Systemic vulnerability of coastal territories to erosion and marine flooding: A conceptual and methodological approach applied to Brittany (France)

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Iwan LE BERRE[1], Catherine MEUR-FEREC[1], Véronique CUQ[1], Elisabeth GUILLOU[2], Thibaud LAMI[1], Nicolas LE DANTEC[3,4], Pauline LETORTU[1], Caroline LUMMERT[4], Manuelle PHILIPPE[5], Mathias ROUAN[1], Camille NOÛS[6], Alain HENAFF[1]

[1] Université de Brest, IUEM, LETG UMR CNRS 6554, 29280 Plouzané, iwan.leberre@univ-brest.fr, meurferec@univ-brest.fr, veronique.cuq@univ-brest.fr, mathias.rouan@univ-brest.fr, alain.henaff@univ-brest.fr ,

[2] Université de Brest, LP3C EA 1285, 20 rue Duquesne – CS 93837, 29 238 Brest Cedex 3, Elisabeth.Guillou@univ-brest.fr

[3] Université de Brest, IUEM UAR 3113, 29280 Plouzané

[4] Université de Brest, IUEM, GO UMR CNRS 6538, 29280 Plouzané, nicolas.ledantec@univ-brest.fr

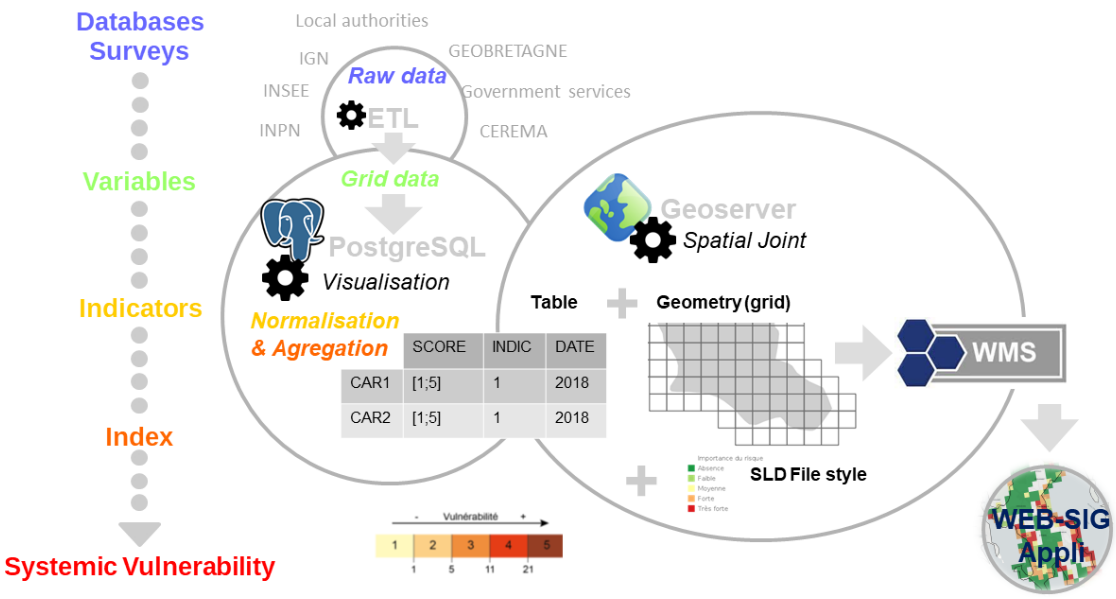
[5] Université de Brest, IUEM, AMURE UMR CNRS 6308, 29280 Plouzané, caroline.lummert@univ-brest.fr, manuelle.philippe@univ-brest.fr

[6] laboratoire Cogitamus, camille.nous@noussommesluniversite.fr

Corresponding author: Iwan Le Berre, iwan.leberre@univ-brest.fr

Abstract: The attractiveness of the coasts tends to increase their exposure to erosion and marine flooding risks. This exposure is exacerbated by the effects of climate change, in particular sea level rise. To contribute to strategic thinking on the vulnerability of coastal areas, it is essential to develop, share and collectively maintain relevant knowledge on risks. This article will present the thinking behind the setting up of a coastal risks observatory in Brittany, a region located in north-western France. It relies on a conceptual approach to systemic vulnerability based on four components: hazards, assets, management, and social representations. Hazards and assets underpin the notion of risk and tend to increase the vulnerability, management tends to mitigate it, and representations can play a part in increasing or decreasing it depending on the context. To understand and analyze this system of vulnerability, our approach is based on the generation of a set of 62 indicators combined into different types of indices. A web-GIS interface was developed to navigate through and map this system of vulnerability. The difficulties associated with this type of synthetic approach will be discussed, whether they are related to data availability, to the links between scientific research and operational territorial management requirements, or to an understanding of the dynamics of all of the vulnerability components and their interactions. Ultimately, the approach developed has been successful in mobilising scientific and operational stakeholders around the co-construction of a diagnosis of territories with regard to their vulnerability to coastal risks.

Graphic Abstract:



Keywords: coastal risks, erosion, flooding, vulnerability, web-GIS interface

Highlights:

- Demographic and environmental trends increase the exposure of coastal areas to risks
- Systemic vulnerability relies on hazards, assets, management and social representations
- This complex system is analysed through 62 indicators combined into several indices
- A web-GIS interface allows to navigate through this system of vulnerability
- It helps scientific and stakeholders to share a common diagnosis on coastal risks

1. Introduction

As an interface between land and sea, coastal zones are particularly productive environments that have attracted human societies from the nineteenth century [1–3]. As they have developed, these societies have intensified and diversified their exploitation of coastal resources, whether for food, mineral materials, energy or leisure. Human settlements moved closer to the sea in order to make the most of these resources and have become ever more massive. Because these settlements are static, they have contributed to changing the dynamic balance of hydro-sedimentary coastal systems [4,5].

These trends have resulted in an increased exposure to coastal risks [6,7], that is further intensified by the effects of climate change [8–10]. Coastal territories have therefore developed management strategies and measures to guard against these risks and mitigate their vulnerability. These strategies include in particular the improvement of knowledge on the processes of exposure to risk, and on the modalities of mitigating the vulnerability of coastal territories to these risks. One the one hand, while erosion can be seen as a continuous, thus predictable process when considering long time scales, making short-term predictions of coastal retreat remains quite challenging due to temporal and spatial variability of erosion processes. Marine flooding, on the other hand, is a more sudden phenomenon. However, in reality both processes are intertwined: today's erosion leads to tomorrow's flooding. Besides, in the context of upcoming, rapidly increasing sea-level rise, the adjustment of the coastline position will sometimes likely be the result of significant coastal landscape remodelling, and currently observed retreat rates may turn out to be poor proxies for assessing future coastline position. This is particularly true in the case of Brittany, where the physical geography of coastal territories is highly heterogeneous [11]. Regardless of uncertainties on future erosion and marine flooding risks, for this knowledge to contribute to the strategic thinking on territorial vulnerability, it must be developed, shared and collectively maintained, not only by scientists but also by users of the territories, especially coastal risk management stakeholders [12].

The experiment presented in this article aims to build a collective response to this question through the development of a regional coastal risk observatory. This observatory relies on a rather original partnership network bringing together scientists from different disciplines, and managers of the coastal territories of Brittany, a region located in the northwest of France and bordered by the English Channel and the Atlantic Ocean. The cornerstones of this observatory are the adoption of a common conceptual framework of vulnerability between scientists and managers, the co-construction of a shared database describing the components of the systemic vulnerability of Brittany territories to coastal risks, and the development of a WEB-GIS tool to navigate through indicators and indices of this vulnerability system.

The first section of this article aims to define the main concepts used in our project, and to present its general framework in the context of coastal vulnerability assessment. The second section will be dedicated to the conceptual and methodological approach we have adopted in our work to achieve this objective. After the presentation of our main results, illustrating the output the system of vulnerability for the observation of coastal risks at regional level of the whole Brittany coastline, the article will finish with a discussion on the scope and limitation of this work in view to setting up a regional observatory of coastal vulnerability.

2. Context

2.1. From hazard to vulnerability

A hazard is a potentially dangerous event, generated by forcing of various origins, whether natural (tectonic, meteorological, hydrological, biological) or man-made (technological, biotechnological). It can take various forms (cyclone, earthquake, biological invasion, pollution, destruction of natural environments, etc.) and materialise at different spatial and temporal scales [7,13]. In addition to its spatial extent, duration and timing (immediate or delayed), the hazard can be characterised by its intensity, magnitude (or power) and its related probability of occurrence [14,15]. Because of their location at the interface between land and sea, and often at the edge of continental plates, coastal areas are particularly exposed to meteorological (storms and hurricanes in particular) or tectonic (earthquakes, tsunamis) hazards [7]. Besides, generally, coastal areas are also particularly densely populated territories, where many human, economic and environmental assets are concentrated [7,13,14]. It is therefore a place of "spatial coincidence" between hazards and assets, which is where exposure to risk is materialised [13,16]. Moreover, exposure to coastal risks tends to increase under the combined effect of population growth [17,18] and sea-level rise [8,19].

In the coastal risks' literature, hazards have long been the focus of attention: based on magnitude and occurrence probability approaches from the earth and engineering sciences, the emphasis is on defining and assessing exposure [20–24]. Assets were then progressively taken into account, first by a basic identification particularly for producing “risk maps” [25,26], then in terms of structural, material or physical sensitivity related to buildings and infrastructure (strength and durability of materials, means of physical mitigation etc.) [27], for example, by establishing a "risk incurred" index [28]. Little by little, social sciences have entered the sphere of natural risks [29]. At the turn of the 1980s and 1990s, the notion of a social vulnerability is developed [30–32], in this context concerning the structural and functional factors of societies exposed to risk (demographic structure, social and political organisation, uses, beliefs, etc.). Integrating geophysical and social dimensions allows the system's resilience to be analysed [4,33,34]. Originating from ecology, this approach considers environmental systems as being in a state of dynamic equilibrium and in permanent adaptation [35]. It therefore focuses on the analysis of the system's capacity to adapt and reorganise after a disturbance [4,35]. Vulnerability can then be seen as the inverse of this adaptive capacity [36], i.e., to paraphrase the commonly used IPCC definition, the predisposition to be adversely affected by a hazard, depending on its nature, intensity, extent and duration, and its probability of occurrence [10]. The cognitive and behavioural dimensions can also be taken into account to understand the influence of social representations and behaviour of the population (e.g., stakeholders, residents) facing the risks, in crisis or preventive situations [37–40]

This overview of the diversity of approaches shows that vulnerability can be assimilated to a complex system [41], open, structured by interacting components, and continuously modified by interactions that determine dynamic equilibrium points. The vulnerability system is also specific to each territory [4,36,42]. It depends on both its geophysical characteristics (exposure to hazards, topography, climate, etc.), its land use and land cover (forms of urbanisation, economic activities, environmental and cultural heritage, etc.), but also its management policies (prevention and adaptation strategies and actions), as well as the awareness and knowledge of risk that its stakeholders and residents may have developed.

