GEOMATICS, NATURAL HAZARDS AND RISK, 2017
VOL. 8, NO. 2, 1103–1125
http://dx.doi.org/10.1080/19475705.2017.1294114

Taylor & Francis
Taylor & Francis Group

OPEN ACCESS

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

Christian Fraser, Pascal Bernatchez and Steeve Dugas

Chair in Coastal Geoscience, University of Quebec in Rimouski, Rimouski, Québec, Canada

ABSTRACT

This study presents the development of a geographic information system (GIS) land-use planning tool for coastal areas based on the calculated exposure to coastal erosion of buildings and infrastructure. Responding to the needs of land-use planners, who are involved in the project from the beginning, this tool facilitates identification of adaptation solutions based on coastal sensitivity to erosion. All buildings, roads, railways, aqueducts, sewer systems, hiking trails and bicycle routes were mapped at high resolution, and an exposure value was assigned to each for seven time horizons between 2015 and 2100. The calculations were based on three parameters: (1) the distance between the structure and the shoreline or coastline; (2) the most likely shoreline or coastline migration rate for each coastal geomorphology behaviour unit (CGBU); and (3) the maximum event retreat measured during a storm for each type of coast. This method was applied to Baie des Chaleurs in Québec, Canada. The area comprises 11 municipalities with a total of 105 km of coast. The approach not only produces current and future portraits of building and infrastructure exposed to erosion, but also provides an original land-use planning and intervention tool for coastal areas.

ARTICLE HISTORY
Received 15 November 2016
Accepted 8 February 2017

KEYWORDS
Adaptation tool; GIS planning tool; coastal erosion; coastal hazards; exposure assessment; vulnerability; knowledge transfer process

1. Introduction

Coastal erosion is a major challenge for many communities around the world (Degbe 2009; Marchand 2010; USGS 2012; Silva et al. 2014; European Commission 2004a; 2004b; Goussard 2014; Jouzel et al. 2015), and climate change, which has affected shorelines for several decades now, exacerbates erosional processes (Zhang et al. 2004; Allison 2009; IPCC 2013). The coasts of Québec have not been spared this trend (Bernatchez et al. 2008; Bernatchez & Fraser 2012; Drejza et al. 2014). Socio-economic stakes associated with this problem means that coastal communities must adapt quickly, even though they lack the tools and knowledge to adequately plan and manage how coastal areas are used (Jude et al. 2006).

In response to this need, several vulnerability studies have suggested that an overall portrait is required to fully grasp the diversity of the stakes and the severity of the issues related to coastal hazards (Thieler & Hammar-Klose 1999; Boruff et al. 2005; Vafeidis et al. 2008; Crowell et al. 2010). These studies can be applied to large-scale regions and can be used to define government policy directions in risk management (Abuodha & Woodroffe 2006; Sterr 2008; Boruff et al. 2005). Nevertheless, it is often difficult for those responsible for community-scale planning to apply the results of

CONTACT Christian Fraser christian_fraser@uqar.ca

these studies, and consequently the results may be of little use for adaptation (Gornitz et al. 1991; Sullivan & Meigh 2005; Sterr 2008 Hinkel 2011; Yoo et al. 2011; Holsten & Kropp 2012). However, Sterr (2008) and O'Brien et al. (2004) have stated that studies covering large areas facilitate the selection of smaller and more tightly defined areas that are more suitable for analysing regional or local-scale vulnerability.

Considering that coastal communities and governments lack the tools to cope with coastal hazards, it is essential that coastal vulnerability research provides concrete support to local coastal management (Preston et al. 2011). As emphasized by Boyer-Villemaire et al. (2014b) and Few et al. (2007), the legal responsibility for risk often reverts to the central government, thereby curtailing local involvement and community-scale initiatives. Nonetheless, it has been demonstrated that the involvement of local authorities is essential for successful adaptation (Jude et al. 2006; Preston et al. 2011; Yoo et al. 2011; Boyer-Villemaire et al. 2014a).

The main objectives of this study are (1) to respond to the need for more knowledge to reduce the vulnerability of communities to coastal erosion, (2) to improve land-use planning for the area and (3) to facilitate the choice of adaptation solutions in the short, medium and long term. The originality of our approach lies in the involving from the beginning of the process the stakeholders of local, regional and provincial governments, who clearly identified their needs through individual meetings and questionnaires, and who provided much of the information needed for our research. Following this survey component, high-resolution data on the exposure of buildings and infrastructure to coastal erosion were generated using geographic information system (GIS) in the study area for seven time horizons from now until 2100. The results are based on a rigorous analysis of coastal dynamics that takes into consideration historical coastal migration from 1934 to 2007, and forecasts of future climate, geomorphological and oceanographic conditions. The final products include maps, technical data sheets and a structured GIS database that provides a concrete and easy-to-use tool for those responsible for land-use planning at the local level. This paper also discusses the involvement of local and regional authorities, the knowledge transfer, the magnitude of coastal erosion issues for local and regional authorities, the high-resolution spatial and temporal analysis, and the exposure to flooding.

1.1. Study area description and selection

To develop our method, we selected an area in Baie des Chaleurs (Figure 1) comprising a total population of 16, 552 inhabitants from 11 municipalities (Institut de la statistique du Québec 2015) along 105 km of coast. The area was selected for the diversity of its coastal systems and for its multiple issues and stakes.

The study area includes eight types of coastal systems and a few artificial sections (harbour and backfill zones). Rocky cliffs, including those with a part of unconsolidated deposits, represent 50% of the total coastline whereas entire unconsolidated cliffs account for 17%. Low lying coasts such as spit, beach terrace and salt marsh account for 29% of the coastline. We observe that 18% of the total coastline is protected by a defence structure, showing the importance of coastal erosion issues. Moreover, 53% of the coastline shows important erosion evidences and 22% are classified as partly stable. Only 7% are considered as stable or with accumulation. Historical shoreline migration rates from 1934 to 2007 vary between −0.03 m/y for beach terraces to −1.44 m/y for salt marshes. Rock cliffs show an average of −0.11 m/y and unconsolidated cliffs vary between −0.2 and −0.66 m/y. Those historical measures are not so significant, but recent measures indicate important local retreats during only one storm event: 8.2 m for unconsolidated cliff; 12.2 m for beach terrace and 17.2 m for sand spit.

Since the Chaleur Bay is relatively narrow (average 30 km width) and has an indented coastline, its shape limits the propagation of strong swell from the Gulf of St. Lawrence. The wave regime at the entrance of the Chaleur Bay is characterized by significant wave height averaging 2.1 m with a

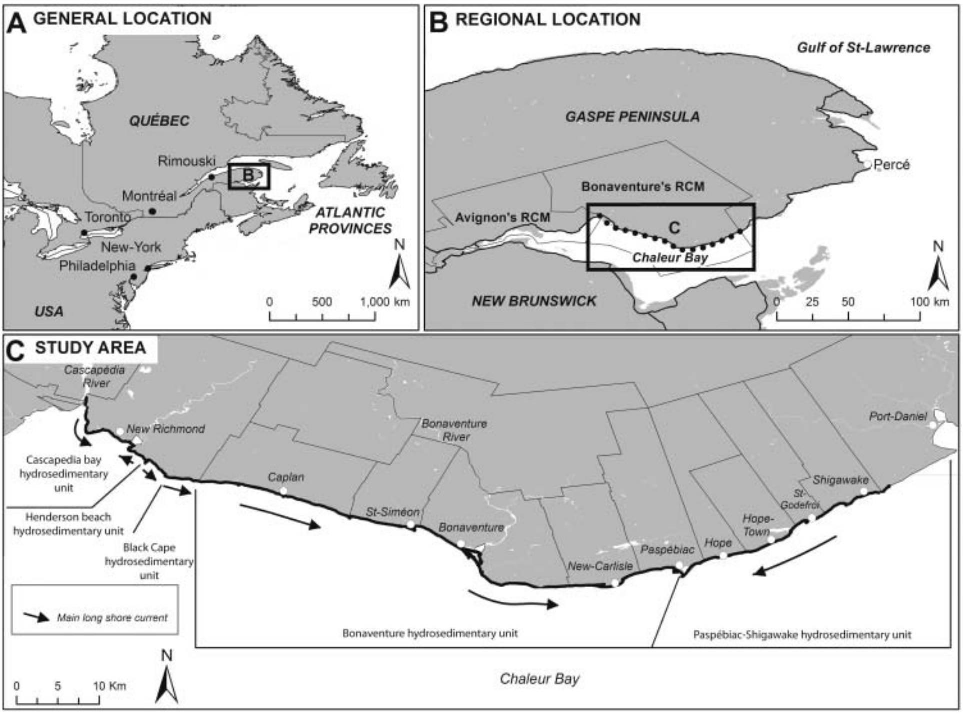

Figure 1. Location of the study area.

period of 9 s (Long 2006). The waves are able to penetrate the bay by diffraction, but they are attenuated on their way to the Bonaventure regional county municipality (RCM) coasts. Eastern part of the study area is more affected by waves whereas western part, in Cascapedia bay, is more sheltered. Despite the fact that the area is sheltered, several storm events have caused coastal flooding over the last decade (Bernatchez et al. 2011; Didier et al. 2015). The main longshore current is mostly eastward while it turns westward in Paspebiac, creating a convergence zone (Figure 1).

The tide in Chaleurs bay is semi-diurnal and tide range slightly increase from east to west due to funnel effect of the bay. Average tide range is thus 1.5 m in Paspebiac and 1.7 m in New-Richmond. During extreme tides, the height of the tide can reach up to 2.3 m in Paspebiac leading to partial flooding of the area's lower coastline.

The area was also selected for the diversity of its issues and stakes (Desmeules & Fraser 2006; Leblanc 2006). Transportation routes (highways and railways) running along the coast are key components of the local and regional economies. The provincial highway is the cornerstone of tourism in the region (Association touristique régionale de la Gaspésie 2015), and the railroad is a major asset for transporting passengers and industrial products (Desjardins et al. 1999). Several segments are already at risk and require significant investments. An issue that affects inhabitants directly on a personal level is residential development (Desmeules & Fraser 2006; Leblanc 2006). According to local authorities, seaside residences are in high demand with buyers, and the market values of these lots and houses are above average for the area. Municipalities thus derive a significant amount of revenue through property taxes. The same applies to the commercial sector where proximity to the coast is an asset in maritime tourism settings (Desjardins et al. 1999). Cultural and heritage issues are also at stake because buildings and historical areas are threatened by erosion (Savard et al. 2013). Given the high number of stakes and their importance, practical tools are needed to guide land-use planning by integrating knowledge on coastal dynamics.

