A multi-criteria approach to coastal flooding risk assessment: from modelling to crisis response

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Abstract

With climate change inducing sea-level rise, the vulnerability of buildings and coastal infrastructure facing marine submersion is increasing. To estimate this vulnerability, our study analyzes sensitive areas with a view to anticipating these crises and raising public awareness. Any emergency response must therefore be prepared and analyzed in advance. Simulations based on the Xynthia storm and IPCC scenarios were used to identify the areas most at risk, enabling an analysis of the vulnerability of assets located in the municipality. An historical analysis of storms has also enabled recurring problems to be catalogued and crisis management strategies to be refined. At the same time, refuge areas were defined according to precise criteria, to optimize people's response to the risk, while providing organizational support for the emergency services. To this end, a dynamic mapping tool has been developed to pinpoint areas at risk and facilitate the implementation of preventive measures. The final objective is to create an interactive digital tool to help emergency services to visualize at-risk areas in real time and optimize their response during an event. Initially, this article will set the scene and present the study area. This will be followed by a description of the methodology used to understand the mapping tool. The last part of this article will be devoted to the results and the analysis of risks and issues.

Keywords: GIS, Coastal Risks, Natural hazard Issues, Vulnerability, Automation, Decision support.

1. Introduction and context

1.1 The impact of climate change on marine submersion crises

Climate change is intensifying the frequency of climatic events, affecting many areas, particularly coastal zones. With sea-level rise projected to increase between 0.4 and 0.9m in 2100 (Pörtner et al., 2019), coastal areas are vulnerable to changes in weather patterns, and are particularly exposed to coastal erosion and marine flooding. Worldwide, 11% of the population lives in coastal areas less than 10 meters above sea level (Thiéblemont, 2023). The societal stakes are therefore particularly high and the development of crisis management tools remains a major challenge today.

Marine submersions, as the inundation of land by ocean waters is the hazard studied in this work. To carry out the methodology employed, a study area located in the Pays de la Loire region of France was determined, as this region was marked by the Xynthia storm in 2010. With significant marine flooding reported, 47 people died, including 29 in the commune of La Faute-sur-Mer in the Vendée). If the emergency services had not intervened, over dozens more people could have died on the night of the event (Mercier & Chadenas, 2012). Today, the region is also affected by a rise in sea levels of up to 70 cm, according to the latest IPCC report for the Pays de la Loire region (Raisson-Victor et al., 2023). In the wake of these events, measures have been put in place to limit the vulnerability of people and their assets. Risk prevention plans have been modified, revealing ‘black’ or ‘solidarity’ zones, where it is too dangerous to maintain living or working areas (Mercier et al., 2012). Today, this threat is growing and requires the introduction of a new form of crisis management involving both the emergency services and, above all, the local population. Raising awareness is essential to the smooth operation of emergency and evacuation plans. The management and anticipation of a marine submersion crisis is essential today and will help to avoid similar disasters in the future, as they expect to be more frequent with climate change.

1.2 Crisis anticipation and emergency preparedness

Anticipating and preparing for a meteorological crisis is vital, not only for the emergency services and elected representatives, but also and above all for the local population. A number of events have shown that poor anticipation of such events can result in many deaths. The example of storm Xynthia in 2010 is one of the most striking in France, with dense urbanization in low-lying areas was singled out for criticism. Other events, such as storm Alex in 2020 in the Roya Valley, which caused 10 deaths (Fouache et al., 2023), or the floods of October 2024 in the Valencia region of Spain (Zurriaga et al., 2024), which claimed more than 100 victims, illustrate the consequences of inadequate hazard prevention and a lack of public awareness. Although several documents are currently available to the public, very few are actually consulted (Douvinet et al., 2013). Inhabitants and tourists are not really well informed about the risks (Ferrer et al., 2016). During the 2024 floods in Valence, the vast majority of victims were trying to evacuate on roads that were completely saturated, disrupting the arrival of emergency services. These reactions are the result of a lack of information and knowledge about vulnerable areas. A significant proportion of these deaths could probably have been avoided if evacuation operations had been better anticipated. The introduction of new adaptive and interventional crisis management tools is therefore essential for current and future meteorological risks, and this work will particularly contribute by focusing on the simulation of population evacuation.