This spatial, social and environmental differentiation, as well as the diversity of disciplinary approaches, explains the coexistence of multiple definitions of vulnerability, a term that is still widely debated as shown by the number of reviews addressing this question [4,35,42–48]. However, acquiring knowledge on the vulnerability is essential for defining and implementing public policies of risk management [12,44]. Although to a large extent risk management is defined by laws and regulations, local stakeholders still have some autonomy to implement their own management strategy. The on-going transfer of responsibilities from national to local authorities is increasing this autonomy in the development of local risk management strategies. Understanding the general issues of their territory and the driving factors of their vulnerability to risks, enables to develop longer-term strategies than the immediate reaction to a local event, which is often guided by emotion and pressure from local stakeholders, and to better anticipate the effects of their policy choices and practical measures [11]. Finally, the assessment of the vulnerability system is still very commonly used for strategic purposes, awareness raising, and to carry out spatial and often temporal comparisons [33,39,49].

2.2. Evaluating and mapping systemic coastal vulnerability

Instead of cultivating the illusion that a single conceptual approach can be applied to all areas and at all scales, Gallopín [47] considers important to adopt local trade-offs that are satisfactory both at the scientific and operational levels. This is shown by the diversity of assessment methods of vulnerability to coastal risks, and the multiple variations of indices and maps presented in the literature. Indeed, the conceptual evolution presented in the previous section has been accompanied by methodological developments, consisting in an increasing integration of the different dimensions of vulnerability, and considering that social, economic, cultural, and geophysical factors should be recognised as equally important in shaping systemic vulnerability [44,50].

One of the most popular approaches, as demonstrated in the review by Bukvic et al.[44], is the Coastal Vulnerability Index (CVI) developed for the North American coasts [51,52]. Based on a description of the coastline's physical characteristics, its objective is to assess the exposure of homogenous sectors of the coastline to the hazards of coastal erosion and marine flooding. Because of its relative simplicity (seven biophysical measures) and the fact that it can be applied at various scales, it has been widely disseminated and has undergone various regional adaptations [53–56]. However, since it is based on physical variables, the CVI only describes the susceptibility of the coastline.

Social vulnerability may be assessed using numerous factors that have long been identified in the literature [31,32,57,58]. They relate to demography (population size and characteristics: age, household composition, education, etc.); housing (number of dwellings, ownership status, property value, building characteristics), employment (number of employees, type of employment, income, unemployment rate, etc.), equipment and infrastructure (roads, railways, ports, industrial estates, etc.). As observed by [44], most studies use their own vulnerability framework, either by the adding socio-economic data to the physical forcing variables of the CVI [59], or by processing them separately in a specific component, usually from the population census and land use data [31]. A significant part of this type of study is based on Social Vulnerability Index (SoVI) introduced by Cutter et al. [57] for the USA coasts, applied and adapted elsewhere by numerous authors [23,33,60,61]. This work uses numerous parameters, usually at local scales and linked to administrative divisions. These data are analysed using multivariate methods, which allow the differenciation and characterisation of the socio-economic profiles of the administrative units studied. At local scale, these methods are very dependent on data availability [32,62,63]. The Place Vulnerability Index (PVI) by Boruff et al. [64] ties in with this approach by integrating the (CVI) with the SoVI.

In search of a more comprehensive description of systemic vulnerability, additional components may be integrated in the assessment, whether linked to the structural characteristics of territories (planning, infrastructure) or to their management methods (response capabilities). For example, the Coastal City Flood Vulnerability Index (CCFVI) [33] is based on a set of 19 indicators divided into four components (hydrogeological, social, economic and politicaladministrative), to calculate the vulnerability to marine flooding of large cities in low-lying coastal areas, particularly deltaic ones, at a worldwide scale. The World Risk Index (WRI) [65] aims to combine the average annual percentage per country of people exposed to natural hazards (storms, floods, droughts) with societal vulnerability expressed by three components: the structural characteristics of the territories (susceptibility), the means available to reduce damage (response capacity), and adaptation measures. Coastline applications of the WRI relate to coastal hazards such as storms, marine flooding, storm surges, tsunamis, and sea-level rise [34,66]. Applied at the local level [67], the WRI focuses on defining a social vulnerability index that combines exposure (number of people exposed to marine flooding by hectares), susceptibility, i.e. the structural characteristics predisposing each territory to undergoing hazard-related damage (number of vulnerable people, male-female ratio) and adaptive capacity (number of multi-storey constructions, children aged under six years old, population with over six years of secondary education, illiterate persons, migrants).

In addition, approaches developed in human and social sciences, based on face-to-face or online surveys, aim at analysing the opinion of a population with respect to risks: knowledge of hazards, feeling of exposure or danger, understanding and confidence in mitigation measures [68]. They may also examine the socio-economic profiles of disaster victims, as well as the causes and circumstances of accidents, in an attempt to detect vulnerability factors, whether individual or collective, social, environmental or behavioural [37,38]. However, as social survey data is subject to individual confidentiality rules, and as perceptions change rapidly in response to circumstances, these data are seldom included in systemic vulnerability indices.

2.3. Challenges for systemic vulnerability assessment

The benefit sought through producing systemic index lies in the possibility of linking different notions, that can be analysed independently, and then aggregated to provide an overall vulnerability assessment [47]. Levrel et al. [69] refer to a "distancing" intended to synthesise and simplify a complex reality by defining the relevant metrics to observe the evolution of a territory in relation to a phenomenon or a trend (here, coastal vulnerability), to carry out spatial comparisons (between territories) and/or temporal ones, and of course, to communicate to different types of public [36]. Beyond observation, the aim is to understand the complex interactions between components of the vulnerability system [4], both to enhance scientific knowledge and provide management assistance. Nevertheless, some general pitfalls involved in this type of "synthesis" can be mentioned [70,71].

Scale and granularity

The analysis of the literature shows a great diversity of scales of analysis, depending on the objectives of the studies and the institutions that conduct them. The broadest scales, global or regional, are adopted for strategic analyses, to highlight and compare the influence of development inequalities on national or subnational vulnerability [33,65,72]. In international assessments, administrative units (from country to counties or regions) are the most popular [65]. They correspond to the statistical unit for the collection or dissemination of data. Most of the databases set up by international organisations involved in development programs and inequalities reduction (World Bank, Global Data Lab, PNUD, etc.) are disseminated to the general public at national, and sometimes, sub-regional levels (sub-regional Human Development Index, European NUTS regions). However, these units generally exceed the areas exposed to hazards, particularly coastal erosion and flooding, which usually only concern small areas and, in any case, are spatially independent of administrative divisions.

At the local level, where people are actually confronted with the risk, the studies have a more operational aim. The assessments are particularly aimed at identifying and spatialising the factors of individual vulnerability, which are required for the definition of public policies on risk prevention and management [31,73]. Thus, local studies should both focus on the hazard-prone areas, and rely on data of sufficient resolution to describe the study areas in detail (e.g., coastal/inland, exposed/non-exposed areas). To focus on the areas actually exposed to hazards, some studies use buffer zones calculated from the coastline position [74], or water level applied to digital elevation models [8]. The most widely used approach, although basic, is based on the calculation of flooding envelopes from reference water levels (bathtub model) [44,75]. When the study is part of an operational approach to local risk management, hydrodynamic modelling can be used, particularly to refine potential disaster scenarios [75–77]. However, the requirements of this type of modelling impose significant constraints (spatial resolution of the topographic reference frame, calculation time, etc.), which limits them to very localised applications [78]. Notably, improvements in census data collection and processing methods, as well as the incorporation of open data principles in legislation and practices for data dissemination in many countries (e.g. INSPIRE Directive and national transcriptions in Europe), enable the realisation of very detailed assessments at local level [79,80].

Of course, the data collection effort depends on the level of knowledge to be acquired [23,32]. Increasing the number of indicators increases the likelihood to face the lack of accurate, up-to-date and accessible data for all of the indicators processed or for the entire study area. To alleviate this difficulty, the stakeholders (territorial authorities, government services) responsible for coastal risks management must be involved in populating the database. This involvement is particularly crucial for certain data that are not available in the reference databases and that must therefore be collected on the field or within local institutions: building adaptations (elevation, refuge floor, emergency window on the roof), local management strategies and devices, residents' representations, etc. The territorial legitimacy that the municipalities benefit from can also make individual data collection (dwelling status: main or secondary, occupant profile, etc.) more acceptable in the eyes of the residents, and with regard to the legal conditions linked to the confidentiality of individual data, or even their strategic value.

Data analysis

Data analysis requires methodological choices concerning the integration of variables, their ranking and weighting, and the formulation of indices.

The assessment of systemic vulnerability is generally based on a multidisciplinary approach mobilising data of various types, sources and scales [49,60,81]: field surveys, census data, geographic information, etc. Their integration into a common reference framework is often mentioned in the literature. In theory, when the variables do not have the same precision, the coarsest variable determines the quality of the results and should therefore be used to integrate all variables into a common reference system [49,74]. This explains why administrative divisions (countries, counties, municipalities) are the units in which data are most often aggregated. In practice, the use of GIS and spatial analysis methods allows for the combination of data from different sources and formats. For example, "dasymetric" methods are commonly used to disaggregate information from available datasets and refine the results [49,63,82]. But lower quality data always determines the quality of the final results.

It can be seen that different methods are used to produce vulnerability indices. They can be based on an a priori choice of variables, or subject to multivariate analysis [83], on a simple ranking of variables, or on more complex quantitative approaches, introducing or not weighting, etc.