2. Methodology

The methodology presented in the following sections is summarized in Figure 2. The first step was to survey local and regional authorities to make sure the project answers real needs in terms of knowledge and tools and also to develop a common language. Then, the technical steps about (1) coastal characterization, (2) shoreline migration measurements and (3) building and infrastructure mapping have been done to lead to the calculation of the exposure to coastal erosion. Finally, meetings and workshops have been organized for the diffusion and implementation of the tool to local and regional instances.

2.1. *Methodology development, and survey of local and regional municipal authorities responsible for land-use planning and emergency management*

Individual meetings were held with local and regional representatives to present the concept of coastal hazard vulnerability and exposure, and to identify their needs in terms of knowledge and tools in order to help reduce the vulnerability of coastal communities. The survey was conducted between September 3 and 27, 2013. In all, 22 people from tree level of governance (provincial, regional and local) were interviewed and completed a questionnaire (Table 1). At the provincial level, two professionals from two ministries directly involved in risk management and land-use planning have been met (Table 1). At the regional level, the researchers met with land-use planners from the two RCMs involved in the study. RCMs are administrative entities that combine several municipalities. They were set up through Québec's Act Respecting Land Use Planning and Development to primarily oversee land management (Ministére des Affaires municipales, des Régions et de l'Occupation du Territoire du Québec 2009). The majority of the people surveyed (18/22) are directly involved at the local level in the small municipalities. Given the sparse population of the study area, general directors of municipalities and other municipal stakeholders are in direct contact with citizens, and are involved in all development issues and land-use planning in their area.

Coastal hazard vulnerability was defined and discussed at each meeting. Vulnerability is a complex concept (Green & McFadden 2007), that requires a dialogue with stakeholders to build a common language and a common definition. A schematic representation (Figure 3) made the concept easier to understand. In his comprehensive literature review, Adger (2006) summed up vulnerability

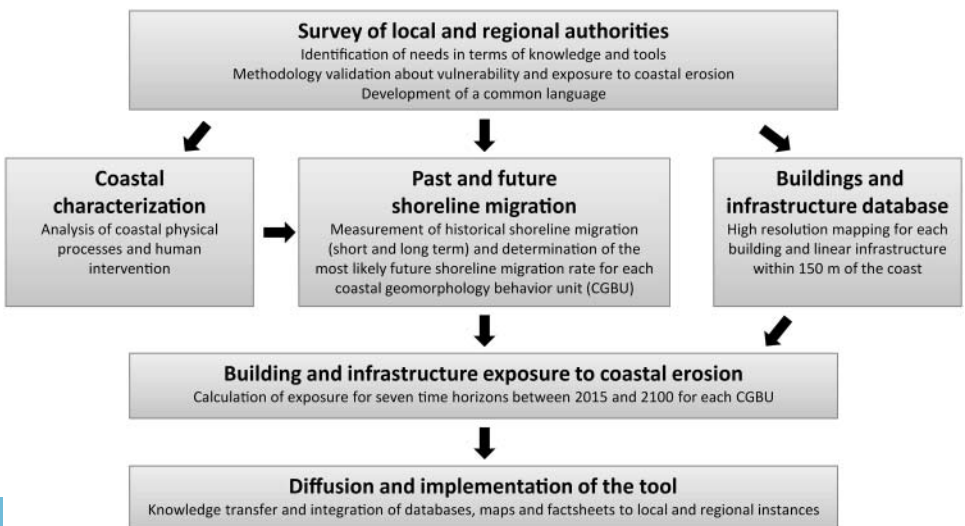

Figure 2. Key steps for the development of a GIS coastal land-use planning tool for coastal erosion adaptation.

Table 1. Position of survey respondents.

Level	Position	Number of people surveyed
Local	Director general of a municipality	11
	Municipal councillor	1
	Municipal inspector	3
	Urban planner	2
	Public works director	1
Regional	RCM land-use planner	1
	RCM land-use planner and director general	1
Provincial	Emergency management professional from the Ministry of Public Safety of Québec	1
	Regional operations councillor from the Ministry of Municipal Affairs and Land Occupancy of Québec	1

as ‘the state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt’. The formula in Figure 3 encompasses all the components of this definition, and is well suited to the coastal hazards of erosion and flooding. The definition of vulnerability to climate change used by the Intergovernmental Panel on Climate Change (IPCC) (McCarthy et al. 2001) also invokes the concepts of exposure to natural hazards and the capacity of systems to adapt. As proposed by Cutter (1996), Klein and Nicholls (1999), and Brooks (2003), ‘social vulnerability is distinguished from biophysical vulnerability’. In our definition, we distinguish natural habitats, built environment and infrastructure stakes, which are tangible and mappable elements directly associated with *physical vulnerability*, from stakes related to land use, human activities, socio-economic and cultural conditions, and modes of governance, which are often intangible elements associated with *social vulnerability*. Although buildings and infrastructure are human constructions and integral components of the social fabric (Cutter et al. 2003), their exposure to hazards can be measured using geophysical criteria. As illustrated in Figure 3, the exposure of stakes to coastal hazards constitutes impacts, which are mitigated by physical and social adaptation measures that reduce vulnerability and increase the resilience or resistance of natural and socio-economic systems (Klein & Nicholls 1999; Sterr et al. 2003). As pointed out by Paul (2013), vulnerability has many discipline-dependent definitions. The definition used herein is appropriate for natural hazards.

Without exception, the survey participants understood and accepted this definition of vulnerability. They also conveyed their opinion that the first step to dealing with coastal hazards in a land-use planning perspective is to improve the level of knowledge on the exposure of physical vulnerability. Analysing the built environment and infrastructure stakes makes it easier to select local-scale adaptation solutions, and then to select target locations for carrying out vulnerability assessments. Priority was given to erosion hazards because coastal retreat leads to irreversible damage. For this reason, the project’s methodological framework focused on assessing the exposure of tangible stakes to erosion hazards. According to local and regional authorities, these stakes are easier to address in practical operational terms for land-use planning purposes.

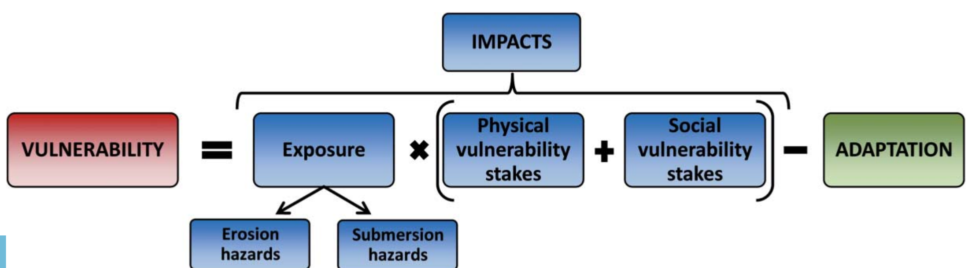

Figure 3. Schematic definition of vulnerability.

2.2. Definition of coastal erosion exposure

Exposure is defined as the nature and degree to which a system experiences environmental or socio-political stress (Adger 2006). In the context of climate change, Fussel and Klein (2006) speak of the exposure to significant climatic variations. For the present study, which focuses on erosion hazards, we define it as the likelihood that a structure (building or infrastructure component) will be affected either by progressive retreat of the shoreline or by sudden retreat during a storm event. Figure 4 shows the formula for calculating exposure. The parameters used to determine exposure are as follows: (1) the distance between the structure and the shoreline or coastline, (2) the most likely shoreline or coastline migration rate, and (3) the maximum retreat event measured during a storm. These parameters were unanimously deemed pertinent by the survey respondents.

The results are presented for seven time horizons between 2015 and 2100 (Figure 5). Horizons 2015 and 2020 represent the current and short-term exposure; 2030, 2040 and 2050 are the medium-term projection, and 2060 and 2100 are the long-term projection.

2.3. Characterization and coastal migration

A detailed characterization of the coast's current state and its migration over time was performed using photo interpretation. The work was based on a method developed by researchers of the Research Chair in Coastal Geoscience at the Université du Québec à Rimouski (UQAR) (Fraser et al. 2012; Bernatchez et al. 2012a, 2012b). A database was also generated to analyse coastal types and states, active coastal processes, types and states of coastal protection (Table 2) (Drejza et al. 2014).

Historical coastal migration was calculated by photo-interpretation using Digital Shoreline Analysis System v. 3.1 in a GIS (Thieler et al. 2005). This software automatically generated transects every 50 m across the shorelines of 1934, 1963 and 2007 (Figure 6). An important step consists in validating the rates obtained for each transect. This manual validation reduces the total maximum error to 0.06 m/yr. (Bernatchez & Fraser 2012; Fraser et al. 2012).

2.4. Future coastal migration scenarios

Future coastal migration scenarios were calculated for homogenous geomorphological zones along the shore termed coastal geomorphology behaviour units (CGBU). CGBUs are subdivisions of

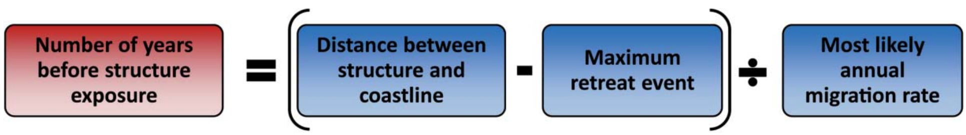

Figure 4. Calculation for evaluating the exposure of a structure (building or infrastructure) to coastal erosion.