1.3 Development of an interactive mapping tool for risk management

The aim of the proposed method and tool is to revise and adapt the mapping of hazards and coastal issues. In municipalities affected by different hazards, there are a multitude of issues at stake. These are mainly linked to the presence of humans in the area (people, housing, economic activity, infrastructure, etc.) and are sometimes very difficult to identify precisely because each hazard causes different levels of vulnerability (UVED, 2006). Marine submersion can have an impact on a multitude of risk issues (from the point of view of infrastructure, traffic routes or the environment), creating a high level of vulnerability in certain areas with an altitude of less than 4.2 meters. Each issue has its own vulnerability, which depends on the elements exposed and their resistance to the hazard. It can be determined in advance of a crisis but needs to be readjusted during the event (human activity, visitor numbers, fragility of buildings, etc.). All these aspects must be considered during a coastal event. To this end, emergency services have access to crisis management plans that stipulate which areas should be prioritized. However, these tools are fixed and do not allow events to be considered on an ongoing basis.

The first part of this tool aims to develop a simulation of the coastal flooding and allows both past and future climatic events to be considered. In the same time, our tool provides a detailed and comprehensive analysis of the vulnerability of human, economic or environmental issues impacted during a marine submersion crisis. The aim is then to target the most vulnerable issues upfront depending on the submersion scenarios, while at the same time raising awareness among the population. An historical study of extreme meteorological events in the study area is also used as a comparative analysis and validation of our study. The second part proposes the location of relevant refuge areas within the study area. This is an essential aspect, as it enables residents to find safety during a crisis. In some communes, safe high areas are used to receive the public. Some residents also offer their help in receiving people during events of this type. In this context, it is important for the emergency services to have access to all this information before and during a crisis in order to optimize their response and target the areas to be prioritized. The creation of this mapping tool will enable a detailed, up-to-date and adaptable territorial analysis to be put in place.

2. Methodology and study framework

2.1 Case study: the municipality of Batz-sur-Mer

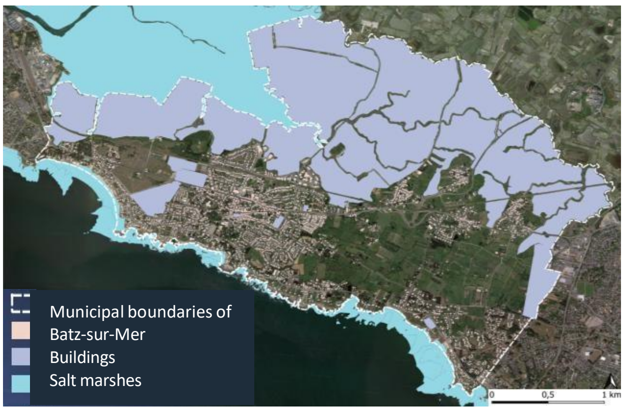

Figure 1. Cartographic analysis of the municipality of Batz-sur-Mer.

One of the objectives in developing this tool is is to be able to adapt to each region, which may have their own physical and socio-economical spatial parameters. For instance, infrastructure, topography and biodiversity are unique to each area. It is therefore important to take all these parameters into account by creating an adaptive methodology that can be applied in a wide range of contexts. To this end, this work is mainly based on the use of open-source databases. The following methodology is therefore applicable to all territories and can also be used for other types of risk, such as fires, volcanoes or industrial contaminations. It is essential to select a study site that meets all the necessary characteristics to guarantee a simulation that is both relevant and realistic. To do this, we chose a town on a peninsula, with a large area of submersible zone.

The town of Batz-sur-Mer in the Loire-Atlantique region is a pertinent site. It lies on the Guérande Peninsula, between Le Croisic and Le Pouliguen. The salt marshes are an emblematic feature of the Batz-sur-Mer landscape. Located in the north of the area, the marshes have a relatively low topography (between 0 and 5 m), making them extremely fragile and sensitive to the effects of rising sea levels linked to climate change (Pouzet et al., 2018). The municipality has two schools, one of which is located very close to the area at risk of marine submersion. Batz-sur-Mer has a permanent population of 2,823 (INSEE, 2021), but this can rise to 18,000 during the peak summer season (Ouest-France, 2022). The municipality is covered by a number of protective measures: PPRL (coastal risk prevention plan), PSC (local safeguard plan), SCOT (territorial coherence plan), DDRM (departmental file on major risks), PPRI (flood risk prevention plan), PAPI (flood prevention action plan), not to mention the installation of protective structures. All these documents enable us to anticipate and analyze the risks of marine submersion present in the municipality. The town has become increasingly densely populated as a result of the coastal development that has been taking place in France since the mid-20th century, and urban projects are constantly being planned to accommodate the new population (Mauduit et Muzart, 2021). In Batz-sur-Mer and the surrounding communes, this risk is particularly high as 500 homes and 11 business buildings are vulnerable to flooding (figure 2) as they are located in low-lying coastal areas.

