas and estuaries. Environ Res Lett. 13(8):084012.

Wheaton JM, Brasington J, Darby SE, Sear DA. 2009. Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. Earth Surf Proc Land. 35:136–156.

Williams AT, Rangel-Buitrago N, Pranzini E, Anfuso G. 2018. The management of coastal erosion. Ocean Coast Manage. 156:4–20.

Williams F, Moore P, Isenhart T, Tomer M. 2020. Automated measurement of eroding streambank volume from high-resolution aerial imagery and terrain analysis. Geomorphology. 367:107313.

Winterbottom SJ, Gilvear DJ. 2000. A GIS-based approach to mapping probabilities of river bank erosion: regulated River Tummel. Regul Rivers: Res Mgmt. 16(2):127–140.

Wohl E. 2020. Rivers in the Anthropocene: the U.S. perspective. Geomorphology. 366:106600.

Zaggia L, Lorenzetti G, Manfé G, Scarpa GM, Molinaroli E, Parnell KE, Rapaglia JP, Gionta M, Soomere T. 2017. Fast shoreline erosion induced by ship wakes in a coastal lagoon: field evidence and remote sensing analysis. PLoS One. 12(10):e0187210.