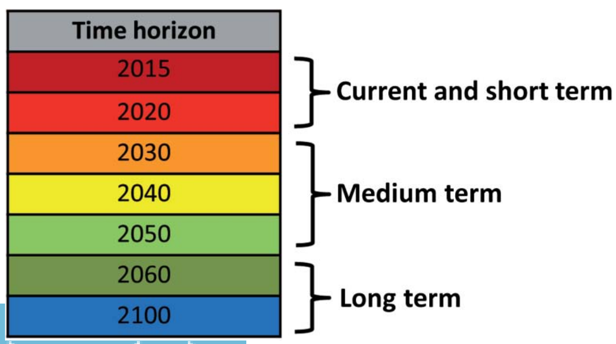

Figure 5. Time horizons used for projections of exposure to coastal erosion.

Table 2. Parameters used for coastal characterization.

Parameter	Variables	Definition
Type of coast	Unconsolidated cliff	High cliff (>5 m) composed of unconsolidated deposits (clay, silt, sand, gravel, shingle, block, etc.).
	Low unconsolidated cliff	Low cliff (<5 m) composed of unconsolidated deposits.
	Unconsolidated cliff with rock base	Cliff composed of unconsolidated deposits superimposed on a rock outcroping making less than half the cliff height.
	Rock cliff	Cliff composed of consolidated rock.
	Rock cliff with unconsolidated top	Cliff composed of consolidated rock topped with unconsolidated deposits making less than half the cliff height and that influences cliff retreat.
	Spit	Narrow sand, gravel or shingle coastal accumulation landform that is tied to the coast at one end. Spits are formed by the longshore movement of sediment and frequently form where the coast abruptly changes direction and often occur across the mouths of estuaries.
	Beach terrace	Sand, gravel or shingle wave-built accumulation landform forming a flat low-lying coast generally covered by plants
	Coastal salt marsh	Fine sediment accumulation coastal zone regularly flooded by the tides and colonized by salt-tolerant plants such as herbs, grasses or low shrubs.
Coastal state	Accumulation	Active beach building processes.
	Stable	No erosion process (>75% plant cover).
	Partly stable	Active erosion processes (25%–75% plant cover).
	Erosion (active)	Active erosion processes. Cliff, low cliff and micro cliff is active (< 25% plant cover).
Type of coastal protection	Rock armor	Shore-parallel assemblage of stones erected on shoreline.
	Sea wall	Vertical or near vertical shore-parallel rigid structure made of wood, concrete or metal and erected on shoreline.
	Groyne	Wood or stone shore-perpendicular structure designed to trap sand from the longshore drift.
	Breakwater	Assemblage of stones erected foreshore to reduce the intensity of wave action on the shoreline.
	Embankment	Artificial bank built over and beyond the shoreline to extend terrestrial land towards the sea.
State of coastal protection	Good	No alteration sign (>75% good).
	Partly damaged	Punctually altered or collapsed (50%–75% good).
	Very damaged	Generally altered (25%–50% good).
	Completely damaged	Structure completely destroyed. No more coastal protection (<25% good).
Active coastal processes	Waves	Wave action on shoreline (low coasts) or on coastline (cliff).
	Flood	Episodic high sea level flooding coastal low lands.
	Drift ice	Sediment movement by drifting sea ice.
	Gelifraction	Rock breaking under freeze-thaw action.
	Surficial slide	Small gravitative movement on a slope.
	Collapse	Vertical rock-fall on a rock cliff surface.
	Ravine	Gully deepening under flowing of rain and snow melt water.
	Suffosion	Cavity formation in a cliff caused by underground water flow at resurgence point.

hydrosedimentary cells characterized by the type of coast and the homogeneity of the coastal migration. They are similar to the cliff behaviour units of Lee and Clark (2002), which represent sections of cliffs with comparable geology and hydrodynamics.

Two scenarios were calculated for each CGBU (Table 3). The most probable scenario was then selected based on our understanding of the coastal dynamics and forecasted climate scenarios (Bernatchez et al. 2008). Measurements could not be taken where human actions modified the coast of a CGBU (e.g. if backfill or a harbour was added at any point in time, or if defence structures were present throughout the period of analysis). Moreover, if aerial photographs were missing or the distortion was too severe, no measurements were taken and no scenarios were developed.

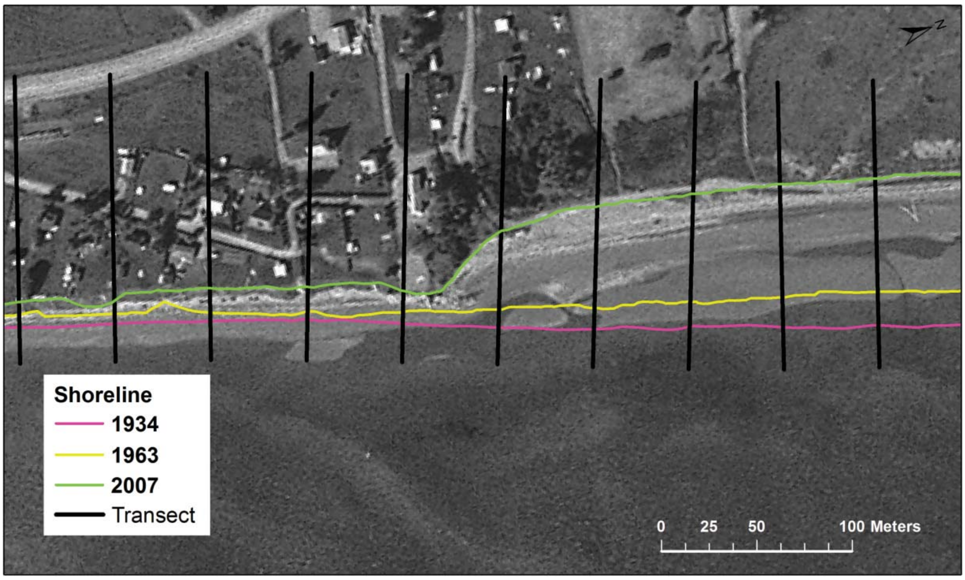

Figure 6. Example of coastal migration measurement.

2.5. Measured and anticipated retreat event

The retreat event is the maximum retreat measured during a storm event for each type of coast. The values are based on measurements taken at coastal erosion monitoring stations established along the shore since 2005 by the UQAR Laboratory of Dynamic and Integrated Management of Coastal Zones (Bernatchez & Drejza 2015). In the Baie des Chaleurs, based on 481 monitoring stations, retreat values measured after storm events range from 3 m along rocky cliffs to 17.2 m on spits. Retreat event values are important to integrate to the annual migration rate because it represents the distance below which a residence or any kind of infrastructure could be affected by a single storm event.

For some rocky cliffs, a maximum notch value, measured in the field, was also added. Notches are created by wave action at the base of cliffs (basal notches) (Figure 7), or by weathering or hydrogeological processes acting on the more friable layers of a rock face (summital or mid-cliff notches).

2.6. Data processing for buildings

All buildings in the study were treated in a GIS (ArcView 9.2) as single-point structures. In Québec, buildings and land lots are assigned property values that are updated regularly, and this information is available from the Ministry of Municipal Affairs and Land Occupancy. The province's municipal assessment roll for 2010 was used to create an inventory of all buildings, their functions and their assessed values. Using aerial photographs from 2007, each centroid point falling within 150 m of the coast was shifted to the sea-facing side of the building, at a scale of 1:600. Oblique images, taken from a helicopter in September 2010, were also used to obtain better accuracy and to spatially

Table 3. Definition of shoreline projection scenarios.

Coastal migration scenario	Definition
Scenario 1	Average of all migration rate measurements (positive, negative or nil) for a CGBU during the longest period.
Scenario 2	Average of all retreat rates (excluding positive or nil migration rates) for the most intense period of retreat. Therefore, Scenario 2 represents an accelerated rate of coastal erosion compared to the historical average.

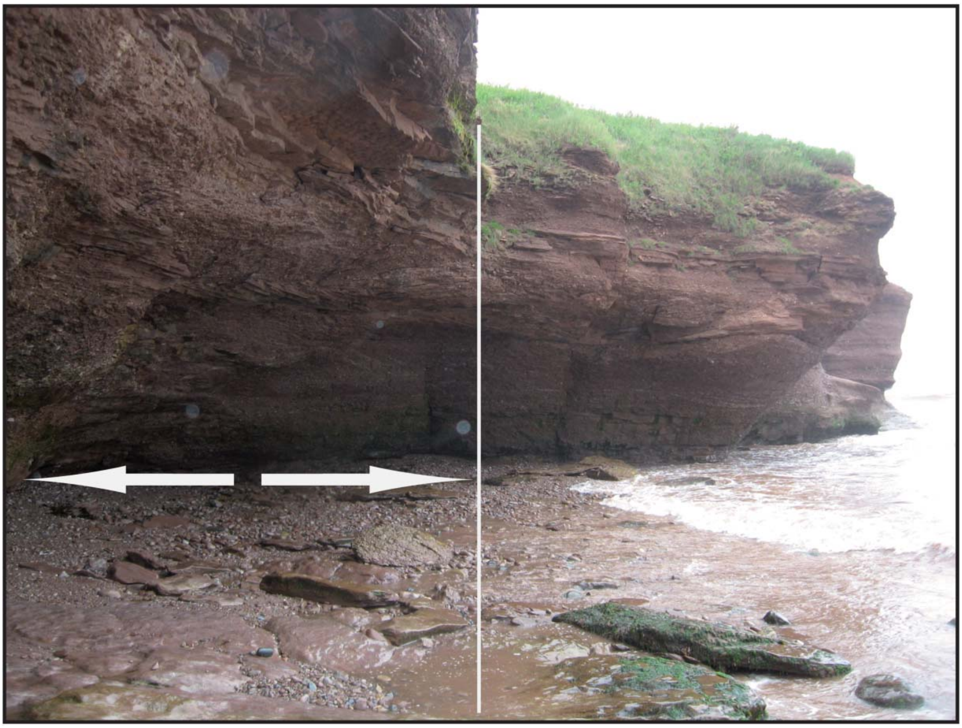

Figure 7. Example of a basal wave-notch measurement.

position the database information. Each building's identification and function was validated against the Digital Cadastral Database provided by the regional administration (i.e. the RCM). Field verifications were also necessary for some zones to ensure the centroid of the property matrix was matched with the right building. The exposure calculation was performed for each building.