Over and above all these specific aspects, the geological formation of this municipality is also one of its distinctive features. While to the north of Batz-sur-Mer there are large areas of salt marshes, to the south the geological bedrock is mainly granitic (Sellier and Portal, 2013). This formation can be seen all along the south coast along a predominantly rocky and steep coastline. This geological formation, which is sensitive to erosion over the very long term, protects the entire southern coastal strip from the risk of flooding, expected for several more sensitive sandy bay such as the Baie de la Barière that linking the rocky Batz platform with the Croisic Peninsula.

2.1 Assessing infrastructures' vulnerability level

The commune of Batz is therefore caught between the southern rocky areas spaced out by a few sandy bays, northern salt marshes and urban areas located between these physical formations. The latter faces a very high risk of marine submersion and numerous infrastructures could therefore be seriously damaged during an intense storm. Feedback from the Xynthia disaster shows that some areas were more severely affected, with more than 20 deaths in some communes. Infrastructure must therefore be identified as a priority, based on precise parameters. The idea is to measure the level of vulnerability at the scale of all infrastructures.

In order to control and anticipate a crisis situation upstream, each infrastructure must be protected and adapted, with particular attention paid to preventive measures for local residents. This work involves creating a precise methodology for identifying vulnerable infrastructures during a marine submersion crisis. Following a territorial and bibliographical study, the elements that have an impact on the vulnerability of areas are:

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Data Used and score	Subcategories and score example	Database
Building	° Types of buildings (for example "residential","school" = -1, or agricultural holding = 0.5) ° Presence of floors (=1) or not (-1) ° Building height (between -1 et 1)	BD topo, IGN
Road networks	° Type of roads (for example highway =0.8 or path = 0.1)	BD topo, IGN
Population density	°Population density distribution	INSEE
Topography	° Altitude (between -1 et 1) ° Risk zones (between -1 et 1)	BD Alti, IGN IPCC Report
Refuge areas	° Location of refuge areas (between -1 et 1) ° Refuge area size (between -1 et 1)	Data extractions from BD Topo and BD Alti (IGN) (Altitude higher than ... from the worst-case IPCC scenario and area calculation >100m²)

Precise identification of these parameters should help to optimize crisis management for emergency services. The main aim is to carry out operations in the best possible conditions and as efficiently as possible. In combination with these factors, refuge areas must be identified to ensure the safety of the inhabitants.

2.2 Historical analysis of storms

The implementation of this adaptive methodology must be based on tangible elements. This requires a historical analysis of storms to gain a better understanding of the vulnerability of the areas concerned.

Numerous sedimentary studies carried out in the region have highlighted several historical occurrences of marine submersion (Pouzet et al., 2021). One of the major events took place around 1940. According to meteorological records, a violent storm hit the Atlantic coast from 16 to 17 November 1940. A great deal of damage was caused by the wind (chimneys blown off, telephone lines cut, etc.). Protective embankments have collapsed over an 8 km stretch near Guérande, a few kilometers northern to Batz-sur-Mer. Météo-France also reported a great deal of damage due to marine submersion, in particular a break in the dyke and the use of the term 'tidal wave'. Old maps of the municipality of Batz-sur-Mer specifically show the presence of numerous agricultural areas in the northern part of the municipality, which is now inhabited: 'Animals were drowned, and many crops lost'. (Extract from the Météo France website). The socio-economic impact of this storm has been estimated at several tens of millions of francs, causing considerable shock and loss for many residents. The storm was mentioned in local newspapers more than 6 months later, revealing the scale of the crisis. However, these former farmlands are now urbanized and inhabited.