As an alternative to the selection of variables by experts [84,85], some authors [23,32,86] use methods of multivariate analysis to analyse the correlations within a high number (sometimes several dozen) of variables, and reduce their number without speculating on their respective contribution to vulnerability. For example, from the factorial analysis of 39 variables, Boruff et al. [64] identified 10 indicators that explain the key dimensions (82% of variance) of the social vulnerability of the USA coastline. Once the variables have been selected, the formulation of the index must be defined. To define the formulation of the CVI, Gornitz, et al (1997) compared the results obtained from 6 different aggregation methods. The chosen method of calculation was the square root of the product of the variables over their number, which seemed to them to be the best compromise between sensitivity to classification errors or missing data, and clarity of formulation. This method was also used in the SoVI by Cutter et al [32] and applied to different sites [53,87]. In another application [88], simple addition of indicators was preferred to avoid reciprocal actions of variables. However, the addition of variables can pose a problem of linearisation of information: sets of moderate values can yield higher scores than sets with a single high value. This may be contradictory to the objectives of vulnerability assessment. Some authors also wish to assign different weights to the variables on which their index is based. For this weighting, the main two methods used are also the expertise of local stakeholders and scientists [84], and factor analysis [34]. In all cases, the choice of weighting reflects a political and strategic vision of vulnerability, which must be clearly explained [74,89]. Thus, in several studies, researchers have chosen not to weight the variables or to propose equal weighting [34,64,67], as they could not justify differences in the weights attributed to the factors on which their index rely.

Navigating through the system of vulnerability

Whatever the formula is, and even though the indices aim to provide a synthetic vision of a complex reality, they are primarily interpretations [69,71]. Indeed, the meaning given to the results and their appropriation by the stakeholders (managers, decision-makers, inhabitants, etc.) are decisive factors in the outcome, its analysis and in its operational application to management [12,49,69,71].

It should therefore be stressed that systemic indices can generate a “black box” effect inherent to the quality and availability of the input data, poorly or insufficiently explained methodological choices, and the complexity of the systems studied [4,33]. The use of rating systems must be based on explicit and duly justified hypotheses. But this effort to achieve scientific objectivity is not sufficient to guarantee the practical usefulness of an index. Indeed, the complexity of its formulation can render an index difficult to understand for some of its users [90], and could be an obstacle to its acceptance and recognition as a basis for decisions in an operational context, which generally relies on compromise, or some form of consensus. In fact, there is a possible gap between a systemic assessment for scientific or strategic purposes, and the practical needs related to managing vulnerability at the local level [12,36]. The latter generally presents territorial specificities likely to be hidden by the universal assessment, and must be flexible enough so that it can be adjusted to the variability of the processes [64], while still maintaining the transparency needed to justify the choices made.

It is therefore essential to define shared conceptual and methodological approaches that are accepted and understood by all stakeholders. Therefore, tools to disaggregate the indices must be made available to navigate the vulnerability system and understand the relative contribution of its components [64]. Graphical representation is an ergonomic and intuitive way of disaggregating the indices by visualising the variables and their components: graphical breakdown of vulnerability into subsystems that can be analysed separately [6,33,91], separate mapping of each component of vulnerability [31,92]. The cartographic representation of indices is legitimate, whether in the form of choropleth maps, notably based on administrative units [49,67], or a grid reference system [84], because it allows vulnerability to be restored in its territorial dimension [57]. Such representation makes the index less dependent on the quality of the available data, and allows the user to disaggregate the index into components in order to visualise their respective contributions and relations.

The literature review shows that the process of creating indices is primarily dependent on the conceptual definition adopted, which in part determines the components of vulnerability and the variables chosen to describe it. Secondly, it depends on the scale and granularity of the analysis, which is often dependent on the data available. Finally, it involves defining formulations and calculation methods, which may be derived from statistical analyses or from the choices of the stakeholders involved in the assessment process. Indeed, as Runfola et al [93] have shown, index construction methods derive primarily from a choice of representation. It is therefore the ultimate purpose of the indices that guides their construction. Consequently, while the literature does not provide ready-made answers, it does provide the necessary basis for these choices.

Through the concept of vulnerability of place, the geographical approach developed by Cutter et al [32] promotes pragmatic approaches based on the characteristics and issues of the territories analysed, by choosing a clear conceptual framework and a terminology shared and understood by all the stakeholders [12,94]. This requires the involvement of these stakeholders at a very early stage in the process of developing the indices (from the choice of variables, or even from the production of data), the adaptation of the approach to the characteristics of the territory (physical, socio-economic or political), as well as to the availability of the data. Such an approach also requires the development of tools to navigate the collectively constructed vulnerability system, in order to promote the replicability of the methods implemented in an operational and long-term observation perspective.

3. Territorial, conceptual and methodological framework

The research was carried out in the Brittany region. In addition to its geographic relevance with regards to coastal risks, this region offered the opportunity of developing an appropriate partnership framework with coastal risk stakeholders (local authorities, government services, public organisms) to set up a conceptual and methodological reflection, and to develop an appropriate tool to integrate and share geographic information on vulnerability.

3.1. Study area

The study area covers the entire region of Brittany (Fig. 1). This region is located in north-west France, where it forms a peninsula surrounded by 2,500 km of coastline[i]. Brittany coasts consist of over 40% rocky cliffs, 20% unconsolidated cliffs, 7% low-lying rocky coastline, and over 8% artificial coastline. Sedimentary coasts make up nearly 25% of the coastline, partly in the form of “pocket beaches” set in rocky shores [14]. So, from a geomorphological perspective, the Brittany coastline appears to be relatively less exposed to coastal hazards than other French coasts: tectonically stable crystalline basement and few extensive low-lying areas. However, 35% of its beaches have been showing a tendency for coastal erosion since the 1950s [95]. Moreover, since the 19th century, the old maritime marshes were drained for agricultural purposes before they were urbanised in the second half of the 20th century. Generally modest in size, but very numerous, they occupy a total surface area of around 500 km^2 in Brittany and today they are one of the low-lying built-up areas that are particularly exposed to marine flooding.

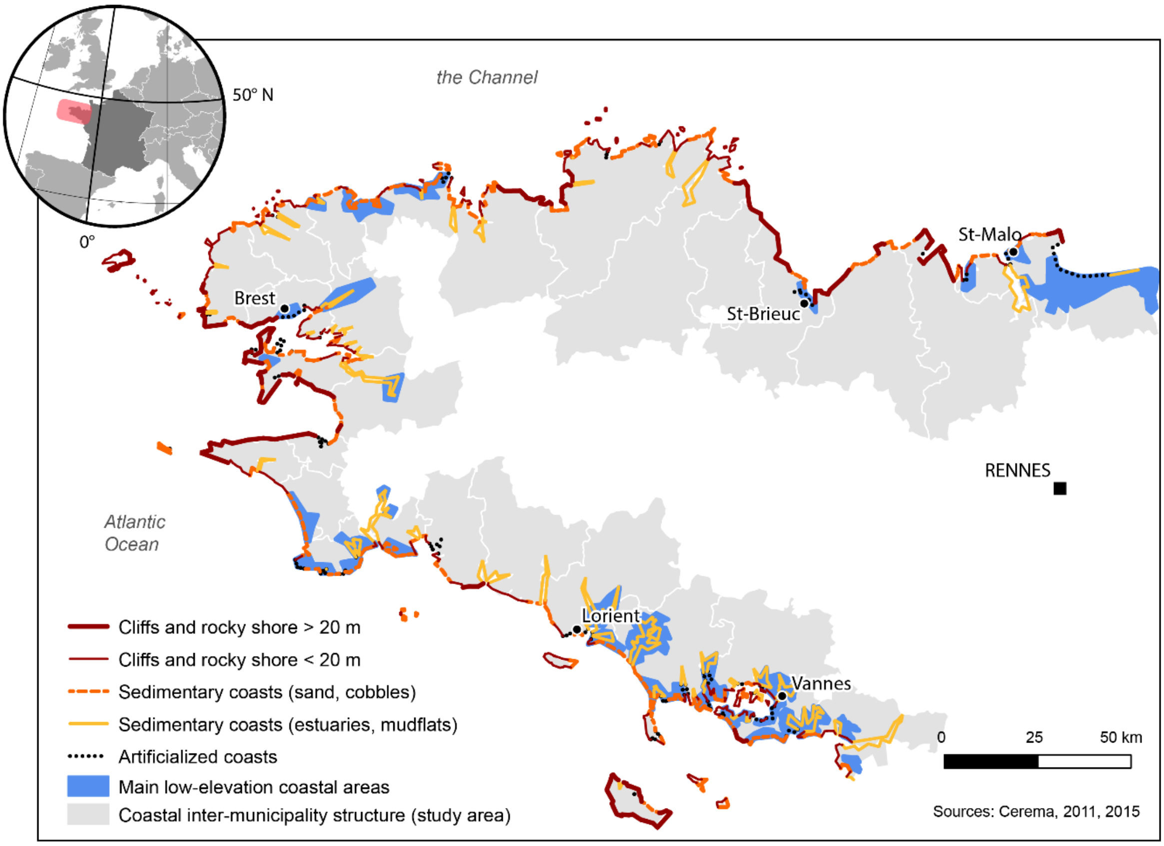


Figure 1: Location of the study area [color]

The region history and geography mean that the Brittany population mainly live on the coast. This is true for the main cities, with the exception of the region capital Rennes, and these coastal communities have been one of France's most demographically attractive territories for several decades [96,97]. They are home to over one third of the regional population (36.7% of inhabitants for 18.5% of the territory), for a density of 239 inhabitants/km, which is twice the regional (and national) average density. These small coastal communities are still appealing although their demographic growth is beginning to slow down in favour of cities and suburban communities, their population is ageing and the number of secondary homes is increasing [98][ii]. They receive 76% of the 12.8 million tourists that come to Brittany every year[iii]. Therefore, a significant number of socio-economic assets are located on the coast and potentially exposed to coastal erosion and marine flooding, possibly in combination.

Indeed the French national framework of coastline management [99], considers these two kinds of hazards: coastal erosion, including coastline retreat and ground movements (due to cliffs failure), and marine flooding. Tsunamis are considered as part of seismic hazards and, anyway, their probability of occurrence is very low in Brittany [100]. Brittany is no longer affected by coastal dune migrations [101]. Therefore, only erosion and marine flooding were considered for the *Hazards* component index.

3.2. Partnership framework

At this regional scale, the observation of risks and the assessment of the resulting vulnerability of coastal territories requires the development of collective, interdisciplinary and inter-institutional expertise. Indeed, only a collective approach allows combining the conceptual and methodological expertise on coastal risks, their legislative and regulatory management framework, with a detailed field knowledge and an effective deployment capacity to monitor their evolution with an appropriate frequency and resolution. This collective approach is also essential to develop homogenous knowledge shared by local and regional stakeholders, in order to improve risk management by coordinating local policies and avoiding the immediate logic of action, guided by emotion and pressure exerted by local residents, which often prevails but proves to be costly and ineffective. For this purpose, we have initiated a partnership between scientists from complementary fields (environment, geosciences, human and social sciences, law and economics) and coastal risk management stakeholders, competent on local to regional territories (fig. 2): local elected officials, engineers and technicians from local authorities and government departments. The aim was to develop an observatory on coastal risks in line with managers' strategic concerns at the regional level.