Building values do not include reconstruction costs, and we did not evaluate current or future market values. Moreover, the values do not include the cost of rebuilding or repairing defence structures. Property values, which do take into account actual market values, were used to provide an idea of overall worth. We consider the building values used in this study to be minimum values.

2.7. Data processing for linear infrastructure

The linear infrastructure considered in this study comprises the provincial and municipal roads, the aqueduct and sewer systems, the railway, and the hiking trails and bicycle paths. Using aerial photographs from 2007, sea-side infrastructure was digitally traced in a GIS (ArcView 9.2) by the project team. Where the information could not be obtained from these aerial photographs for the case study, they were provided by the Bonaventure MRC. Once validated with local land-use planners, these features were divided into 10-m segments. The segments were automatically generated using a function in ArcGIS. The exposure calculation was performed for each segment.

Construction and replacement values for linear infrastructure are not uniform along their traces; the characteristics and constraints vary from segment to segment, influencing the cost. Moreover, there are several types of roads, ranging from secondary unpaved roads to highways. It was decided that for the purposes of this study, roads would be divided into two categories: provincial and municipal. The objective is to provide a reasonable idea of the economic importance of each type of infrastructure. To obtain realistic values, we called upon the expertise of representatives from the provincial ministries and specialized private contractors.

2.8. Coastal defence structures

Unlike vulnerability assessments, which take into consideration adaptation solutions, exposure projections do not account for existing coastal defence structures. Likely migration rates are based on the historical coastal migration of a CGBU, whether or not it was protected by defence structures. Thus, it is possible that our calculations could identify buildings or infrastructure actually in a protected zone as exposed in the short, medium or long term. The real date at which exposure will occur depends on the quality and maintenance of the structure. This approach was adopted for the following three reasons:

(1) it is not possible to know beyond a reasonable doubt the degree to which existing defence structures are maintained, or what structures will be built in the future;
(2) even if the infrastructure considered exposed is not affected within the given timeframe because defence structures are present, this information calls attention to the importance of preserving the structures, which is in turn useful for land-use planning in the area; and
(3) defence structures, even those that are recent and solidly constructed, can be affected by event retreat. As observed during the event of 6 December 2010, in Eastern Québec (Quintin et al. 2013), a single storm can completely destroy parts of seawalls and rock armour. While some structures might be repaired or rebuilt, others are abandoned, leaving the coast to retrieve its natural profile. Event retreat is thus taken into consideration in the calculations for all CGBUs with defence structures.

3. Results of the survey of local and regional municipal authorities responsible for land-use planning and emergency management

Questionnaires were used to find out what would make land management easier in areas faced with coastal hazards. The answers were used to guide the development of our land-use planning tool. All respondents (22/22) answered 'no' to the question, 'Is your community well-enough equipped to adapt to coastal hazards?' The lack of tools thus extends to both the local and regional scales.

3.1. Types of tools

When questioned about the type of tools needed, 9 out of 22 respondents wanted a regulatory tool (Figure 8). The regulatory tool most mentioned was the implementation of erosion-risk zoning. However, respondents were of the opinion that a regulation alone would not be enough, and more than half (12/22) answered that they need a reference tool.

The reference tools mentioned by the respondents included high resolution coastal migration mapping, access to coastal databases (sensitivity, vulnerability, risk, uses, etc.) and availability of substantive scientific studies that are locally relevant. They felt that such tools would provide them with a firm understanding of the coastal erosion phenomenon in their area, thereby improving their ability to plan, act and inform the public. The tool developed by the present study meets this need and goes a step further by providing future projections. Some respondents also mentioned training and raising awareness, setting up a field laboratory to test protection methods and a development plan that takes coastal evolution into consideration.

3.2. Usefulness of the tool

When asked about the functional purpose for which they would use a tool that measures the exposure of the built environment, respondents answered that the tool would be used to plan land development (16/22), to inform citizens and raise awareness (10/22), and to help develop and apply regulations (9/22) (Figure 9). At the local level, decision-makers face pressure from people to

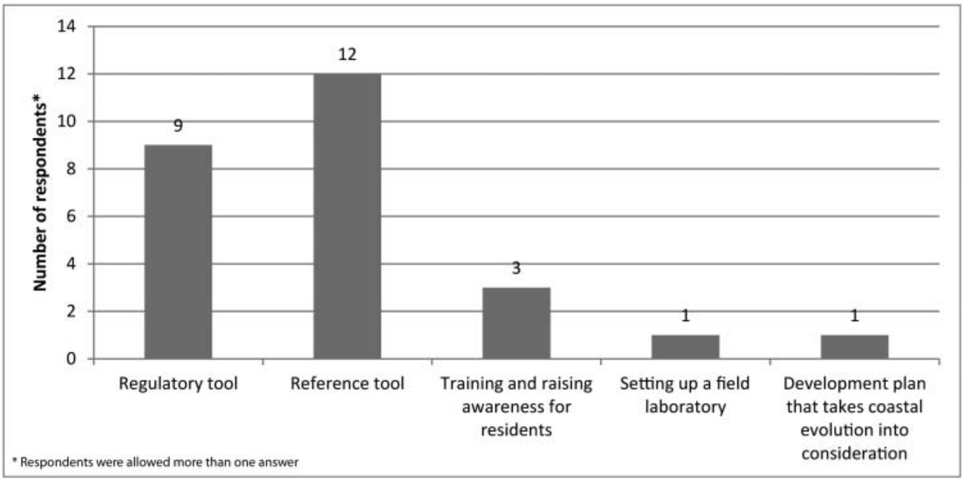

Figure 8. Answers to the question: 'What kind of tool would you need to help you choose the best adaptation solution for coastal erosion and flooding, and to improve land-use planning in the context of climate change?'.

develop the land along the coast. A tool based on scientific data would greatly facilitate their work, allowing them to rely on objective data and properly inform citizens. The tool would thus directly respond to an identified need and, coupled with a regulatory tool, would provide a solid framework for medium- and long-term development projects.

3.3. Diffusion and implementation of the tool

It is important, even crucial, to develop tools that promote communication between members of a community (Jude et al. 2006). Therefore, our tool must appeal to the community members who are involved in coastal management if they are to benefit from the information contained in the database (Jude et al. 2006; Johnston et al. 2014). The majority of the respondents involved in small rural

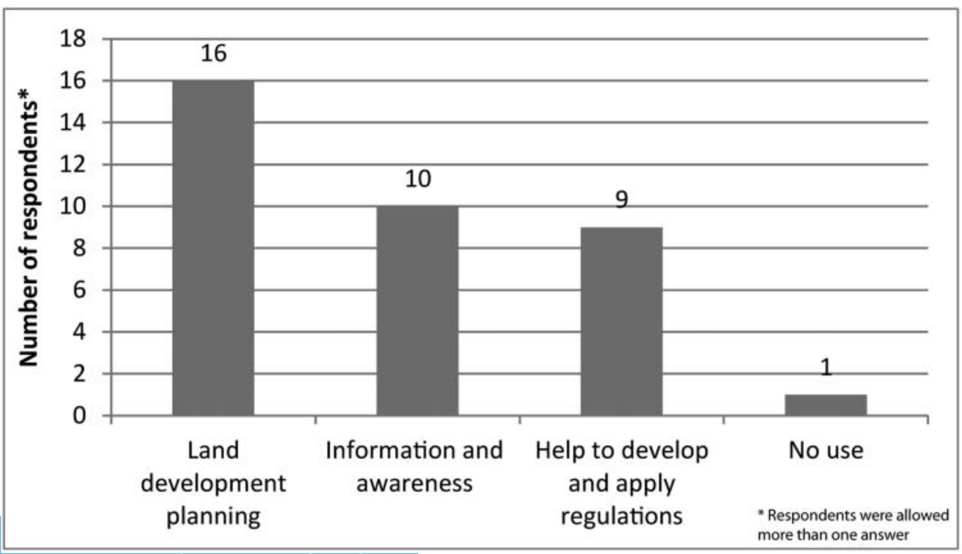

Figure 9. Answers to the question: 'For what functional purpose would you use a building and infrastructure exposure tool?'.

municipalities do not have the necessary equipment or training to use GIS software. Most of the respondents (19/22) indicated that a Web-based application would be ideal for navigating the database and for consulting the cartographic information. Much effort has gone into developing such tools for natural hazard management and prevention in recent years in order to facilitate the elaboration of emergency evacuation plans (Chakraborty et al. 2005; Szlafsztein & Sterr 2007; Tate et al. 2010; Le Cozannet et al. 2014) or as a means of risk visualization and communication (Brown et al. 2006). This option would also allow data to be updated from a single source. The Web platform for this study is still being developed at the time of publication. So that information is accessible in the meantime, exposure maps were produced at a scale of 1:5000 and sent to each municipality. For RCMs with GIS software, the numerical data were transferred and assistance was provided to help integrate the data into their system.

3.4. Fact sheets

Short-, medium- or long-term exposure provides factual information and identifies intervention priorities, but it cannot guide adaptation strategies without in-depth knowledge of coastal dynamics. Almost all respondents (21/22) do not have access to coastal databases (types of coast, retreat rates, sensitive zones, etc.), and some (9/22) never had ready access to studies on coastal dynamics. Therefore, it was suggested that an easy-to-understand fact sheet be prepared for each problem area, documenting coastal dynamics and local particularities (Figure 10). Land-use and urban planners would thus have all the necessary information to understand infrastructure exposure, and would be in a position to properly assess the situation and determine the best land management approach.

4. Case study

The method was applied to the Bonaventure RCM in the Baie des Chaleurs area (Figure 1). In all, 76 maps at a scale of 1:5,000 and 28 fact sheets were produced. Over a total length of 105 km of coast, our assessment indicated that 5.8 km of linear infrastructure and 72 buildings were exposed in the short term (from now until 2020), representing a value of $19 million (Canadian dollars) (Table 4). In the long term (from now until 2100), the numbers rise to 33.3 km of linear infrastructure and 310 buildings for a value of $47.4 million.