Figure 2: Comparison of two aerial images of Batz-sur-mer (1950 at the top and 2023 at the bottom). The circles correspond to the demographic expansion of the population in the risk zone. Photographs taken from the IGN's Remonter le temps website (Remonter le temps. https://remonterletemps.ign.fr. .)

This urban area is therefore highly sensitive to the risk of marine submersion. There is a concentration of living spaces and public areas in an area that has already been flooded.

The second methodological phase therefore involved analyzing these historical storms in order to pinpoint the areas at risk in the municipality. Three main zones were identified: a high-risk zone (regular flooding, mainly associated with salt marshes), a medium-risk zone (historical accounts of flooding in this zone) and a low-risk zone (based on storm Xynthia in 2010). Two additional zones have been mapped, in order to take into account, the rise in sea level according to the IPCC scenarios for the Pays de la Loire region. These mapping results (Figure 4) will make it possible to consider past and future elements linked to this hazard. In addition to this visualization of the hazard, a three-dimensional map was chosen to provide a more explicit representation. This type of mapping helps to raise public awareness of the hazard by showing how the water rises over the area (figure 5).

A digital terrain model was used to produce these maps (see table). This altimetric model is used to locate areas at certain altitudes using a raster calculator (for example, all areas below 4.20m will immediately be considered to be at risk). The IPCC thresholds are then added to this calculation, enabling all these scenarios to be identified. Subsequently, 3-dimensional mapping is possible using scenic tools. The water will then wait for the different thresholds, providing a complete and realistic visualization of the event.

2.3 Mapping refuge areas

At the same time, safety zones need to be set up to receive and manage residents. Each zone that can be designated as a refuge must be precisely targeted beforehand, so that as many people as possible can be accommodated.
The following areas are therefore defined as refuge areas:

- Any area located above 30 cm of the worst-case scenario (*i.e.* 5.10 m) combined with a surface area greater than 100 m².
- Any area that can accommodate the public at a higher altitude (gymnasium, village hall, etc.).
- Determination of a neighborhood initiative: 15% of residents located in a refuge zone can accommodate 1 to 4 people. This method has been put in place in some vulnerable municipality. In the commune of Saffré, 'hyper-neighbors' have been set up to deal with this type of problem. This methodology is the result of discussions with the SDIS 44

These areas must be known to the local population before a crisis occurs and secured by the emergency services. A map needs to be drawn up to identify these areas, make it easier to raise risk awareness and define the appropriate reactions depending on the location of the inhabitants.

2.4 Dynamic mapping and territorial analysis

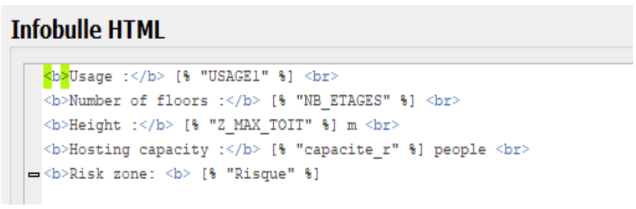
All these elements must be easily identifiable. To this end, the aim of our methodology is to create a tool for identifying vulnerable areas according to the different scenarios. To do this, we will need to use the © QGIS software with integrating all the results obtained previously. Each building and traffic route will be given a computer graphic tooltip on QGIS summarizing each parameter. The aim is to obtain, in a few moments, all the information needed to plan about a possible intervention. As a result, each building bubble will contain the following information:

- Type of building
- Number of stories
- Building height
- Shelter capacity
- Risk zone

Concerning traffic routes:

- Type of route
- Width of road
- Number of lanes
- Altitude of the road
- Risk zone
- Located in the refuge zone

All these elements are integrated into the QGIS tooltips dialogue box using HTML (Figure 3). So, for example, the integrated code for buildings is as follows:


Infobulle HTML

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<b>Usage :</b> [% "USAGE1" %] <br>
<b>Number of floors :</b> [% "NB_ETAGES" %] <br>
<b>Height :</b> [% "Z_MAX_TOIT" %] m <br>
<b>Hosting capacity :</b> [% "capacite_r" %] people <br>
<b>Risk zone: <b> [% "Risque" %]
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Figure 3: Example of HTML code inserted in building tooltips

All this information is displayed when the building or road is selected in the software, enabling infrastructure characteristics to be viewed quickly and efficiently by residents or security services agents

