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Method to Identify the Likelihood of Death in Residential Buildings during Coastal Flooding

Axel Creach [1,*], Emilio Bastidas-Arteaga [2], Sophie Pardo [3] and Denis Mercier [1]

1 Laboratory of Physical Geography: Actual and Quaternary Environments, Geography and Planning Department, Sorbonne University, 191 Rue Saint-Jacques, 75005 Paris, France; denis.mercier@sorbonne-universite.fr
2 Laboratory of Engineering Sciences for Environment, LaSIE UMR CNRS 7356, La Rochelle University, Avenue Michel Crépeau, CEDEX 1, 17042 La Rochelle, France; ebastida@univ-lr.fr
3 Laboratory of Economics and Management of Nantes, LEMNA—Nantes University, Chemin de la Censive du Tertre–Bâtiment Erdre, 44322 Nantes, France; sophie.pardo@univ-nantes.fr
* Correspondence: axel.creach@sorbonne-universite.fr

Abstract: Tools exist to predict fatalities related to floods, but current models do not focus on fatalities in buildings. For example, Storm Xynthia in France in 2010 resulted in 41 drowning deaths inside buildings. Therefore, there has been increasing recognition of the risk of people becoming trapped in buildings during floods. To identify buildings which could expose their occupants to a risk of death in the case of flooding, we propose the use of the extreme vulnerability index (VIE index), which identifies which buildings are at greatest risk of trapping people during floods. In addition, the "mortality function method" is used to further estimate the expected number of fatalities based on (1) groups of vulnerable people (e.g., aged or disabled), (2) the location of buildings in relation to major watercourses, and (3) the configuration of buildings (e.g., single or multiple entries and single or multiple stories). The overall framework is derived from case studies from Storm Xynthia which give a deterministic approach for deaths inside buildings for coastal floods, which is suited for low-lying areas protected by walls or sandy barriers. This methodology provides a tool which could help make decisions for adaptation strategy implementation to preserve human life.

Keywords: coastal flooding risk; loss of life; fatality assessment; residential buildings; climate change adaptation; VIE index

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1. Introduction

Floods killed 8 million people in the last century [1]. The conditions under which 235 fatalities occurred in relation to 13 floods events (hurricanes and storms) were analyzed. It was concluded that 68% of the deaths were caused by people drowning in cars and on foot (33 and 25%, respectively), while just 6% occurred inside buildings [1]. By contrast, 54% (out of 771 people) were drowned in buildings during Hurricane Katrina in 2005 [2], while all of the fatalities (41) caused by Storm Xynthia in France were those drowned in buildings [3,4]. Boissier [5] suggested that for high-magnitude, low-frequency events, most of the fatalities occur inside buildings.

Storm Xynthia (28 February 2010) had major impacts along the Atlantic coast of France, especially between the Loire and Gironde estuaries. The analysis of fatalities provided by Vinet et al. [3,4] for Storm Xynthia highlighted how buildings can trap people during floods. In addition to factors such as the time of day (e.g., nighttime) and the fact no warning was given [6], they showed that (1) most drownings occurred when the flood level exceeded 1 m, (2) 90% of drownings occurred inside buildings located within 400 m of the flood defenses which failed, and (3) 78% of the drownings occurred inside single-story houses.

Subsequently, Creach et al. [7] defined areas where people could be trapped inside buildings in case of flooding as zones of "extreme vulnerability".

In response to Storm Xynthia, the French government instigated the “black zone” policy, which listed 1628 buildings in areas of extreme flood risk for demolition at a cost of EUR 315.7 million [8]. This policy attracted significant criticism, however, principally on the grounds of the lack of methodological transparency [9], expenditure, and failure to engage local communities in a timely manner. However, of principal concern was the fact that the strategy did not result in any appreciable reduction in human vulnerability to flooding hazards along French coasts, as it was also limited in scope to areas flooded in 2010 [10,11]. Thus, the policy was a reactive adaptation which lacked cost-benefit analysis and time to make an enlightened choice in association with locals.