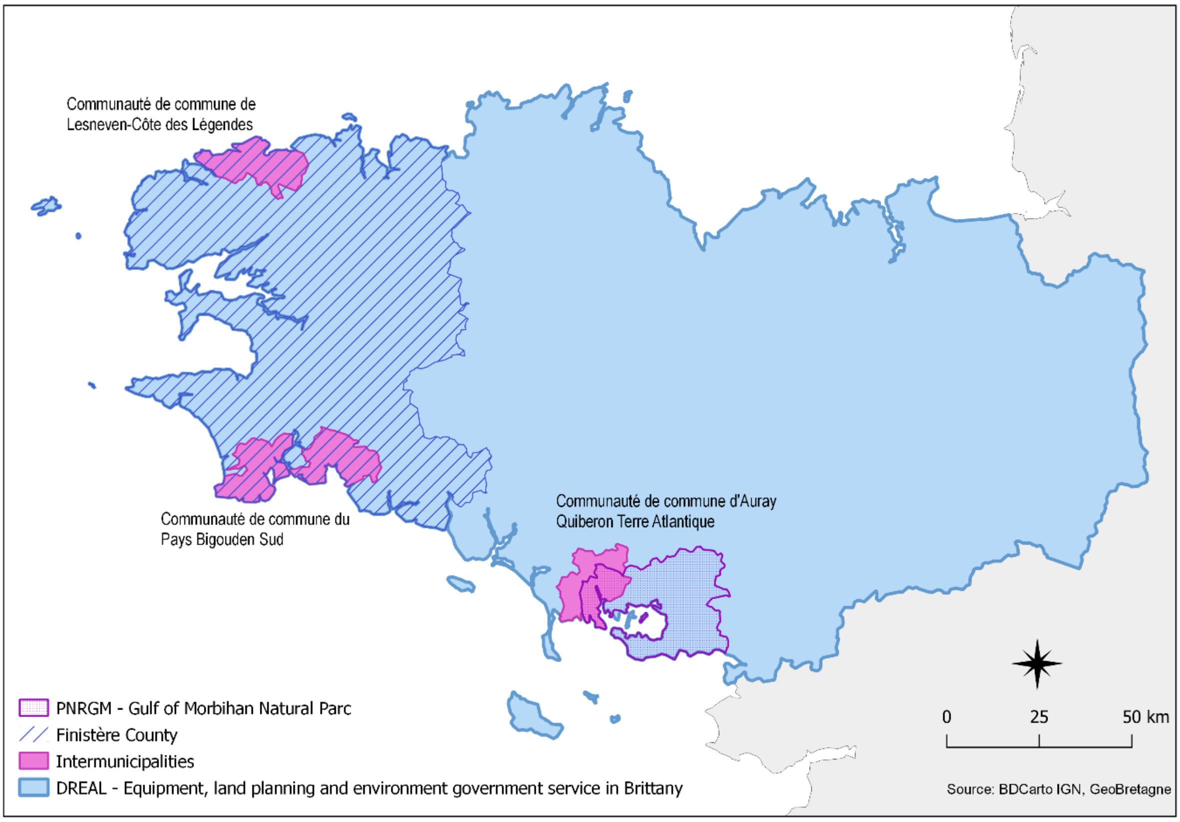


Figure 2: Institutions involved in the partnership and their territories [color]

It is within this partnership that the conceptual and methodological choices at the heart of the project were made: outline of the partnership, shared conceptual framework of systemic vulnerability, indicators and indices, scale and resolution, development of a public web-GIS interface, etc. The choices were made either on a case-by-case basis, by mobilising the most competent partners on thematic or methodological questions, or during plenary seminars bringing together 10 to 30 partners to discuss different development options, test them and get feedback.

3.3. A common conceptual framework of vulnerability

Within this partnership, the work we carried out for several years has led to the adoption of a framework of vulnerability as a complex system resulting from a combination of four interdependent components [94]: Hazards ("what can happen") and Assets ("what we risk losing"), that determine the risk; Management, "what is put in place to limit the damage" by mitigating exposure to hazards and by regulating the development of exposed territories (for instance through land planning, risk zonings);

Representations ("what inhabitants think about their living environment") may inform management, direct awareness and regulate the assets (Fig. 3).

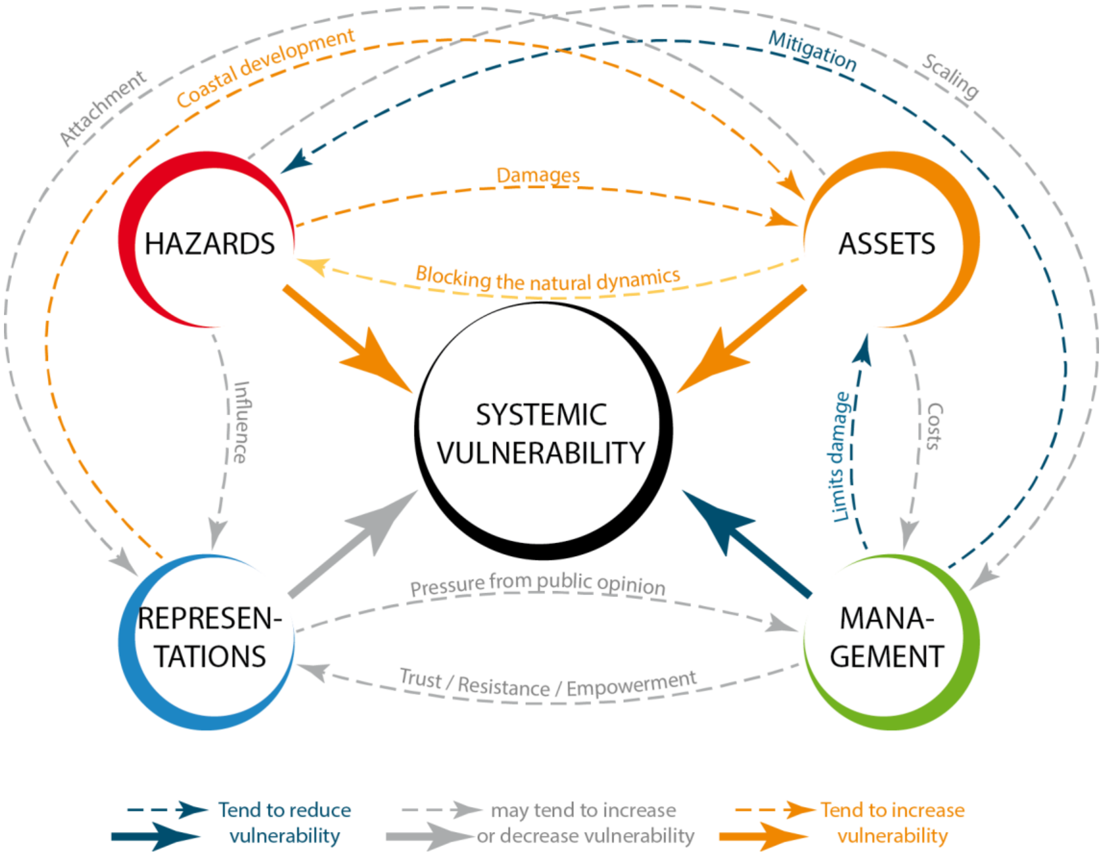


Figure 3: The four components of vulnerability (after [39,94]) [color]

These internal and external factors are largely interdependent and form the basis of a territory's vulnerability. Firstly, we consider that risk can only materialise if assets are exposed to hazards. Secondly, coastal hazard regulation and management measures can prevent the development of assets in hazard-prone areas, or impose building regulations to mitigate hazard-related damage. Finally, the representations that inhabitants have of the risks to which they are exposed and their confidence in the management measures implemented to addres them, can influence the acceptability of these measures and therefore their effectiveness. Indeed, vulnerability is intimately linked to the history of the territory, its occupation, its population and activities, and the values it upholds.

On this basis, the integration of hazards in the definition of systemic vulnerability, which is still not widely used, allows a global understanding of the problem of coastal risks. It allows to combine components that are closely intertwined in the field and constantly interrelated [102], which fully justify a multidisciplinary approach. It breaks the traditional division of labour between "hard" sciences that focus on hazards and social sciences that analyse vulnerability [20], by basing the reflection in each component on their interrelationships according to levels of mutual or univocal dependence [94].

Furthermore, the disaggregation of the vulnerability system into components simplifies interdisciplinary collaboration, facilitates data collection and processing, as well as methodological developments to improve the overall understanding of the system. Moreover, this disaggregation facilitates the monitoring of these four components which, although intertwined, have their own spatiotemporal evolution.

3.4. Database construction

Definition of the Indicators

Variables are chosen through a threefold process: (1) research, field work and exchange processes, (2) validation, and (3) adjustments implemented (in several stages and at several scales) involving scientists and stakeholders collaborating in the project [24,94]. Each selected variable generates an indicator. The indicator aims to transform the raw data (collected in the field or from a database) into a hierarchical value. In total, 62 indicators were defined [94].

Data collection

The data are collected by various methods according to each component, which are described in detail in [94]. In the *Hazards* component, data are extracted from reference datasets: the National coastal erosion indicator (INEC), and the low-lying coastal areas, both available in the Geolittoral Spatial data infrastructure[iv]. In most exposed areas, surveys are conducted on reference points, along transects, or on coastline segments of homogeneous geomorphology [95]. These surveys are eventually carried out by the local authorities involved in the partnership. The *Assets* description is based on the exploitation of reference data from various national and regional sources: the national mapping agency (IGN), the national institute of statistics (INSEE), government services (equipment and environment, land registry, tax department, etc.). For a few specific themes (vulnerable population and buildings), the data must be collected from local authorities: their spatial coverage may then be less complete. In the *Management* component, surveys are conducted at the effective scale of implementation of coastal risk management measures, that is, the municipality or the inter-municipality. Therefore, the minimum scale of rendering and presentation of the management indicators is the municipality scale. Finally, in the *Representations* component, surveys are conducted at the individual scale (person or household), but data are rendered at the municipality scale to respect data confidentiality and respondent anonymity.

Integration (grid frame)

As the scales of data collection vary, the spatial unit differ from one component to another, e.g. from measurement points to municipality area. A common spatial reference system must then be adopted in order to integrate the data and to be able to analyse them jointly. This requires defining the dimension of the elementary spatial entity adopted to describe the study area.