3. Results and analysis

3.1 Hazard analysis

The initial mapping results show that the studied area is widely vulnerable to the risk of marine submersion (figure 4)

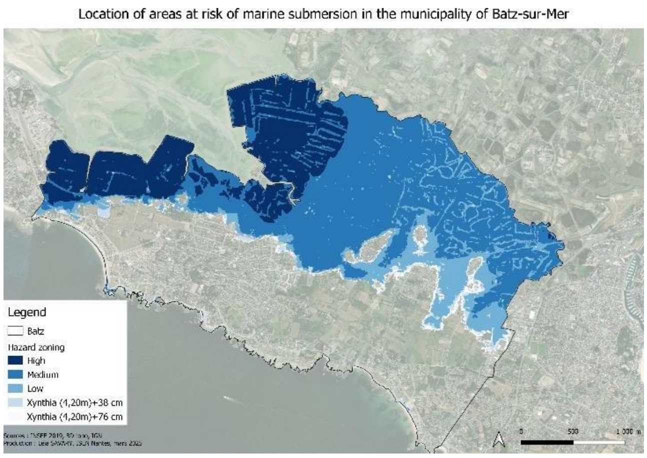

Figure 4: Map of the marine submersion hazard in the commune of Batz-sur-Mer in France

The hazard in Batz is concentrated on the northern side of the town. 54% of the commune could be affected by a scenario identical to the Xynthia storm of 2010 (*i.e.*, a surge of more than 4.2m in some areas). Future scenarios based on the IPCC indicate an additional flood risk of around 4%, moving towards the middle of the town (lighter blue).

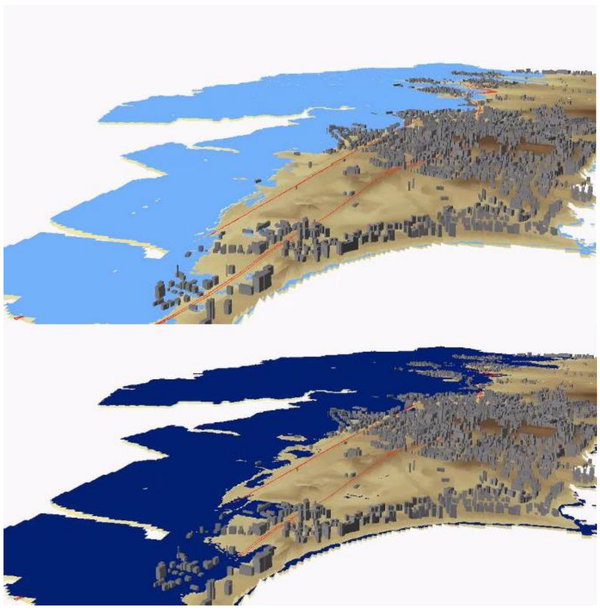

Figure 5: 3D mapping of the flooding scenario based on storm Xynthia (light blue) and the flooding scenario based on IPCC scenario 8.5 for Pays de la Loire (+76 cm water level) (navy blue)

3-D mapping has 2 main uses in our study. Firstly, they are highly visual and make it possible to visualize the arrival of the hazard and to raise awareness.

The second use is to validate the aforementioned scenarios. The submerged areas are the same across various scenarios, which allows to compare and validate with historical data.

In addition, this representation tool, which can also be distributed in video form, highlights the various problems associated with this hazard. In the case of Batz-sur-Mer, the link with the town of Le Croisic (located on a peninsula to the west of Batz-sur-Mer) could prove very complex in the event of marine submersion. While the Xynthia level of 4.20 m (light blue) leaves room for traffic (roads colored red), IPCC scenario 8.5 for the Pays de la Loire region shows a total paralysis of traffic and potential evacuations. Similarly, the formation of isolated islands to the north-east of the city poses a problem of accessibility for the emergency services. By 2100, risk management could be changing very rapidly. The creation of this tool makes it possible to visualize the hazard while understanding the extent of its impact on the issues at stake.

3.2 Vulnerability analysis

These initial mapping results show the pervasiveness of the marine submersion hazard over a large part of the municipality. In fact, 985 buildings would be affected by this threat (17.6% of the total urban area). Roads and railways would be heavily impacted in the event of a crisis of this type.