The French Atlantic Coast is particularly susceptible to flooding. For instance, it is predicted that a centennial flood could cause 354,079 ha to be submerged [12]. In this area, there are 535,500 permanent inhabitants [13] and 136,711 buildings [12], 22% of which are single-story constructions [13]. Furthermore, flooding is likely to be exacerbated further under the current trajectory of global warming and resulting sea level rise [14–16]. Moreover, other areas along the French Atlantic coast are also exposed to floods [12], and additionally, the sea level is rising, which will inevitably increase coastal flooding.

To address these problems, in this paper, we propose a global framework to evaluate potential fatalities specifically inside buildings in relation to coastal flooding. To achieve this, the novelty is to use extreme vulnerability index (VIE index) to evaluate the buildings at greatest risk of flooding and to assess the implications for human fatalities [7] in addition to the population’s features. Using lessons learned from Storm Xynthia, this yields a deterministic approach which is suited for low-lying areas exposed to coastal floods with numerous single-story houses, features which are those of the French Atlantic coast. Thus, this paper will demonstrate the value of the VIE index in assessing and locating most risky houses which could, in fact, help decision makers to establish strategies to protect human life from flood risk in the future.

2. Materials and Methods

2.1. State of the Art of Fatality Assessment Methods

2.1.1. General Principles of Fatality Assessment

The assessment of fatalities due to floods is a relatively new research field [17,18], with research shifting from the hydrological process to its management [19]. Several major studies have been conducted in the UK, Netherlands, and Canada [20,21] because of greater data availability pertaining to the conditions under which flood-related fatalities occurred. These data have been crucial to the development of numerical models. In particular, these studies focused on coastal or inland floods due to breaches in flood defenses, and they differ from other work that has focused on fatalities caused by tsunamis or hurricanes [22–24].

According to Di Mauro et al. [21], fatalities are mainly influenced by the number of exposed people which could be reduced by preventive evacuation. The flood magnitude, frequency, and location, as well as the types of buildings and people’s vulnerability and behavior are shown to be the main variables controlling fatality risk.

Fatalities can be evaluated in two different ways on the basis of scale [21,25]: (1) at the microscale, which pertains to “individual risk”, and (2) the macroscale, which considers the overall risk to society. Microscale studies are useful for understanding individual human responses to flooding, but data are lacking, and as a result, numerical models rely on interpolation and possess limited predictive power [21,26]. Macroscale risk is simpler in terms of assessing the likelihood that deaths will occur in relation to several factors [20,21]. This probability has been estimated through examining the statistical relationships between the fatalities and characteristics of past floods [17]. For example, Klijn et al. [27] estimated that 0.3% of people could die in the Netherlands due to a flood, and according to Jonkman et al. [17], 1% of exposed people globally are expected to die in coastal floods.

2.1.2. Methods for Assessing Fatalities

Three different methods are used to assess fatalities in relation to floods [21]. First, the Life Safety Model (LSM) focuses on individual risk. It was developed in Canada to assess potential fatalities due to dam failure [28,29], and it involves modeling of the behavior of individuals during floods using an automated 2D cellular model. The health of individual people is considered in the model. The method requires specific data about the hazard characteristics (e.g., timing and magnitude), the age and health of the people, and the building type, configuration, and general accessibility for the purpose of evacuation [21]. This model is useful for simulating evacuation planning and evaluating the mitigative effects of warning systems on crisis management [21]. It can also be used for educational purposes to define the best course of action on what to do in the case of flooding.

Second, there is the Flood Risk to People (FRP) methodology—developed in the UK [30–32]—which can assess both societal and individual risk. The societal risk aims to evaluate the potential consequences of a flood. It functions by multiplying the exposed population by a rating factor defined for different sectors. This rating is based on the assessment of the characteristics of the flood (e.g., water height, water flow, and debris content), area vulnerability (e.g., type of land use and building configuration to offer shelters), and the population characteristics (e.g., age and mobility). For each of these aspects, areas with similar properties are demarcated. The number of people at risk is obtained through a census [33], which is then divided into residential buildings, and the number of potential deaths is thus estimated. This method is used to assess the consequences of different floods to derive a large-scale risk assessment.