The maps show the locations of exposed features, as well as the type and state of coastal defence structures. Building and infrastructure exposure is indicated for the seven different time horizons using the colour code presented in Figure 5. Fact sheets were prepared for sectors with high concentrations of features to provide additional information on the coastal dynamics of the area and local particularities (Figure 10). Some examples are shown in Figure 11.

The GIS database can present the results for an RCM, a municipality or a CGBU. Figure 12 provides such an example, and shows the length of exposed road for each municipality. Moreover, it is possible to identify the type of building or linear infrastructure (main road, secondary road, aqueduct system, sewer system, bike path, etc.), as well as the value of each exposed feature. This type of portrait quickly identifies critical problem areas, and those that will be problematic in the medium to long term.

5. Discussion

This study provides a procedure for determining the current and future exposure of features to coastal erosion, thereby responding to a need identified by coastal communities. The exposure calculation incorporates event retreat and the most likely migration rate of the shoreline or coastline using a GIS. The credibility of the tool relies heavily on the quality of the exposure calculation, and

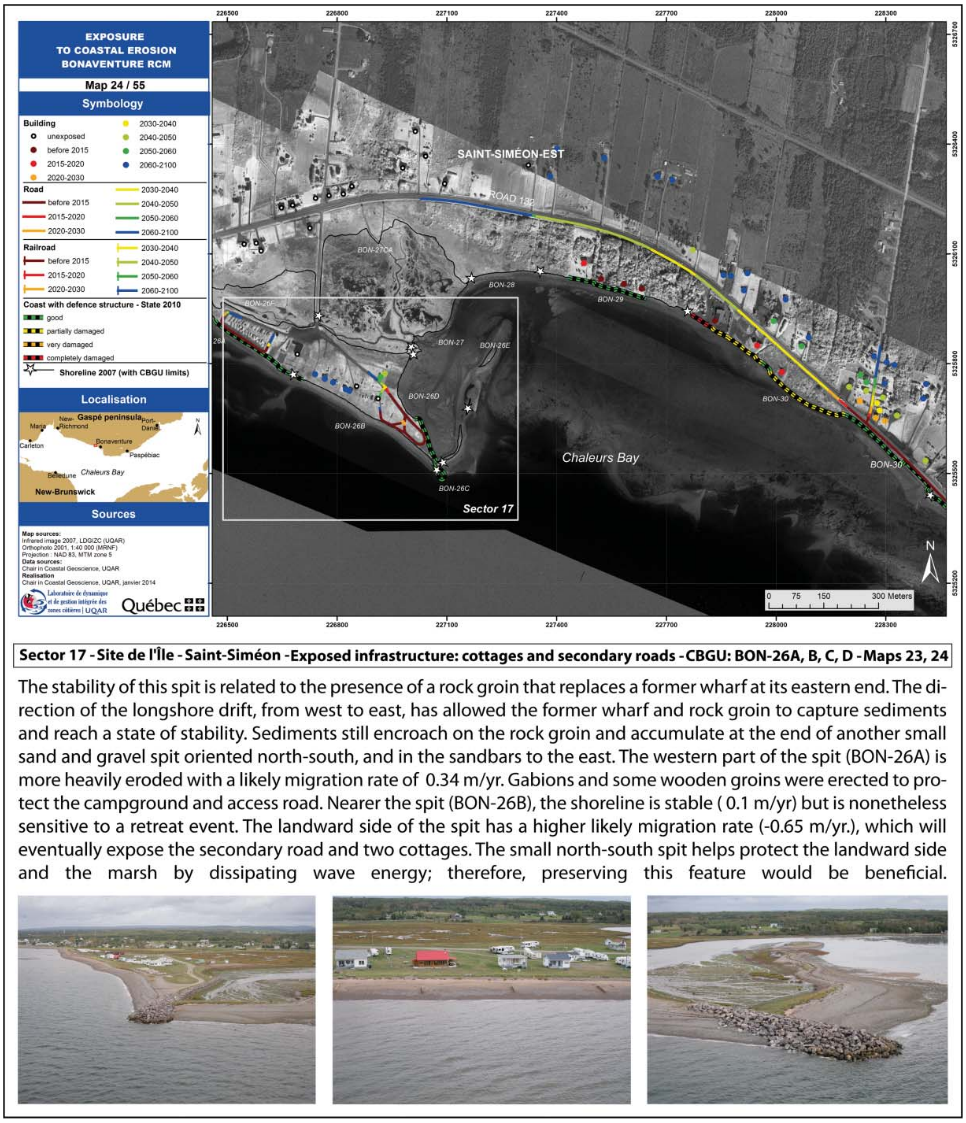

Figure 10. Example of a map of buildings and infrastructure exposed to coastal erosion, along with a fact sheet for part of the Bonaventure RCM.

Table 4. Overview of exposed infrastructure for the Bonaventure RCM.

	2020 - Short term			2050 - Medium term			2100 - Long term		
Type of infrastructure	Length (km)	Number	Value (CAN $M)	Length (km)	Number	Value (CAN $M)	Length (km)	Number	Value (CAN $M)
Buildings	n/a	72	3.8	n/a	161	8.6	n/a	310	18.8
Roads	8.3	n/a	9.4	12.4	n/a	14.0	15.9	n/a	17.8
Aqueducts and sewers	5.6	n/a	5.3	6.9	n/a	6.6	7.9	n/a	7.4
Railway	0.8	n/a	0.5	2.8	n/a	1.7	5.5	n/a	3.4
Recreational paths	1.0	n/a	0.01	2.5	n/a	0.01	4.0	n/a	0.02
TOTAL	15.8	72	19.01	24.6	161	31.01	33.3	310	47.42

Note: Values are cumulative over time

Figure 11. Examples of exposed features in different coastal settings: (A) commercial building – rock cliff; (B) primary residences – rock cliff; (C) railway – unconsolidated cliff with rock base; (D) provincial highway, aqueduct and sewer system, and stores – low unconsolidated cliff with rock armour; (E) commercial buildings (motel) – beach terrace; and (F) warehouse, campground facilities and aqueduct – spit.

thus on the method for establishing the projected likely rate. But the optimal use of the tool and the integration of scientific results of the exposure assessment in the land planning depend on the involvement from the beginning of the process of local and regional authorities (Nguyen et al. 2016). Aspects of the methodology are discussed below, and the advantages and limitations of this approach are also presented.

5.1. Involvement of the local and regional authorities, and knowledge transfer

The involvement of land-use and urban planners in research on coastal hazard vulnerability is vital when the overall goal is knowledge transfer and functional applications in the field (Hinkel 2011; Gorokhovich et al. 2014). According to Boyer-Villemaire et al. (2014a), research and planning projects should always include a mechanism of active community involvement to reduce vulnerability and increase resilience. Unfortunately, there is often a lack of participation by stakeholders in processes aiming to determine and map climate change vulnerability (Preston et al. 2011). Several vulnerability indexes were developed by scientists without any participation from local communities

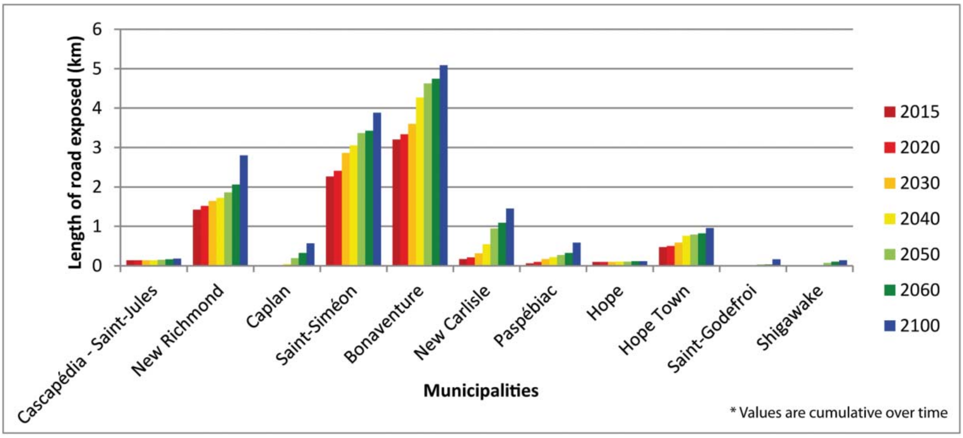

Figure 12. Length of road exposed to coastal erosion from now until 2100.

and regional organizations (Thieler & Hammar-Klose 1999; Boruff et al. 2005; Vafeidis et al. 2008; Crowell et al. 2010). Yet, the reality of the situation can be very different from one region to another (Gornitz et al. 1991; Sterr 2008; Hinkel 2011; Yoo et al. 2011; Holsten & Kropp 2012). In Québec, the perceptions of risk and environmental change are remarkably different among five surveyed regions (Friesinger & Bernatchez 2010). Therefore, it is desirable that the weight assigned to each indicator when developing an index be vary depending on the local and regional situations (Yoo et al. 2011). Hinkel (2011) even concluded that indexes based on indicators are only suitable at local scales where systems have been precisely defined.

With this in mind, we established a relationship with the people responsible for local and regional land-use planning. First, the use of a common language is important from the beginning. The meaning of the words is not necessarily the same for all stakeholders especially for such a complex concept that vulnerability (Green & McFadden 2007). Meeting with these people right from the start of the project allowed us to properly identify their needs, thereby ensuring the applicability of our research at the local level. Stakeholders have identified the exposure as being the component to quantify initially in a vulnerability assessment approach. Mapping the exposure of physical issues is perceived as an objective and tangible approach when planning land use according to coastal hazards in itself constitute an effective adaptation measure.

Zoning hazards is generally seen as an excellent preventive measure to reduce future risks (Mahendra et al. 2011; Roy and Ferland 2014). This measure is usually implemented in a top-down approach from central government to local governments. According to local actors, the exchange of knowledge, as a measure deployed alone, is not sufficient to reduce vulnerability. This has also been observed elsewhere in Eastern Quebec where the implementation of zoning and land use regulations in the 1980s was not able to limit the number of buildings at risk in the coastal zone (Drejza et al. 2011). These results show the importance of developing a strategy to communicate the risks, but also to establish a close collaboration between the different actors. Discussions also yielded information on their level of understanding of natural processes, the impacts, and the related issues and stakes, in addition to learning about their adaptation and emergency measures, and their mode of governance. This information sheds light on the specifics of the local setting that will need to be considered in a vulnerability assessment. Moreover, Yoo et al. (2011) assert that local sensitivity to climate change is better defined when local stakeholders are involved in the survey process. Co-construction could thus be an interesting approach to ensure that research results are actually used, particularly in the field of climate change and natural risk adaptation. Aubé and Zaiem (2013) conclude that the co-construction approach allowed key stakeholders in the region to work together and develop a broader and more inclusive vision of the problems and the adaptation measures.