We decided to adopt the reference grid used by the French National Institute of Statistics (INSEE) for the dissemination of census and tax data (collected from each household). Its 200m resolution is a good compromise between the data collection effort required at the regional scale, the expected accuracy of the collected data and the confidentiality of the individual data (fig. 4). The other advantage to this resolution is that it is independent of territorial administrative divisions, which is fundamental for recording the naturalist data of the Hazard component. Finally, adopting a standardised entity allows for the aggregation or the disaggregation of data to facilitate the integration of indicators of different components in the indices, while avoiding the modifying effect of spatial units [103].

Figure 4: View of the 200m grid used to integrate various data in the indicators database (map base: BD ORTHO IGN) [color]

Normalisation and ranking

Due to the diversity of data collected in the four components, a normalisation method must be defined to make the data comparable. In order to compare the qualitative and quantitative data expressed in different units (distance, surface, area, number, proportion, etc.), we decided to order them. This involved moving from an absolute value (from a measurement or a fact established during research) to a relative value. According to the preferences expressed within the partnership, this relative value is expressed by a rating in five ordered classes (Fig. 5). Depending on the nature of the raw data, these classes can be delimited by statistical, arithmetic or empirical methods. It should be noted that the contribution of the indicator to systemic vulnerability can be positive, inverse or not directly correlated to vulnerability. Indeed, the increasing number of hazards and assets tends to increase vulnerability, while management measures aim to mitigate it. Measurements of social representations, on the other hand, are indirectly related to vulnerability: it is the knowledge of these representations, whatever they may be, that reduces vulnerability. These component-specific characteristics have implications on the development of indices.

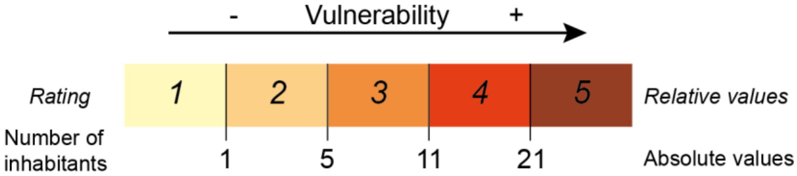


Figure 5: Ranking principle (example of the human assets' indicator based on the number of inhabitants per 200m grid) [color]

From indicators to indices: aggregation methods

The standardised indicators can then be combined to produce indices. From a theoretical point of view, four index categories are distinguished (Fig. 6).

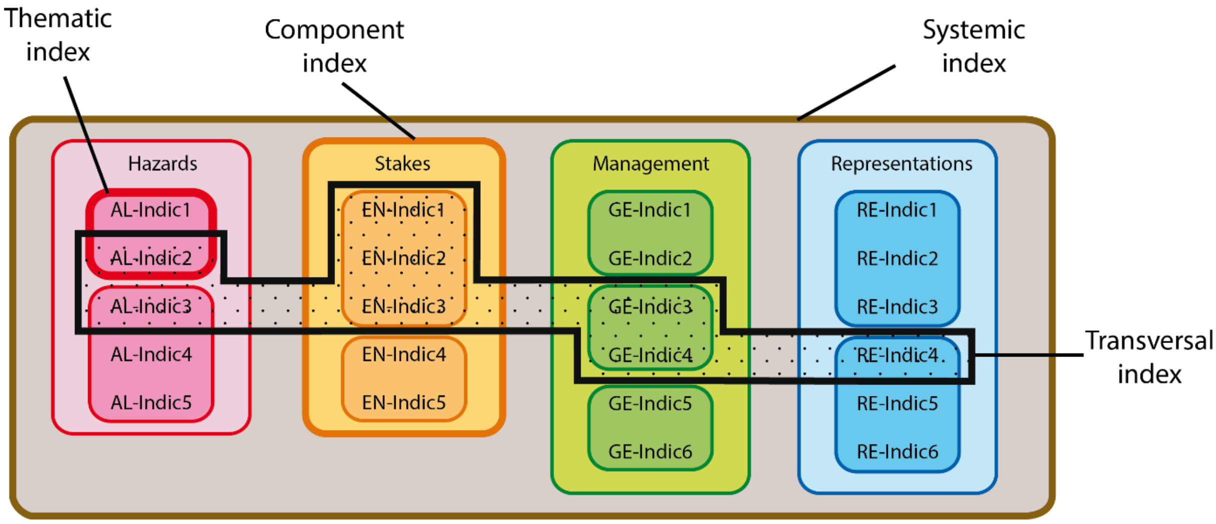


Figure 6: Methods of aggregating indicators for generating indices [color]

Thematic indices integrate a limited set of indicators that are from the same component and describe the same theme (for example, an erosion index or a human assets index). Aggregation of thematic indices enables the generation of a *Component index* (in our case Hazards, Assets, Management, or Representations). *Transversal indices* correspond to a third category that integrates indicators dealing with a particular subject matter: for example, human vulnerability [104], vulnerability of buildings to coastal erosion [105] or to marine flooding [73]. The transversal dimension of this index category results from the fact that the indicators or indices that constitute them come from different components. In this sense, a risk index, integrating assets and hazard indicators, is a transversal index. Finally, the component indices, combined together, can give rise to a *Systemic index* that describes the four components of vulnerability that were retained in our conceptual approach. It should be noted that this modular approach makes it possible to integrate other components, such as claims' ratio [106].

From a practical point of view, simple computation methods have been chosen, following feedback from stakeholders, so that any type of user can understand them. The aim is not so much to produce a unique index allowing the assessment of global vulnerability of a territory, but to be able to navigate through a vulnerability system in order to understand the factors controlling vulnerability and their relative contributions. Thus, when producing thematic and component indices for hazards and assets, the maximal values among aggregated indicators were chosen. Despite the saturation effect induced by this computation rule, it is efficient to output the hazards hotspots.

Risk is considered as the probability that a hazard will occur affecting the assets that are exposed to it. Therefore the risk index is produced using a matrix, following [85], that assigns, from an empirical choice, a value to each cells at the intersection of hazards value and assets value. The assignment of the values of the risk matrix is meant to optimize the distribution of risk values over the entire scale. In this index the absence of hazards or assets (rated 1) means the absence of coastal risk (fig. 7).

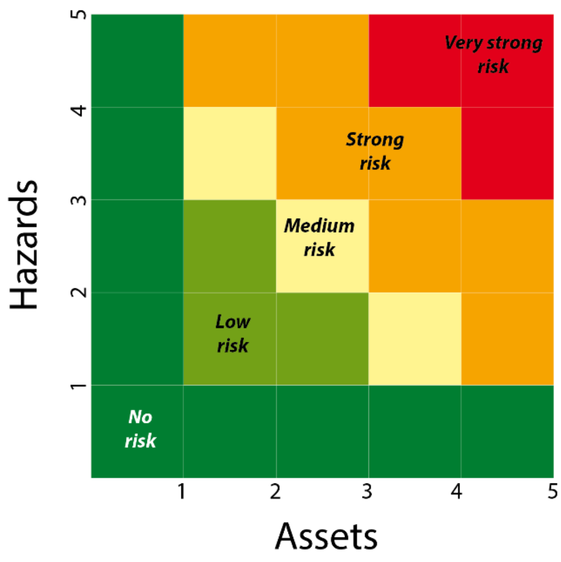


Figure 7: The risk matrix is the result of the intersection of observed (erosion) or potential (low-lying areas subject to flooding) hazards and assets. [color]

The indicators scale has been calibrated to situations encountered in Brittany. Higher values exist at other sites in France. Colours were chosen intentionally so as to create a contrasted map: attention is drawn locally to the most at-risk areas.

3.5. Development of a web-GIS interface

To map indicators and indices, we developed a web-GIS interface that allowed our set of indicators and indices to be explored, and enabled the reader to understand the methodological foundations (data sources, generation protocols, interpretation keys), while at the same time making it possible to navigate through the components using indices that can be aggregated and disaggregated [107].

First, this application, called OSI, has to allow integrating the data from both stakeholders and scientists and publish it into a coherent and secure database. It then sets out to make sure that users can access the entire inventory, indices and their metadata. Finally, it offers an interactive graphical and mapping dashboard that allows to visualise and follow vulnerability in all its spatial, thematic and temporal dimensions. Its architecture is based on open source solutions [108] – React.js, postgreSQL/postGIS and geoserver – and underwent specific modifications to improve its ergonomics and appearance.

The OSI interface is open-source and freely accessible on the Internet[v]. The navigation interface is accessible through the project presentation window. It is organised around a map display that allows the user to choose a territory (a municipality or an inter-municipality) and a navigation menu through the indicator and index structure (Fig. 8). Once these choices have been made, the map and its caption are displayed, as well as its metadata (in a simplified form, but which can be consulted in more detail via another window). Each grid can be queried to consult the values of the component indicators.