Uncertainties exist regarding the evaluation of the number of people at risk depending on the timing of the flood [30–32]. The methodology nevertheless provides an estimate of the areas at greatest risk of flooding. It was originally designed to be used as an operational tool for decision makers in the UK, but only the flood hazard parameter was used. Priest et al. [34] adapted the FRP methodology for continental floods in Europe. They showed that the FRP methodology overestimated the number of deaths outside the UK due to the fact it did not consider population behavior and preventive evacuation. The Risk to Life Model (RLM) introduced a "mitigation" component to the methodology, which is defined by the level of awareness and the ease by which people can be evacuated. It is divided into four classes, depending on the evacuation rate, from >75% to >25%.

Third, the mortality functions method [17,25,35] focuses on fatalities related to coastal and inland floods following the failure of flood defenses. It is particularly useful for areas reclaimed from the sea (polders) with flat land protected from floods by flood defenses. The goal of the method is to estimate the fraction of fatalities from the total population exposed to flooding to derive the number of potential fatalities (Equation (1)):

$$N = F_D N_{EXP} \tag{1}$$

where N is the potential number of deaths, F_D is the mortality fraction, and N_{EXP} is the number of exposed people.

The mortality fraction (F_D) is defined by the severity of the hazard, which is controlled by the extent of the flooded area, water depth, the kinetic properties of the flood, or the proximity to flood defenses. Jonkman et al. [17] employed a 2D model to simulate different flooding scenarios. The simulated flooded area is divided into three zones ranked according to the conditions of the flood defenses: (1) the breached zone (torrential flow), (2) the zone of rapidly rising water, and (3) the zone with minimal flooding. For each zone, a mortality function is given depending on the flood characteristics (i.e., from 1 (certain death) to 0 (no risk of death)). Thus, in the breached zone (maximum of 300 m behind the breach), the mortality fraction is theoretically equal to 1 [35], though most recent works on Storm Katrina show a value of 0.053 [2].

The mortality function is then multiplied by the number of exposed people (N_{EXP}). This number depends on (1) the total number of inhabitants in the flooded area, (2) the number of people evacuated before the flood, (3) the number of people in the process of evacuating during the flood, and (4) the number of people rescued. The method is simple in that it only requires an estimation of the number of fatalities from the total number of exposed people in a specific area. However, the model parameters are based primarily on the characteristics of the flood.

In theory, the model could be modified to explicitly account for fatalities inside buildings. Consideration of a building's configuration as a control on the vulnerability of people to flooding would result in a different mortality function estimate. A simple solution would be to multiply this value by the total number of exposed people inside buildings.

2.1.3. Limits of Fatality Assessments

The advantages and limitations of the various methods are listed in Table 1. Generally, micro-tools require numerous hypotheses regarding (1) the behavior of people during floods, (2) flood wave kinetics, and (3) accurate data about the occupation of buildings. Furthermore, powerful software is then needed to simulate the spatial and temporal properties of the flood and the time needed for evacuation in different flood scenarios.

Table 1. Advantages and limitations of the three fatality assessment methods.

Type or Scale	Method	Advantages	Drawbacks
Micro	Life Safety Model (LSM)	Realistic, accurate locations of deaths	Technical, fine data needed for modulization
Macro	Flood Risk to People (FRP)	Takes into account several dimensions of vulnerability	Data not fully available in France
Macro	Mortality functions	Easy to use	Mainly driven by hazard characteristics

Macro-models try to assess the potential number of deaths through several factors pertaining to flood characteristics and the vulnerability of people. Thus, an important objective is to assess the potential for fatalities that occur inside buildings at the building scale.

The FRP methodology [30–32,34] provides a holistic approach including parameters related to the flood hazard, such as the vulnerability of a given area and the vulnerability of people living in or occupying that area. However, this approach was originally designed in relation to floods in the UK and is relevant thanks to a wide range of accurate data available there.

The mortality function method [17] is advantageous for its simplicity of use. However, as stated earlier, it relies on the characteristics of floods to define the mortality fraction. In this paper, we suppose that the configurations and locations of buildings are also crucial contributing factors to fatalities. The methodology proposed is a complementary approach to the mortality function method but with an increased emphasis on vulnerability.