Moreover, municipalities will be more likely to share between them their challenges and ideas on climate change adaptation, and will be more willing to adopt a regional adaptation approach. The lessons learned from our experience show that the integration of stakeholders from different levels of government (local, regional and national) in the process allows increasing the level of trust in each and to better understand the role and contribution of each organization in reducing the vulnerability of coastal communities, which can promote the development of more efficient adaptation strategies (Juhola & Westerhoff 2011).

To complement stakeholder involvement, it is essential to follow through with knowledge transfer (Sheate & Partidario 2010; Lemos 2015), but also integration. Many studies emphasize the importance of knowledge transfer, but this alone is insufficient (Dagenais et al. 2013). It is important to work directly with people at the local level and integrate the research results in usable format, not simply transfer them. This is even more important when a GIS is used, especially by identifying, in the beginning of the project, the digital format used by municipalities. Follow-up and providing assistance help ensure the data are actually used. The discussions that were held with local and regional representatives revealed that access to relevant scientific studies adapted to local condition is essential for land-use planners. During the present study, once the tool had been developed, we met with all municipal, RCM and ministry representatives involved in the project to provide technical support and to ensure the data had been properly integrated into their databases. Despite the usefulness of GIS for land management, not all municipalities can afford this geomatics specialty. As we have seen above, more than 86% of respondents have identified that the development of a GIS-WEB platform would be a relevant tool for coastal risks management and prevention and would increase access to digital data.

5.2. Magnitude of the coastal erosion issue for local and regional municipal authorities

Tools that assist with coastal erosion management have good applicability only if the problem is already known to local authorities from the outset (Jude et al. 2006; Gorokhovich et al. 2014). Our individual meetings with 22 representatives involved in land-use planning helped us understand the degree to which the problem affected the study area at the local and regional levels. The results demonstrated that the stakeholders are aware of the coastal erosion problem and already pay it a great deal of attention. Twenty of the 22 respondents confirmed that coastal erosion affects their territory, and 85% of them have noticed an increase in the severity of erosion over time. Moreover, these same respondents stated that storm waves have an adverse impact on their territory, and three quarters of them have noticed an increase in the number of storm event. The same proportion of respondents has noticed a thinning of sea ice cover, which is known to exacerbate coastal erosion (Bernatchez et al., 2008). These observations agree with the findings of two studies that confirm that coastal residents in the Baie des Chaleurs are generally aware of the coastal erosion problem and are fairly knowledgeable about its causes (Friesinger & Bernatchez 2010; Boyer-Villemaire et al. 2014b). Thus, coastal erosion is currently a high-priority issue for coastal communities and stakeholders. The respondents also listed the following types of infrastructure that are affected by coastal hazards (in order of importance): roads, municipal infrastructure, cottages, historical buildings and residences (Figure 13).

This awareness of both the issues and processes is also prevalent among citizens. Friesinger & Bernatchez (2010) surveyed 232 coastal residents in Eastern Québec, 59 of which were in Baie des Chaleurs, and found that the respondents were generally very familiar with the coastal erosion process and its causes.

5.3. High-resolution spatial and temporal analysis

As pointed out by Klein and Nicholls (1999), and by Sterr et al. (2003), assessments of coastal vulnerability always begin with an in-depth study of the physical conditions of the natural

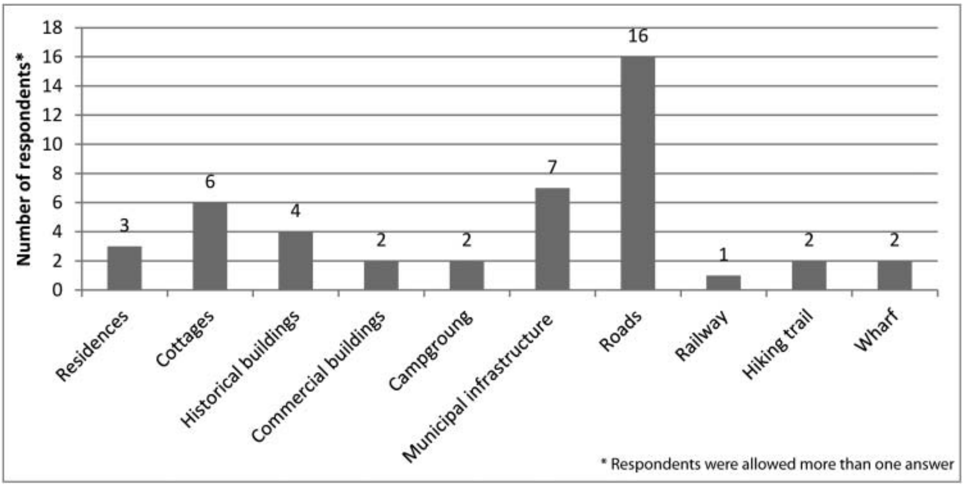

Figure 13. Answers to the question: 'What types of infrastructure are affected by coastal erosion and flooding?'.

environment. Vulnerability assessments based on approximate or interpolated data can be useful for raising public awareness (Johnston et al. 2014), but are rarely useful for land management and adaptation purposes (Holston & Kropp 2012). High-precision historical coastal migration measurements and high-quality future projections are essential for implementing adaptation measures. Low-precision studies over large areas provide a general overview of the issue, but do not yield concrete solutions for local-scale problems (Hinkel 2011; Sterr 2008). Thus, it is important to provide accurate data that can be used to implement effective adaptation measures (Gorokhovich et al. 2014; Sterr 2008).

The method used for georeferencing the shoreline and calculating the coastal erosion projections minimizes the total maximum error to 0.06 m/yr. The exposure calculations were thus very accurate. Segmentation of the coast into CGBUs (251 in all, with an average length of 420 m) allowed us to take into account all the local variables that could affect the sensitivity of the coast. Thus, the likely migration rate that was used to predict the future shoreline was very representative. Exposure was also based on existing buildings and infrastructure and not on a buffer zone, which allowed each component to be treated separately and assigned its own exposure value. Each single-point structure and each 10-m segment of linear infrastructure were individually entered into the database. This aspect of the methodology is an advantage in terms of future database updates.

A similar approach based on infrastructure type was developed by Johnston et al. (2014) for sea level rise scenarios. The authors found that, for the purposes of raising public awareness, high-precision data was not necessary, as long as the data limitations are recognized. While it is true that the high level of precision in the present study is not critical for the purposes of public awareness, the tool we developed has broader usefulness and goes further in assisting with the development of concrete and functional land-use plans. Also, without in-depth knowledge about the evolution of a given coastal setting, it is difficult to convince local and provincial stakeholders to invest in an adaptation strategy. Moreover, discussions with and survey of local and regional authorities during this study confirmed the lack of accurate, reliable and accessible data on the region's coastal evolution.

While spatial scale is important for adaptation purposes, temporal scale is essential for those involved in land management. According to Horstman et al. (2009) and Few et al. (2007), long-term climate change projections applied to large regions tend to promote a broader and long-lasting vision to combating coastal issues. The lack of long-term projections often leads to small-scale, short-term solutions that amplify erosion problems (European Commission 2004a). Nevertheless, for the majority of cases, local development plans rarely exceed 15 years (Few et al. 2007) and are often imposed or structured by the central government.

The discussions with local and regional representatives during the present study confirmed it is very difficult, if not impossible, to develop or implement long-term development or management plans. Fifty- or 100-year climate change forecasts for coastal migration projections are of little use for those involved in land management, and even less so for elected decision-makers, who must operate within a very short electoral timeframe. Thus, projections should be made for multiple time horizons (in this study, seven between 2015 and 2100) to make it easier to prioritize intervention areas and plan short-, medium- and long-term adaptation solutions. Furthermore, Few et al. (2007) point out that for some coastal management issues, it is possible to adopt a long-term precautionary approach that simultaneously responds to short-term needs. The use of a GIS makes it easier to modulate the time scale according to the needs of the stakeholders involved in coastal management, but also to work at different spatial scales when the database has a fine resolution (McLaughlin & Cooper 2010). Thereby, cartographic results produced with GIS at different spatial and temporal scales can also be used to raise awareness of coastal risks not only for the population but also for decision-makers.

5.4. Application of the approach elsewhere

The approach presented in this study was the subject of a research project funded by the Government of Québec in the context of the implementation of a risk management process. Of course, such a detailed approach over a large territory entails significant costs. In addition, as explained in Section 5.3, high-resolution studies require considerable effort and specific expertise in the fields of coastal geomorphology, geography, geomatics and social sciences. In the case of our project, the benefits are significant in the medium and long term because proper coastal planning will anticipate problems and potentially avoid the high costs related to emergency interventions. However, even with the best intentions and the best project, the developed tools will not be useful if the local and regional actors as well as the different levels of government do not participate in the process from the beginning. Co-construction is the key to ensuring operational results. So we highly recommend following those essential steps to carry out a similar process successfully in another territory (see also Figure 2):

- build a research team that includes expertise in coastal geomorphology, geography, geomatics and social sciences;
- identify needs for adaptation to coastal erosion with local and regional actors through targeted interviews;
- propose a tool well suited to their needs;
- justify the need for the tool at all levels of government in order to obtain adequate funding and to ensure optimal use of the tool;
- develop the tool ensuring a high-resolution analysis;
- disseminate and transfer the results of the study to local and regional actors and ensure a good integration of the tool in each organization.