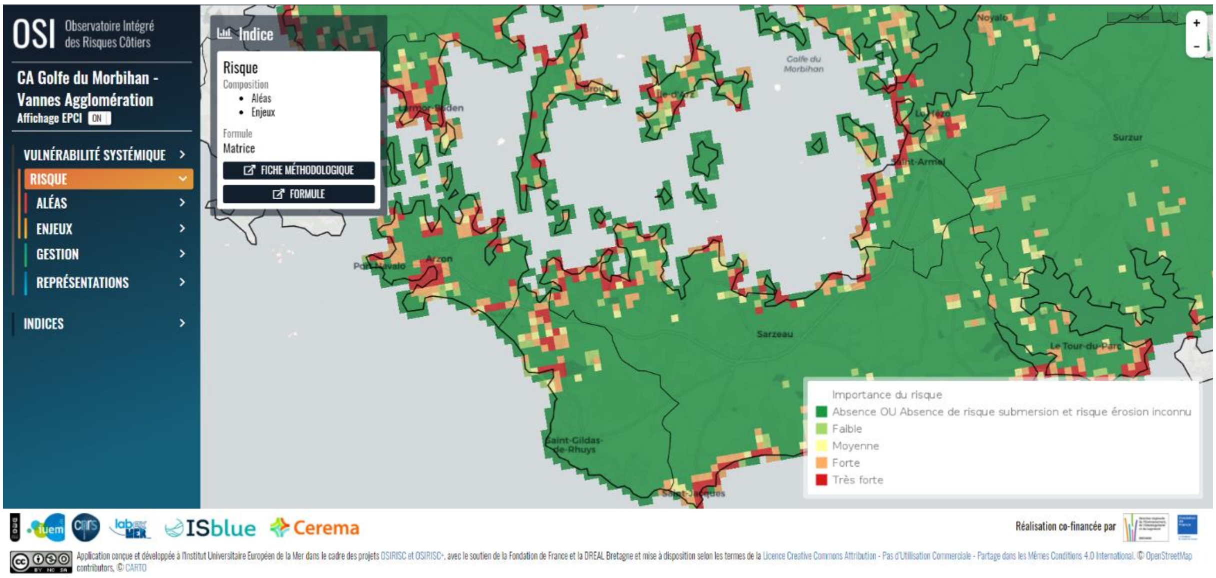


Figure 8: Screenshot of the OSI web-GIS interface

4. Results

4.1. A regional diagnosis of exposition to coastal risks

The Hazard index is computed as the maximum value of each of these indicators in the grid cells, as erosion and flooding hazards are most often closely linked [109]. The Brittany coasts are very diverse in their exposure to hazards, which results from a complex geology determining the coastline orientation in relation to waves and winds, the succession of rocky points and coves of various sizes, and the availability of sedimentary stocks. Under these conditions, several parts of the Brittany coastline appear to have low exposure to coastal risks (fig. 9), either because of their nature (high coasts with rocky cliffs, made of granite or sandstone), or the relatively low density of their assets: e.g. Crozon peninsula, Cap Sizun, or the islands (with the notable exception of the island of Sein, lying at a particularly low elevation). However, as confirmed by the graphical results showing the Hazard index (fig. 9), the areas at risks occupy relatively large surfaces at the local level, although relatively fragmented: to the north, the Bay of Mont-St-Michel and St-Malo, Haut-Léon and Côte des Légendes; to the south, Pays Bigouden and Fouesnant as far as Concarneau, from Lorient to Etel, then the Golfe du Morbihan. Most of them are low-lying areas, consisting of polders developed in the 19th century for agricultural purposes, which underwent significant urbanisation in the second half of the 20th century due to their residential and touristic appeal.

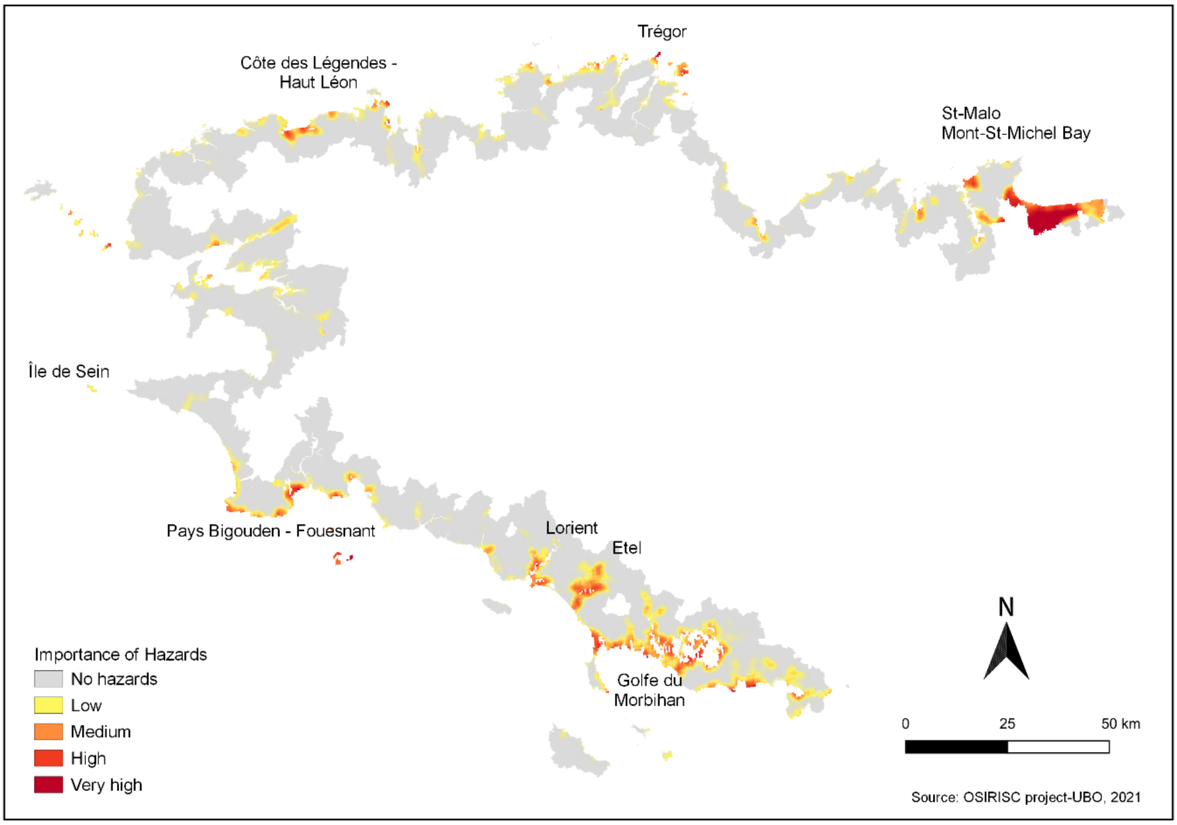


Figure 9: Exposure of Brittany to coastal risks (erosion and flooding)

The 200m grid is quite encompassing and therefore tends to overestimate the areas exposed to hazards, then the risk, especially for erosion. Therefore, the following figures should be treated with caution. With this resolution, the coastline that is exposed to erosion covers a surface of 4,392 hectares over a total of 70,000 hectares of coastal area, i.e. only 6.3%. The assets exposed to this hazard are therefore quantitatively limited and highly localised, but the damage to property would be irreversible. As for the flooding hazard, this covers a surface of 56,000 hectares over a total area of 81,500 hectares (69%) of low-lying areas, including 15,000 hectares (18.5%) that are potentially exposed to a flooding level of over 2.5 m. The analysis primarily shows that erosion and flooding generally occur in association, whereas the regulation frameworks for managing these risks are still highly differentiated in the French system [110]. A recent law, commonly referred to as climate and resilience[vi], has pushed the discrimination even further, pulling coastal erosion out the list of major natural hazards.

In total (Tab. 3), there are 170,000 inhabitants in the grid cells exposed to erosion and/or marine flooding at the regional scale, of which nearly 70,000 are in highly exposed areas. 168,000 residential buildings are exposed to coastal hazards. Although the available data does not allow for a precise estimate, this number includes a significant proportion of secondary homes: 13% at the regional scale but often exceeding 50% or even 70% on the coast, like in the Golfe du Morbihan or on the islands[vii].

The number of jobs exposed to flooding is estimated to be close to 130,000, including over 67,000 in the most exposed areas. Large areas of industrial, commercial and agricultural premises are located in exposed grid cells, (3.6 million m^2), half of which are in areas that are very highly exposed. In addition, agricultural land can, at the local level, be exposed to hazards, particularly in the low-lying areas (nearly 22,000 hectares, 9,500 of which are in areas that are very highly exposed). Finally, 460 historic monuments are located in exposed grid cells, 238 of which are very highly exposed. Although these are mostly small-scale heritage monuments, they play a major role in territorial identity and are an important tourism attraction for Brittany, therefore justifying the implementation of certain management measures.

Table 3: exposure of the assets to coastal risks

Exposure to coastal hazards	Outside of the exposed areas	Low	Medium	High	Very High	Total zones exposed
Population	1 018 430	46 658	25 721	28 622	69 931	170 932
Residential building (no. buildings)	683 873	42 113	25 317	30 942	69 370	167 742
Job (no. jobs)	502 563	30 414	15 486	15 937	67 336	129 173
Industrial, commercial and agricultural buildings (area in m2)	26 680 408	775 587	497 267	469 629	1 866 823	3 609 305
Agricultural land (area ha)	222 658	4 608	3 426	4 287	9 531	21 852
Heritage (no. monuments)	811	88	48	86	238	460

Even if overestimated, the exposure of the Brittany coastline to coastal risks is therefore obvious. Indeed, the public authorities are beginning to consider this problem, particularly as it is expected to worsen in the current context of sea level rise. Increasingly stringent management measures are being put in place, so it is interesting to monitor their development and enforcement.

4.2. Monitoring the implementation of coastal risk management

The French risk management system is particularly complex [111,112]. It has been defined and applied progressively as the public authorities become more aware of the coastal risk-related issues. Some events have played a major role in the evolution of the management policy. For example, the storm Xynthia, which impacted the French Atlantic coasts during the winter of 2010 causing nearly 50 deaths, has had major repercussions on risk management principles [113–115]. However, the sheer number of tools, and the coordination difficulties between strategies often conceived at the national or European level and their application to local situations, result in a very gradual implementation of management systems and in significant gaps between the regulatory texts and their application in real life [112]. In order to comply with national regulations, local authorities must therefore select and prioritize the actions to be implemented at the local level, according to the range of tools proposed and according to the characteristics of their territory, their political priorities and their means of action. As a consequence, the purpose in monitoring the *Management* component in our observatory is as much to analyse the form given to these management strategies, as the diversity of the means implemented and their general effectiveness.

In that purpose, we aim to assess the entire management measures implemented by the territories concerned (municipality or inter-municipality) to prevent, anticipate and manage crises, as well as to raise awareness among the population. Some management tools – i.e. local strategy, Flood prevention action programmes (PAPI), Local safeguarding plan (PCS), the Municipal information document on major risks (DICRIM) - are assessed by two indicators: when one of these tool is not implemented in a territory, only one indicator is considered in the calculation of the index (in order to avoid assessing the absence of the same tool twice).

The management indicators cannot be collected automatically on the Internet through web-harvesting and therefore must be collected in close collaboration with the stakeholders of coastal risk management. As the stakeholders' involvement in the project is strictly voluntary, the database of indicators is gradually being completed as the partnership network is consolidated (fig. 2). Moreover, the process of collective generation of these management indicators fully participates in the mutual information of the partners in view of the definition of a strategic reflection on the medium-term management of coastal risks.

In these conditions, we have chosen to present three examples of this indicator inventory, in three municipalities whose territories have different characteristics and are subject to different conditions of exposure to coastal risks (Fig. 10).

Figure 10 - Influence of management to reduce vulnerability (surveys conducted as of 01/06/2020)

Each indicator is represented by a line in the radar diagram. The longer the radius (value close to 5), the more management contributes to reducing the territory's vulnerability. When information is not available (e.g., state of GEMAPI2 [managing aquatic environments and flood prevention] structures) the indicator is not filled in. Not all management indicators are intended to reach the maximum level of the scale as management is understood as a strategy for reducing vulnerability.