The factors used in various methods are summarized in Table 2. This table shows that it is a challenging task to measure and model all the parameters which could lead to fatalities [17,20,34]. The most complete (FRP) method includes six over seven of these parameters, while the others integrate just four or five. Three factors refer to flood characteristics. Di Mauro and De Brujn [36] stated that results are largely influenced by the extent of the flooded area, which then raises questions about the simulation of flood hazards. The introduction of a new parameter based on vulnerability may considerably enhance fatality estimation.

Table 2. Parameters integrated into the main flood fatality assessment methods (adapted from [20]).

Model	**Sourced**	**Factors Applied**							**Data Obtained from Real Floods (HP) or Laboratory Research (L)**
		Water Depth	**Water Velocity**	**Rate of Water Level Rise**	**Warning and Evacuation**	**Prepardness**	**Collapse of Buildings**	**Vulnerability of Individuals (Weight, Height, Gender, Clothing)**	
LSM	Lumbroso et al. [29]	X	X	X	X		X		
Mortality Functions	Waarts [37]	X	X	X	X				HP
	Vrouwenvelder and Steenhuis [38]	X		X	X		X		HP
	Jonkman [35,39]	X	X	X	X	X			HP/L
FRP	HR Wallingford et al. [31,32]	X	X	X	X		X	X	HP
	Priest [34]	X	X	X	X		X		HP

At present, buildings are only considered in terms of risk of collapse [20], potential shelters [31], or for their own vulnerability [40]. According to Di Mauro and De Bruijn [36], the fact that buildings are scarcely integrated in this type of study is due to the lack of knowledge of mortality inside buildings. In this respect, the studies of the fatalities due to Storm Xynthia [3,4] and Hurricane Katrina [2] are very useful.

Table 2 also shows that most of the tools are based on specific flood case studies, which could affect their applicability to other territories or flood events [17,20,34].

Estimating the number of exposed people to floods also affects the estimation of fatalities [36]. Quantifying the number of exposed people is challenging because this will vary according to the time of day, season, and the amount of time taken to evacuate particular types of buildings (e.g., residential homes and offices). According to Jonkman [35], the goal of mortality functions is not to provide an exact estimate of the number of deaths but to assess the risk level. For Di Mauro and De Bruijn [36], it is more appropriate to give the result as a percentage of fatalities rather than an exact number. To give an appropriate estimation, the best way would be to multiply flood and evacuation scenarios [36] to identify flood-prone areas in which more fatalities are likely.

In summary, the existing tools do not provide a specific assessment of fatalities inside buildings at the building scale. Therefore, we propose a framework that integrates and assesses the risk of death inside buildings at the building scale, which could be an add-on to other methods.

2.2. VIE Index: A Tool to Locate Buildings Which Could Expose Their Occupants to Death

2.2.1. Context

Due to a lack of knowledge about the death risk inside buildings at risk of flooding, there are few integrated fatality assessment methods [36]. We therefore used the VIE index method (*Vulnérabilité Intrinsèque Extrême*, i.e., extreme vulnerability assessment) recently proposed by Creach et al. [7] to integrate the role of the building type and configuration in relation to assessments of fatality risk. Following Storm Xynthia, the deficiencies linked to policies such as the "black zone" and general methods used to identify buildings that put people at serious risk [9,41] resulted in the VIE index being designed to explicitly assess the role of buildings in trapping people during floods. The VIE index does not focus on the risk of building collapse, which is related to the quality and design of buildings. Both tsunami [42–48] and inland flood hazards [34,49] are not treated by the VIE index as ends in themselves. Its main goal is to identify buildings which could trap their occupants during flooding because of their configuration and location. In this way, the VIE index focuses more on the vulnerability parameters than on hazard characteristics.

2.2.2. VIE Index Methodology

The VIE index is based on four major criteria which contributed to people having been trapped in residential buildings during Storm Xynthia [3,4] (Figure 1):

- Cr1: Potential water depth inside buildings;
- Cr2: Distance to flood defenses;
- Cr3: Architectural typology of buildings, since single-story constructions are more likely to trap people than multi-story buildings, where people could escape upstairs;
- Cr4: Proximity to a rescue point to facilitate ease of evacuation.