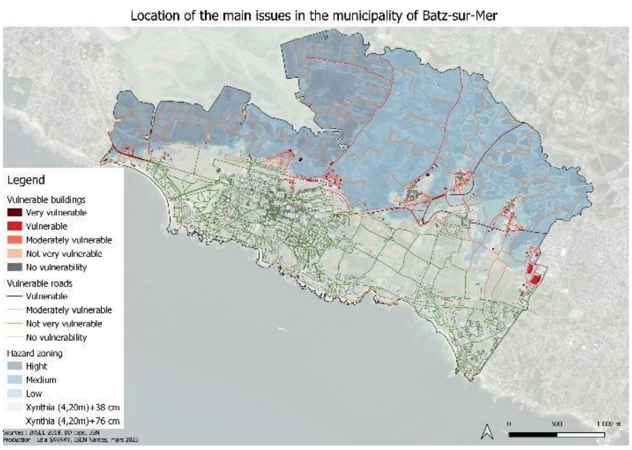

Figure 7: Map of vulnerable areas (buildings and roads) in the municipality of Batz-sur-Mer

This second cartographic representation provides additional information on the vulnerability of issues. The more likely a building is to be used by the public, the more vulnerable it will be (school, retirement home, etc.). These results can also be explained by the choice of scores. The same applies to sensitive industrial areas that are potential polluters. As far as roads are concerned, reports of various crises have shown that the more important the roads are, the more problematic it will be for them to be paralyzed in the event of flooding (evacuation, emergency services, etc.). This method of representation and classification makes it possible to immediately target problem areas according to the strength of the hazard, and thus to enable residents and emergency services to take any necessary decisions. Here, we can see the omnipresence of the risk in the north of the municipality, also explained by the presence of low-lying areas. This type of mapping is an invaluable tool for raising awareness, helping residents to plan ahead and adapt their development accordingly.

3.3 Refuge areas

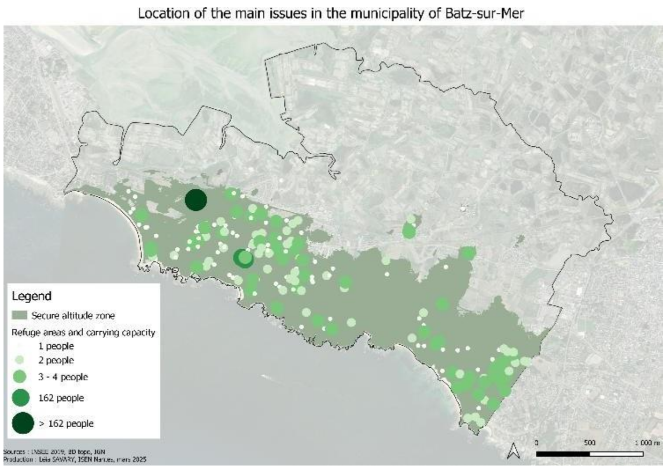

Figure 7: Map of the different refuge areas in the municipality of Batz-sur-Mer in France

The refuge zones that have been created mean that safe spaces can be located as close as possible to people's homes (Figure 7). Some areas, such as the various event halls in Batz-sur-Mer, can accommodate between 160 and 300 people, and are spread across the west of the town. Numerous surveys carried out after Xynthia show that residents are willing to take the risk into account in their daily lives (Rulleau et al., 2015). As a result, some residents (15% of the buildings located in refuge zones) may welcome into their homes residents of the commune (1 to 4) affected by flooding, in a coordinated approach across the entire study area (corresponding to the brightest points in the mapping). An organization can therefore be set up in any coastal area to ensure the safety of all residents.