In Guissény, the value of the management index is 2.6/5. The municipality is highly exposed because it has a large low-lying area, the Curnic, located in a polder separated from the sea by a dike and a pond. It includes 189 dwellings and a campsite. The extraterritorial integration indicator shows that management is carried out on a supra-municipal scale, in this case the Lesneven Côte des Légendes community of municipalities, which has long been aware of coastal risk issues. This is evidenced by the presence of a team dedicated wholly or partly to coastal risk management and by the maintenance of an early-warning system. The management system is also based on a strong knowledge base, acquired through a long-term partnership with our university research team, initiated by the awareness of this risk exposure, but also by the fact that the area belongs to a Natura 2000 site with high environmental value [116].

With an identical value (GI = 2.6/5), the system set up is different at Ile Tudy, a small commune in the south of Finistère which is highly urbanised and exposed to flooding hazards. The system is based on the implementation of a risk prevention plan (PPRL) to control urbanisation and a local management strategy. The particularity of this strategy lies in the strong involvement of the population: local stakeholders in association with government services, associations, schools, towards whom a major effort is made on awareness-raising. In addition, the crisis management is based on various early-warning methods.

In Crac'h, a commune with little exposure to hazards, the management index is 2/5. Indeed, this commune is located in an estuary where erosion is very low and exposure to submersion limited. However, this municipality is part of a local partnership, particularly within a regional natural park (PNRGM), and it is involved in local and inter-municipal management strategies through the PNRGM. It has an emergency plan, active associations and has integrated risk-related restriction zones into its town planning.

We can see that the strategies adopted differ greatly from one territory to another. Of course, these strategies depend primarily on their exposure to hazards and their socio-economic assets. But they also rely strongly on their territorial and institutional integration in structures at different scales (inter-municipalities, natural park, etc.).

Indeed, beyond a dashboard showing risk management progress, our approach reflects different policy choices according to the territorial characteristics. The aim is to give public stakeholders (local authorities, government services) the appropriate knowledge for identifying the strengths and weaknesses of the territories and the additional levers that could be used to reduce vulnerability. Furthermore, certain management measures only need to be implemented if there is a significant risk. Therefore, it may be the case that management indicators appear weak in some territories, but this is not a cause for concern or does not require additional action as there is little or no associated risk.

4.3. Understanding what inhabitants think, the Representations component

This component focuses on identifying the psycho-sociological factors involved in the construction of risk representations, taking into account the context in which they are developed [68,117]. Emphasis is placed on living conditions, the relationship to place and the experience of risk in the construction of these representations. Three main thematic indices are thus evaluated: sense of place (place attachment, identity, related practices, etc.), risk awareness and concern (understood here as reflecting the state of knowledge) and assessment of collective management practices (trust in institutions, evaluation of the effectiveness of collective measures). These different aspects of place contribute to improving understanding of perceived vulnerability, i.e. people's assessment of risk situations and their capacity for social and individual response.

In order to provide information on these indicators, quantitative surveys are carried out on residents of coastal territories, taking into account their status (inhabitants – main residence or holiday homes, stakeholders, workers, etc.). Questionnaires are administered face-to-face or online. The dissemination of the surveys benefits from the support of the local authorities through the use of their usual communication vectors (municipal bulletin, website, etc.).

The example presented is that of the 5 communes of the Auray intercommunality associated with the OSIRISC project (Locmariaquer, Saint-Philibert, Crac'h, Pluneret and Auray), in which a survey was carried out in spring 2019 among 79 residents (fig. 11).

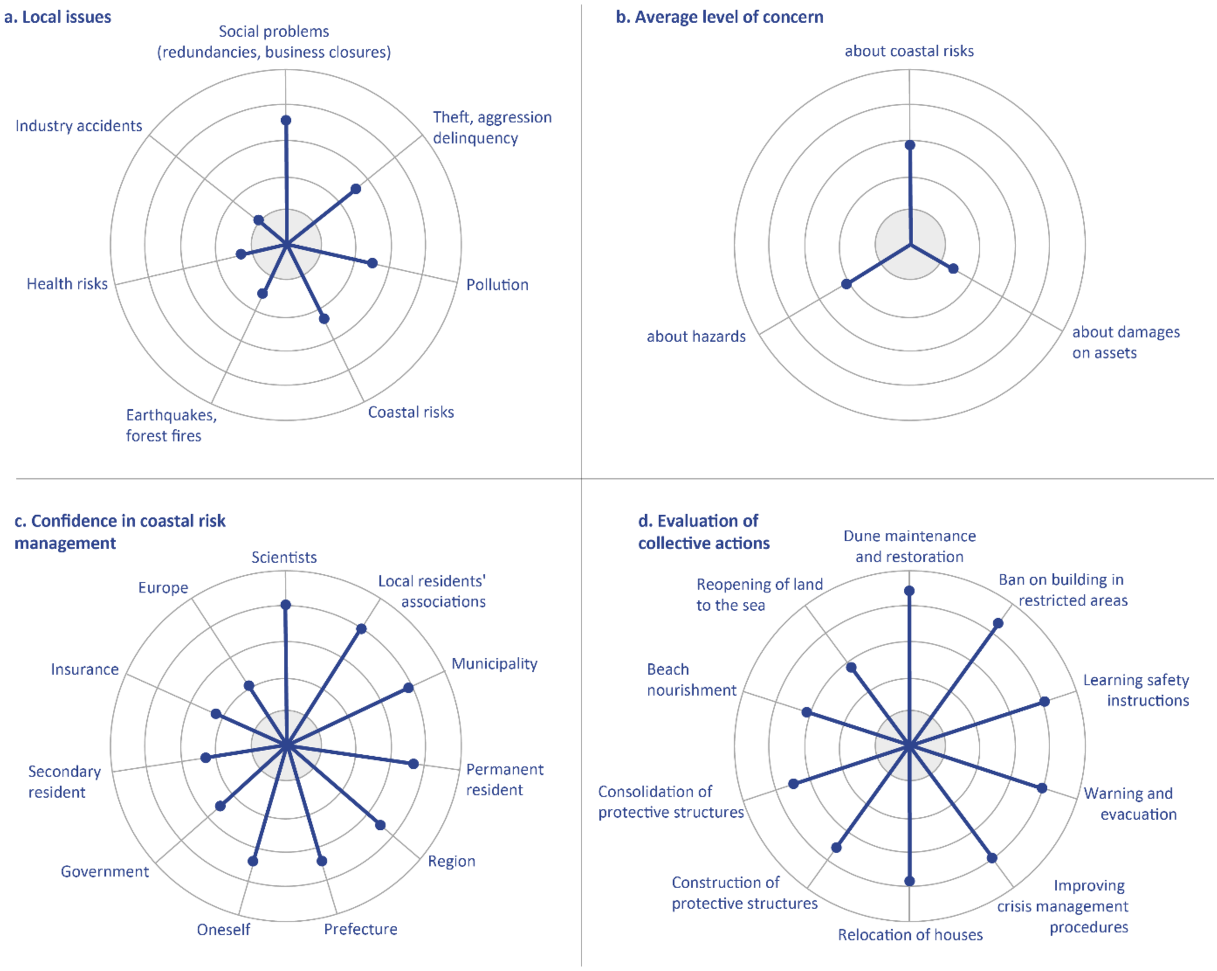


Figure 11 – Results of the survey conducted among the population of the Auray intercommunality

The questions on local issues allow us to compare the importance given to coastal risks in relation to other concerns. They show that the main concern of respondents is the closure of local businesses and the threat to jobs. The problem of incivilities, which, according to the people surveyed, increase during the summer period, comes in second place. Coastal risks are in fourth place, which demonstrates a certain awareness of risk, although this issue is not considered to be preponderant in the territory. A second set of questions measures the concern of the respondents for coastal risks. The results confirm that concern about coastal risks is not major. Respondents are not very concerned about coastal hazards and even less about the assets exposed (possibility of suffering damages from the sea). Nevertheless, more than half the respondents state that they live outside the risk zone. The level of trust in coastal risk management is measured by a series of questions about its stakeholders. Respondents report trusting most the scientists to make decisions about coastal risk management. Finally, respondents were asked about the effectiveness of the actions usually put in place to deal with coastal risks. In the study area the effectiveness of the measures is considered rather good, except for the reopening of land to sea and beach nourishment. However, judging the effectiveness of a measure positively does not prejudge its acceptability. If home demolition and retreat is a collective action that is considered very effective, this does not mean that it is approved. In a previous survey carried out in coastal municipalities in Brittany, 65% of the residents declared themselves unfavourable to this type of measure [40].

Indeed, as most studies show, representations are not directly linked to exposure to danger [40]. As such, high risk awareness can lead to high levels of involvement in risk management, but it can equally lead to an inertia that is linked to resistance to change; among other things. This depends on how the inhabitants perceive the area in which they live, the value they attach to it, and what this area represents for them. Furthermore, just as risk management potentially affects all of the territory's inhabitants, the surveys potentially cover all people concerned by the risks, not just those exposed to the risks. For example, collective adaptation measures such as setting back home may sometimes be deemed effective, but this is mostly by the people who are not exposed. These situations can lead to conflicts that can potentially increase the vulnerability of a territory. In addition, the responses collected are influenced by recent experiences and events and are therefore likely to change over time. Surveys must therefore be repeated regularly, which poses the problem of over-solicitation and possible disinterest of the surveyed populations.

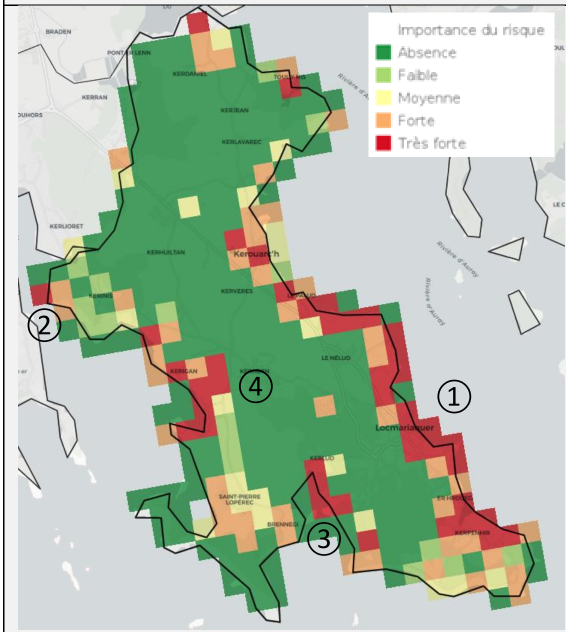
Currently, we are not yet in a position to obtain a rating that would enable us to directly integrate representations into a systemic vulnerability index, as they can both decrease and increase vulnerability [68]. However, they do contribute to the diagnosis of a territory's vulnerability and are an important component for managers.