5.5. Exposure to flooding

The assessment presented in this paper only concerns the hazard of coastal erosion. A similar assessment on the exposure to flooding is also in high demand. The majority of the people responsible for land management involved in this study (16/22) mentioned flooding issues in their territory. In fact, nearly one-third of the coast in the study area consists of low-lying areas that experience flooding (beach terraces, spits, saltwater marshes and some low cliffs). The severity of the flooding hazard will only increase over time due to the subsidence of the southern Gaspé region (Koohzare et al. 2008) and rising sea levels (IPCC 2013; Horton et al. 2014). This highlights the need for a detailed assessment of flooding along Québec's maritime coasts so that development and management can take into consideration all types of coastal hazards. Moreover, defence structures that were erected to reduce coastline retreat often have the opposite effect of increasing the flooding risk, which also emphasizes the importance of incorporating all types of hazards in an assessment. Such a study is underway, and methods that take into account several geomorphological and anthropogenic factors (Bernatchez et al. 2011), as well as runup (Didier et al. 2015), will be used to define setback distances and assess the exposure of buildings and infrastructure to flooding.

6. Conclusion

Scientific research is often criticized for not responding to the expressed needs of local management officials and the communities. This study is an example of research applied to land-use planning that not only yielded scientific data, but also provided, by integrating from the beginning of the process the needs of local communities, a functional tool that can be used by land use managers. The main objectives of this study were (1) to respond to the need for more knowledge to reduce the vulnerability of communities to coastal erosion, (2) to improve land-use planning for the area and (3) to facilitate the choice of adaptation solutions in the short, medium and long term. The first objective has been reached in producing a lot of knowledge about coastal dynamics at local scale. The coast has been studied with great details (recent characterization and historical evolution) enough to understand how each system works and how we can intervene in respect to specific coastal dynamics. The second objective has also been reached by the mapping of buildings and infrastructure exposition to coastal erosion from now until 2100. Critical problem areas are thus quickly identified, as well as those that will be problematic in the medium to long term, thereby allowing preventive measures to be implemented. This makes it easier to develop land management plans and elaborate adaptation solutions before the problem becomes too great to tackle. The third objective has been partly reached. Obviously, the study of coastal dynamics combined with buildings and infrastructure exposition to coastal erosion can help to guide the choices of interventions, but no specific solutions have been suggested yet by the research team. Recommendations for each problematic sector will be done in a further step through a multidisciplinary scientific committee.

This assessment of infrastructure exposure to coastal erosion constitutes a first step in a study on the overall vulnerability of coastal communities facing coastal erosion. The collaboration established during the study will allow us to jointly develop an original process applicable to assessing community vulnerability and resilience to coastal hazards and to lead to implementation of sustainable adaptation measures taking in account social and physical vulnerability in addition to coastal ecosystems.

Finally, this experiment also shows that it is important in the knowledge transfer process to accompany municipalities to integrate the results into their management system, which ensures that the scientific results are well used and that tools are operational.

Acknowledgements

The research team would like to thank the Government of Québec, particularly the Ministry of Public Safety, for its collaboration and financial support from the Québec government initiative on natural risks prevention, as well as the Ministry of Municipal Affairs and Land Occupancy for allowing us to use data from the municipal assessment roll. We are also grateful to the regional county municipalities for sharing their cadastral data. Thanks are also extended to the people responsible for land-use planning in each municipality (director generals, public works managers, municipal inspectors, urban planners, etc.) who are involved in this process and for taking the time to meet with us, answering the questionnaire and providing the documentation and information needed to complete this study.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

Ministry of Public Safety: Government of Québec.

ORCID

Christian Fraser http://orcid.org/0000-0001-7765-2187

References

Abuodha PA, Woodroffe CD. 2006. Assessing vulnerability of coasts to climate change: a review of approaches and their application to the Australian coast. In: Woodroffe CD, Bruce E, Puotinen M, Furness RA, editors. GIS for the coastal zone: a selection of papers from CoastGIS 2006. Wollongong: Australian National Centre for Ocean Resources and Security, University of Wollongong.

Adger WN. 2006. Vulnerability. Global Environ Change. 16:268–281.

Allison I dir. 2009. The Copenhagen Diagnosis, 2009; updating the world on the latest climate science. Sydney: Université de New South Wales. Climate Change Research Centre.

Association touristique régionale de la Gaspésie. 2015. [Internet]. Mont-Joli: Tourisme Gaspésie; [cited 2015 Sept]. Available from: http://www.tourisme-gaspesie.com

Aubé M, Zaiem J. 2013. [Accompanying communities with their adaptation process to climate change (year 2)]. Shippagan (Canada): Institut de recherche sur les zones côtières, Université de Moncton. French.

Bernatchez P, Drejza S. 2015. [Coastal erosion monitoring network for Eastern Quebec – user guide]. Rimouski (Canada): Laboratoire de dynamique et de gestion intégrée des zones côtières et Chaire de recherche en géoscience côtière, Université du Québec à Rimouski. French.

Bernatchez P, Drejza S, Dugas S. 2012a. [Coastal erosion setback zone: past and future coastal evolution for Magdalen's Islands]. Rimouski (Canada): Laboratoire de dynamique et de gestion intégrée des zones côtières, Université du Québec à Rimouski. French.

Bernatchez P, Fraser C. 2012. Evolution of coastal defence structures and consequences for beach width trends, Québec, Canada. J Coast Res. 28:1550–1566.

Bernatchez P, Fraser C, Dugas S, Drejza S. 2012b. [Coastal erosion setback zone: past and future coastal evolution for Avignon's RCM]. Rimouski (Canada): Chaire de recherche en géoscience côtière, Laboratoire de dynamique et de gestion intégrée des zones côtières, Université du Québec à Rimouski. French.

Bernatchez P, Fraser C, Friesinger S, Jolivet Y, Dugas S, Drejza S, Morissette A. 2008. [Climate change impacts on coastal sensitivity and community vulnerability of St-Lawrence gulf]. Rimouski (Canada): Laboratoire de dynamique et de gestion intégrée des zones côtières, Université du Québec à Rimouski. French.

Bernatchez P, Fraser C, Lefaivre D, Dugas S. 2011. Integrating anthropogenic factor, geomorphological indicators and local knowledge in the analysis of coastal flooding and erosion hazards. Ocean Coastal Manage. 54:621–632.

Boruff BJ, Emrich C, Cutter SL. 2005. Erosion hazard vulnerability of US coastal counties. J Coastal Res. 21:932–942.

Boyer-Villemaire U, Benavente J, Cooper A, Bernatchez P. 2014a. Analysis of power distribution and participation in sustainable natural hazard risk governance : a call for active participation. Environ Hazards. 13:38–57.

Boyer-Villemaire U, Bernatchez P, Benavente J, Cooper A. 2014b. Quantifying community's functional awareness of coastal changes and hazards from citizen perception analysis in Canada, UK and Spain. Ocean Coast Manage. 93:106–120.

Brooks N. 2003. Vulnerability, risk and adaptation: a conceptual framework. Working Paper 38. Norwich: Tyndall Centre for Climate Change Research.

Brown I, Jude SR, Koukoulas S, Nicholls R, Dickson M, Walkden M. 2006. Dynamic simulation and visualisation of coastal erosion. Comput Environ Urban Syst. 30:840–860.

Chakraborty J, Tobin GA, Montz BE. 2005. Population evacuation: assessing spatial variability in geophysical risk and social vulnerability to natural Hazards. Nat Hazard Rev. 6:23–33.

Crowell M, Coulton K, Johnson C, Westcott J, Bellomo D, Edelman S, Hirsch E. 2010. An estimate of the U.S. population living in 100-year coastal flood hazard areas. J Coastal Res. 26:201–211. West Palm Beach (Florida), ISSN 0749-0208.

Cutter SL. 1996. Vulnerability to environmental hazards. Progress Human Geogr. 20:529–539

Cutter SL, Boruff BJ, Shirley WL. 2003. Social vulnerability to environmental Hazards. Social Sci Quart. 84:242–261

Dagenais C, Malo M, Robert E, Ouimet M, Berthelette D. 2013. Knowledge transfer on complex social interventions in public health: a scoping study. PLoS One. 8:e80233. doi:10.1371/journal.pone.0080233

Degbe CGE. 2009. [Geomorphology and coastal erosion in Guinée gulf] [Mémoire de Master 2 en Océanographie physique]. Benin: Université d'Abomey-Calavi (UAC). French.