3.4 Setting up a dynamic tool to interact with the data

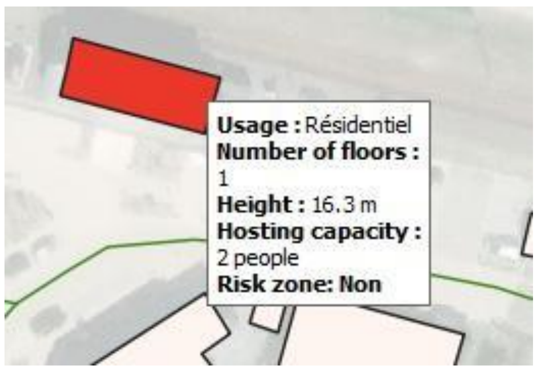

Figure 8: Example of an existing tooltip in Batz-sur-Mer, France

This methodology makes it possible to locate vulnerable areas while taking into account the hazard, the issues at stake and the refuge areas. The creation of a dynamic tool bringing together all this information means that urban features can be located immediately and precisely. In this way, each element is assigned essential data, enabling emergency services to know in advance the specific areas in which they need to intervene. The Figure 8 present the information for a building integrated in the database, such as the number of floors, its height, its capacity as a refuge area and its potential presence in a high-risk zone. This is a very interesting result in terms of crisis management. An interventional organization can then be put in place, adjusting requests and immediately favoring residents in more delicate situations than others.

4. Conclusion and perspectives

4.1 Towards a cartographic decision-making tool

Numerous low-lying and urbanized coastal areas, such as deltas or coastal marshes will becoming more sensitive to sea-level rise in the future decades (Magnan et al., 2022). This means that adaptive and effective crisis management must be put in place to protect the population from meteorological events that can cause marine flooding. The emergency services, often overwhelmed in this kind of situation, need a rapid location tool that enables them to understand and analyze the area in real time. It is essential to know or be able to easily identify the issues present in the area, particularly in the event of emergency services from other regions intervening. A clear view of these elements would enable emergency teams to better grasp the situation and quickly adapt their strategies to provide effective care. The hazard zone, the issues at stake and, above all, the shelter solutions and alternatives available in the locality must be known by the emergency services, while at the same time providing information to the public.

The methodology developed enables all these parameters to be cross-referenced. Firstly, the representation of the hazard analyzed with various probability scenarios, makes it possible to identify and locate potentially problematic areas. Next, a historical study of past risks is used to locate the issues at stake, based on what has already happened. This enables us to understand the vulnerability of each infrastructure. At the same time, refuge areas were identified, offering a safe fallback solution for all residents and reducing the response time for emergency services. Mapping of each zone then locates each element in a structured way, providing all the information needed to set up an intervention. This decision-making tool is helping to put in place new crisis management tools.

4.2 Strengths and limitations of this method

This method not only simplifies the understanding of marine submersion risks but also helps develop solutions adapted to climate change.

However, this tool has several limitations. Implementing such a methodology requires a comprehensive preliminary cartographic study, including data processing. Moreover, historical reports are sometimes difficult to access, too old, or illegible, which limits the validation of the method (Athimon et al., 2022). Improving this tool would primarily involve gaining better access to data on vulnerability, such as the number of people recorded in each household. This would enable emergency services to better plan their interventions. Additionally, increased communication with emergency services is essential to ensure the production of reliable data. This tool will then consider both scientific and operational discussions with security services to develop the most functional and effective in-situ solution possible.

Nevertheless, this tool can be easily and quickly replicated in other municipalities. The methodology could also be adapted for managing other types of natural risks (forest fires, river floods) or industrial risks (transport of hazardous materials, pollution). One of the key strengths of this methodology is its flexibility for both short- and long-term use. Indeed, each past, present, or future scenario can be leveraged through this tool and adapted to a specific situation. This new approach may also complement other multisource risk vulnerability GIS indices centered on the building (Creach et al., 2015), neighborhood (Han et al., 2023), or regional (Rigina and Balkanov, 2002) scales.

4.3 Perspectives

Several perspectives are associated with this tool. First, the automation of geographic processing is currently under development to reduce calculation time and optimize data analysis. This work will make it possible to apply this method to other territories. Additionally, the collection and analysis of feedback from emergency services in the region are underway, which will help refine the prioritization of infrastructure in such situations. Their feedback will enable the assignment of a vulnerability score to each issue. This score will then be calculated using mathematical formulas to provide a grid-based cartographic representation of the territory. The goal of these developments is to create a dynamic tool that can adjust each score, and requirement based on the information contained within each grid cell according to different scenarios.

This tool could also be made available to the public to enhance risk awareness (Islam et al., 2021). When present in the area, residents could thus be informed of the dangers and vulnerabilities related to their location. Ultimately, the tool will help better protect populations by enhancing their knowledge of the risks they face in their territory.

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