4.4. Towards an analysis of systemic vulnerability

The four components must be considered equally, their joint consideration being a prerequisite for a holistic understanding of systemic vulnerability. However, in the framework of our study, we do not present each of the four dimensions in the same way: the hazard and assets indicators have been combined so as to obtain one risk indicator, ranked from 1 to 5, which can be mapped at a resolution of 200 m. As the management indicators are homogenised at the municipality scale, it is worthwhile presenting them individually so as to be able to analyse the management levers that enable vulnerability to be reduced. Finally, representations are presented by illustrative diagrams and each figure is accompanied by an explanatory text. These different methods of rendering and presentation have been used to propose a vision of systemic vulnerability for which, as far as the authors are aware, no numerical index has yet been proposed. As an example, in the Locmariaquer municipality in Morbihan, we can summarise the presentation of the four dimensions as presented in Table 4, an extract of the final report by the OSIRISC PROJECT [118].

Table 4: Extract of the analysis of systemic vulnerability at Locmariaquer (Morbihan)

Risk: combination of hazards and assets

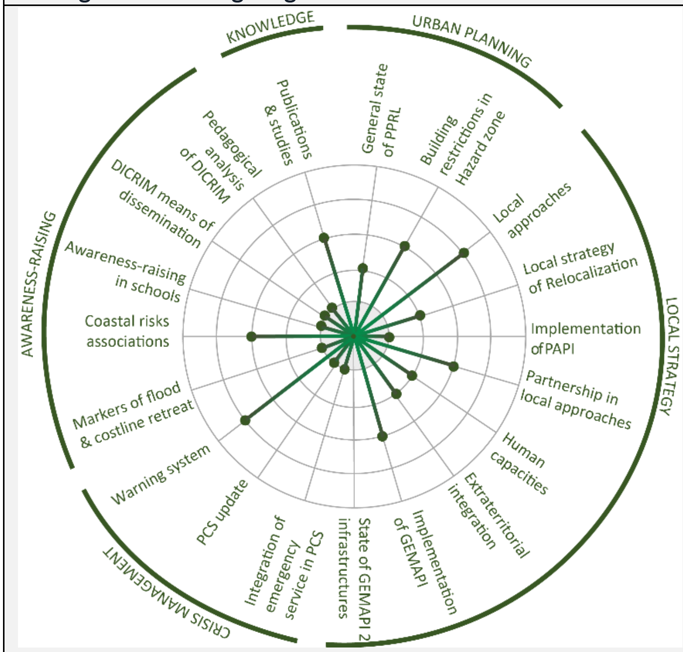


At Locmariaquer, the areas identified as being the most exposed to coastal risks are located on the municipality's western coast (1) where there are many human assets and potentially submersible low-lying areas. Other areas need special attention:

- Kerinis (2): flood risk, vulnerable population;
- Kerlud (3): significant number of low-level income households;
- Le Falzen (4): significant number of low-level income households + presence of a main road and sea protection structures.

N.B.: the potentially submersible low-lying areas are overestimated: only part of each 200m grid may be affected by the flood risk. The risk taken into account is a 100-year flood level (one chance in 100 for it to occur each year).

Management: a mitigating factor of risk



Each indicator is represented by a line in the radar diagram. The longer the radius (figure close to 5), the more management contributes to diminishing the territory's vulnerability. When information is not available (e.g., state of GEMAPI2 [managing aquatic environments and flood prevention] structures) the indicator is not filled in.

In 2018, for Locmariaquer, the indicator of the management component index was 2.1 on a scale of 1 to 5.

Not all management indicators are intended to reach the maximum level of the scale. Management is understood as a strategy for reducing vulnerability. As such, given the causes of risk for the municipality of Locmariaquer, management levers are mainly relative to the PPRL, building constraints, GEMAPI (structure management), Local safeguarding plan (PCS), warning systems, and flood markers.

Representations: experienced or perceived hazards, estimated assets and personal assessment of management

Risk representations have been assessed using surveys conducted in five municipalities (Auray, Locmariaquer, St Philibert, Pluneret and Crac'h). The results presented here are valid for the whole territory. 79 people were interviewed using a questionnaire administered face-to-face and over the internet. The results were analysed qualitatively (textual data analysis) and quantitatively (statistics).

The persons questioned on the different risks affecting their municipality rank coastal risks in fourth position, which shows a certain level of awareness about risk without the issue being seen locally as a predominant one. The persons questioned about their level of concern about coastal risk feel moderately concerned: they are not very worried about hazards and even less so by the assets. However, it must be noted that over half of the persons questioned declared themselves to be outside an at-risk area. In terms of trust in coastal risks management, they said that they trusted the scientists the most, followed by local inhabitants associations, the local council (city hall), inhabitants for which the municipality was their main residence, the Région, and the Préfecture. Finally, collective action to face coastal risks are considered to be the most efficient with, in decreasing order of efficiency: maintenance and restoration of dunes, banning construction in "red" zones, learning security instructions, warning and evacuation, improvements to crisis management, demolition and retreat of houses, construction or consolidation of protective structures.

For this territory, it can be concluded that the persons questioned are aware of the risks, but are not concerned by it. They place their trust mainly in science, and secondarily in local institutions. The actions judged to be the most effective are those dealing with the existing situation; they probably want little or no changes.

5. Discussion

At the current stage of our work, we have produced a database integrating 62 indicators, describing 4 components (hazards, assets, management, social representations) of systemic vulnerability, as conceptualised within our partnership with local authorities. These indicators can be combined to produce indices of different levels (thematic, component, and transversal). Indicators and indices can be visualised in a web-GIS interface that allows navigation through the complex system of coastal vulnerability in the Brittany region, at the municipal or inter-municipal scale and with a spatial resolution of 200 m. Metadata systematically describe the source of the data and the method used to produce the indicators and indices. This interface therefore enables to share the knowledge acquired in the study area, within the partnership developed between scientists and managers, but also with the general public interested in coastal risks. However, there are a number of limitations regarding the content and structure of the database, as well as more technical aspects related to the way it is completed and its durability The discussion will conclude with more general considerations related to systemic vulnerability assessment.

In the current state of our work, the objective of producing a systemic vulnerability index has not yet been achieved: although we have made significant progress, a limiting factor is that the components are at different stages of completion. The indicators of the hazard component are completely filled in from the national reference systems (INEC and low-lying coastal areas). They will be refined on the basis of field measurements carried out by the OSU-IUEM [95], and those carried out by local authorities in the framework of our partnership [119]. The Assets component is also fed by institutional data, supplemented by some field data from stakeholders. Sectoral indices could be added to provide a more detailed description of critical assets (ports, road networks, essential networks), and activities that structure the Brittany coastal economy (shellfish farming, agriculture, tourism). These complements could benefit from various experiences presented in the literature [120–122].

The collection of management indicators requires the support of stakeholders, as most of the data is not directly accessible on the internet and must be collected within the management structures themselves. These data were collected during the year 2020 throughout Finistère by the Departmental Council, and are currently being integrated into the database. In the territories not yet covered, the indicators will be completed as the partnership expands. This is indeed one of the cornerstones of the project, as the database should be jointly populated by scientists and stakeholders. Combined with the hazards and assets, this third component is used to calculate transversal indices, making it possible to assess the vulnerability of territories in relation to their management system.

The Representations component suffers from the constraints inherent to collecting data from individuals, in particular the difficulty in finding participants willing to respond to the survey and consequently have a sufficient number of responses, for each main variables, allowing statistical analysis of quantitative data. When carried out in situ, the individual survey is a time-consuming method that requires the mobilisation of a large number of staff or means. It is not only to find respondents who agree to answer but also respondents who agree to answer and, for example, who have experienced flooding, who are in “at-risk” areas, etc. Online surveys are a solution for increasing the sampled population and partly alleviating these difficulties. This method introduces a bias linked to the digital divide (unequal access to information and communication technologies) which could be offset by continuing local face-to-face surveys. Furthermore, representation of risks evolves over time, and memories can change according to the events experienced by the individuals. As we have seen, social representations can decrease as well as contribute to the vulnerability of territories. Consequently, the surveys should be repeated regularly and it is the repetition of measurements over time that will make possible to give meaning to vulnerability. For all the reasons, it is difficult to assign representations a quotation that can be integrated into a systemic index. At this stage of our work, they are still being analysed and displayed separately and in a qualitative manner. However, this approach already meets some of the expectations of stakeholders, who get a general appreciation of their policies and field actions. Under these conditions, the integration of a fifth component in our conceptual framework of vulnerability could be considered, for example, based on the notion of claims' ratio [39,106].

From a technical point of view, based on the data provided by the partners (scientists and stakeholders), the feeding of the database remains the responsibility of its administrator. The data must be communicated to him in a standardised format so that he can integrate them into the database. A more interactive way could be set up, based on the development of an ETL (Extract-Transform-Load) type interface, in order to allow the project partners to integrate their own data independently, provided some quality-control steps can be implemented as well. Similarly, extractions from the database are currently only done by the administrator. Additional functionalities are being developed to facilitate the extraction of data directly by users, for dissemination purposes of both the indicators dataset and synthetic “dashboard” interpretations such as illustrated in Table 4. These improvements, which are in line with the co-design principles of the observatory, will in any case require further an additional step in organizing the administration of the partnership regarding the database.

Finally, when used individually, the indices provide a static reproduction and presentation of the vulnerability, at a given moment, on a territory that has been clearly delimited. They can contribute to providing enhanced diagnostics to be carried out by the public authorities to assess their vulnerability and define their management policy. However, as the coastline is a system in a dynamic balance [9,11,32], and the systemic vulnerability components are constantly evolving and in constant interaction, [64], it is necessary to renew measures and devise appropriate ways of graphic rendering and presentation. In order to move from describing a state to describing a territory’s evolution, it is worthwhile using the notion of vulnerability pathway or trajectory [47,123]. The reproduction and presentation of vulnerability trajectories of coastal territories is a scientific issue that is key to our work, as it is both retrospective through the integration of historic data, continuous through the follow-up of the system components, and prospective through the forecasting of the effects of policy choices, and of social and regulatory changes, as well as of physical factors (hazard component). By integrating the diverse meanings of vulnerability, trajectory analysis can identify sequences of mutations, transformations and bifurcations in territorial dynamics [124].

This will be the next step in the research we have conducted in the context of implementing a regional observatory on the vulnerability of territories to coastal risks, which has now been institutionally consolidated (Litto’Risques agreement involving the Conseil Départemental du Finistère), received national accreditation[viii], and is being further developed as part of a European project [ix].

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