Desjardins M, Frenette Y, Bélanger J. 1999. [History of Gaspésie]. Quebec (Canada): Presses de l'Université Laval. French.
Desmeules P, Fraser C. 2006. [Cascapedia Bay's integrated management plan: a tool for territory sustainable development]. Maria (Canada): Comité des usagers de la baie de Cascapédia, Comité ZIP Baie des Chaleurs. French.
Didier D, Bernatchez P, Boucher-Brossard G, Lambert A, Fraser C, Barnett RL, Van-Wierts S. 2015. Coastal flood assessment based on field debris measurements and wave runup empirical model. J Marine Sci Eng. 3:560–590.
Drejza S, Bernatchez P, Clermont D. 2011. Effectiveness of land management measures to reduce coastal georisks, eastern Québec, Canada. Ocean Coast Manag. 54:290–301.
Drejza S, Friesinger S, Bernatchez P. 2014. [Vulnerability of Eastern Quebec roads to coastal erosion and flooding in a climate change context: coastal characterisation, hydrosedimentary dynamics and exposition of roads to erosion and flooding, Eastern Quebec, Volume 1, Project X008.1]. Rimouski (Canada): Laboratoire de dynamique et de gestion intégrée des zones côtières, Université du Québec à Rimouski. French.
European Commission. 2004a. Living with Coastal Erosion in Europe; sediment and space for sustainability. Part I – major findings and policy recommendations of the EUROSION project and Part II – maps and statistics. Luxembourg: Office for Official Publications of the European Communities. p. 40. Available from: http://www.eurosion.org/reports-online/part1.pdf
European Commission. 2004b. Living with Coastal Erosion in Europe; sediment and space for sustainability. Part II – maps and statistics. Luxembourg: Office for Official Publications of the European Communities. p. 25. Available from: http://www.eurosion.org/reports-online/part2.pdf
Few R, Brown K, Tompkins EL. 2007. Climate change and coastal management; Decisions: Insights from Christchurch Bay, UK. Coastal Management. 35:255–270.
Fraser C, Bernatchez P, Dugas S, Drejza S. 2012. [Coastal erosion setback zone: past and future coastal evolution for Bonaventure's RCM]. Rimouski (Canada): Chaire de recherche en géoscience côtière, Laboratoire de dynamique et de gestion intégrée des zones côtières, Université du Québec à Rimouski. French.
Friesinger S, Bernatchez P. 2010. Perceptions of Gulf of St-Lawrence coastal communities confronting environmental change: hazards and adaptation, Québec, Canada. Ocean Coast Manag. 53:669–678.
Fussel HM, Klein RJT. 2006. Climate change vulnerability assessments: an evolution of conceptual thinking. Clim Change. 75:301–329.
Gornitz VM, White TW, Cushman RM. 1991. Vulnerability of the US to future sea level rise. In: Proceedings of the 7th Symposium on Coastal and Ocean Management; 1991; Long Beach, CA.
Gorokhovich Y, Leiserowitz A, Dugan, D. 2014. Integrating coastal vulnerability and community-based subsistence resource mapping in Northwest Alaska. J Coastal Res. 30:158–169. Coconut Creek (Florida), ISSN 0749–0208.
Goussard JJ. 2014. [Stakes and challenges of vigilance facing coastal risks in a fast development context; presentation of the coastal risk regional prevention plan of Western Africa and the West African Coastal Observation Mission]. In: Actes du Colloque International : Connaissance et Compréhension des Risques Côtiers : Aléas, Enjeux, Représentations, Gestion; 2014 Jul 3–4; Brest (France), French.
Green C, McFadden L. 2007. Coastal vulnerability as discourse about meanings and values. J Risk Res. 10:1027–1045.
Hinkel J. 2011. Indicators of vulnerability and adaptive capacity: towards a clarification of the science–policy interface. Global Environ Change. 21:198–208.
Holsten A, Kropp JP. 2012. An integrated and transferable climate change vulnerability assessment for regional application. Nat Hazards. 64:1977–1999.
Horstman EM, Wijnberg KM, Smale AJ, Hulscher S JMH. 2009. On the consequences of a long-term perspective for coastal management. Ocean Coastal Manage. 52:593–611.
Horton BP, Rahmstorf S, Engelhart SE, Kempe AC. 2014. Expert assessment of sea-level rise by AD 2100 and AD 2300. Quat Sci Rev. 84:1–6.
Institut de la statistique du Québec. 2015. [Internet]. Quebec; [cited 2016 Sept 22]. Available from: http://www.stat.gouv.qc.ca/statistiques/population-demographie/
IPCC. 2013. Climate Change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM, editors. Cambridge: Cambridge University Press.
Johnston A, Slovinsky P, Yates KL. 2014. Assessing the vulnerability of coastal infrastructure to sea level rise using multi-criteria analysis in Scarborough, Maine (USA). Ocean Coastal Manage. 95:176–188.
Jousel J, Planton S, Le Cozannet G, Cazenave A, Costa S, Douez O, Gaufrès P, Hissel F, Idier D, Laborie V, et al. 2015. [Climate of France during the 21st century, Volume 5; climate change and sea level: from the whole planet to the coasts of France]. Ministère de l'Écologie, du Développement durable et de l'Énergie. French.
Jude S, Jones AP, Andrews JE, Bateman IJ. 2006. Visualisation for participatory coastal zone management: a case study of the norfolk coast, England. J Coastal Res. 226:1527–1538.
Juhola S, Westerhoff L. 2011. Challenges of adaptation to climate change across multiple scales: a case study of network governance in two European countries. Environ Sci Policy. 14:239–247.
Klein RJT, Nicholls RJ. 1999. Assessment of coastal vulnerability to climate change. Ambio. 28:182–187.

Koohzare A, Vanicek P, Santos M. 2008. Compilation of the map of recent vertical crustal movements in eastern Canada using GIS. J Surv Eng, ASCE. 132:160–167.
Leblanc J. 2006. [Integrated managament plan of the Bonaventure coastal zone]. Bonaventure (Canada): Table de concertation du littoral de Bonaventure. French.
Le Cozannet G, Bagni M, Thierry P, Aragno C, Kouokam E. 2014. WebGIS as boundary tools between scientific geoinformation and disaster risk reduction action in volcanic areas. Nat Hazards Earth Syst Sci. 14:1591–1598.
Lee EM, Clark AR. 2002. Investigation and management of soft rock cliffs. London: DEFRA, Thomas Telford.
Lemos MC. 2015. Usable climate knowledge for adaptive and co-managed water governance. Current Opinion Environ Sustain. 12:48–52.
Long B. 2006. [Hydrodynamic, sedimentologic and biological study of Maria, Saint-Siméon, Bonaventure, Newport and Cap d'Espoir sites in Chaleurs Bay, Québec, Canada]. Quebec (Canada): Ministère des Transports du Québec. French.
Mahendra RS, Mohanty PC, Bisoyi H, Kumar TS, Nayak S. 2011. Assessment and management of coastal multi-hazard vulnerability along the Cuddalore-Villupuram, east coast of India using geospatial techniques. Ocean Coastal Manag. 54:302–311.
Marchand M, editor. 2010. Concepts and science for coastal erosion management. Concise report for policy makers. Delft: Deltares.
McCarthy JJ, Canziani OF, Leary NA, Dokken DJ, White KS, editors. 2001. Climate change 2001: impacts, adaptation and vulnerability. Cambridge: Cambridge University Press.
McLaughlin S, Cooper JAG. 2010. A multi-scale coastal vulnerability index: a tool for coastal managers ? Environ Hazards. 9:233–248.
Ministére des Affaires municipales, des Régions et de l'Occupation du Territoire du Québec. 2009. [Regional county municipalities, a guidebook] [Internet]. Quebec; [cited 2015 Sept]. Available from: http://www.mamrot.gouv.qc.ca. French
Nguyen TTX, Bonetti J, Rogers K, Woodroffe CD. 2016. Indicator-based assessment of climate-change impacts on coasts: a review of concepts, methodological approaches and vulnerability indices. Ocean Coastal Manage. 123:18–43.
O'Brien KL, Leichenko R, Kelkar U, Venema H, Aandahl G, Tompkins H, Javed A, Bhadwal S, Barg S, Nygaard L, West J. 2004. Mapping multiple stressors: climate change and economic globalisation in India. Global Environ Change. 14:303–313.
Paul SK. 2013. Vulnerability concepts and its application in various fields: a review on geographical perspective. J Life Earth Sci. 8:63–81.
Preston B, Yuen EJ, Westaway RM. 2011. Putting vulnerability to climate change on the map: a review of approaches, benefits, and risks. Sustain Sci. 6:177–202.
Quintin C, Bernatchez P, Jolivet Y. 2013. [Impacts of the storm of December 6, 2010 on the coasts of Bas-Saint-Laurent and Baie-des-Chaleurs] Rimouski (Canada): Laboratoire de dynamique et de gestion intégrée des zones côtiéres, Chaire de recherche en géoscience côtiére, Université du Québec á Rimouski. French.
Roy F, Ferland Y. 2014. Land use planning for disaster risk management. Land Tenure J. 1:71–102.
Savard M, Beaudry N, Bernatchez P, Desrosiers M, Bossé J, Pagniez R. 2013. [Visual inspection of coastal archeological sites and Gaspésie active coasts recognition]. Rimouski: Université du Québec à Rimouski, Laboratoire d'archéologie et de patrimoine. French.
Sheate WR, Partidario MR. 2010. Strategic approaches and assessment techniques – potential for knowledge brokerage towards sustainability. Environ Impact Assess Rev. 30:278–288.
Silva R, Martínez ML, Hesp P, Catalan P, Osorio AF, Martell R, Fossati M, Miot da Silva G, Mariño-Tapia I, Pereira P et al. 2014. Present and future challenges of coastal erosion in Latin America. In: Silva R, Strusińska-Correia A, editors. Coastal Erosion and Management along Developing Coasts: Selected Cases. Coconut Creek (FL).
Sterr H. 2008. Assessment of vulnerability and adaptation to sea-level rise for the coastal zone of Germany. J Coastal Res. 24:380–393. West Palm Beach (Florida), ISSN 0749–0208.
Sterr H, Klein RJT, Reese S. 2003. Climate change and coastal zones: an overview of the state-of-the-art on regional and local vulnerability assessments. In: Giupponi, C. and Shechter, M, editors. Climate changes in the Mediterranean. Cheltenham: Edward Elgar Publishing, pp. 245–278.
Sullivan C, Meigh J. 2005. Targeting attention on local vulnerabilities using an integrated index approach: the example of the climate vulnerability index. Water Sci Technol 51:69–78.
Szlafsztein C, Sterr H. 2007. A GIS-based vulnerability assessment of coastal natural hazards, state of Pará, Brazil. J Coastal Conserv. 11:53—66.
Tate E, Cutter SL, Berry M. 2010. Integrated multihazard mapping. Environ Planning B Planning Des. 37:646–663.
Thieler ER, Hammar-Klose ES. 1999. National assessment of coastal vulnerability to future sea-level rise: preliminary results for the U.S. Atlantic Coast. U.S. Geological Survey. (Open File Report, 99–593).
Thieler ER, Himmelstoss EA, Zichichi JL, Miller TL. 2005. Digital Shoreline Analysis System (DSAS) version 3.0: An ArcGIS extension for calculating shoreline change. U.S. Geological Survey. (Open-File Report 2005-1304).

[USGS] United States Geological Survey. 2012. National assessment of shoreline change project. [cited 2015 Dec]. Available from: http://coastal.er.usgs.gov/shoreline-change/
Vafeidis T, Nicholls RJ, McFadden L, Tol RSJ, Hinkel J, Spencer T, Grashoff PS, Boot G, Klein RJT. 2008. A new global coastal database for impact and vulnerability analysis to sea-level rise. J Coastal Res. 24:917–924.
Yoo G, Hwang JH, Choi C. 2011. Development and application of a methodology for vulnerability assessment of climate change in coastal cities. Ocean Coast Manage. 54:524–534.
Zhang K, Douglas BC, Leatherman SP. 2004. Global warming and coastal erosion. Clim Change. 64:41–58.