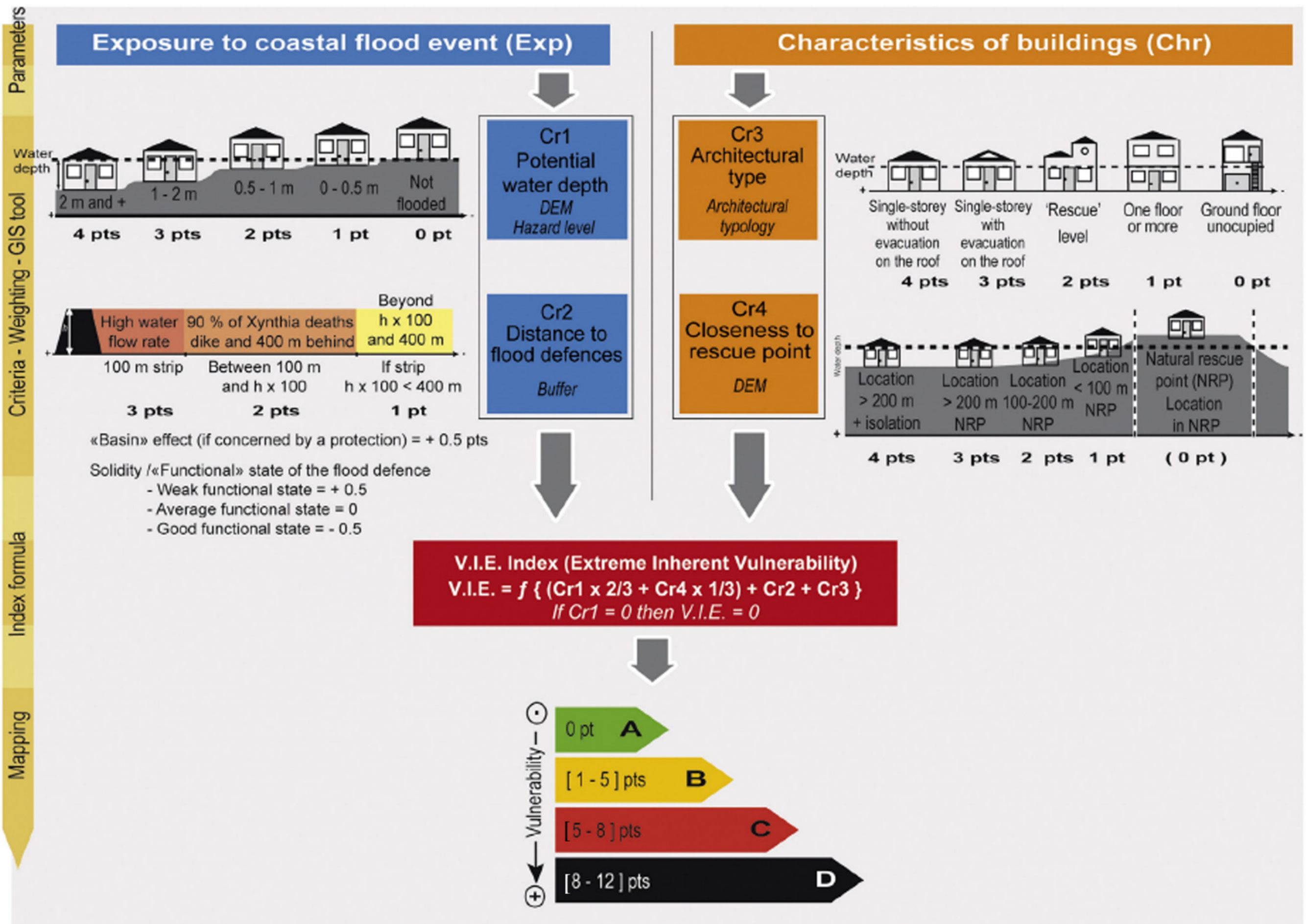

Figure 1. The VIE index methodology (source: [7]). "DEM" corresponds to Digital Elevation Model used for calculation, and "h × 100" strip corresponds to a strip behind flood defenses for which the width is 100 times the height of the dike.

Each of the criteria is rated from 0 (no vulnerability) to 4 (high vulnerability). Creach et al. [11] proposed the formula below (Equation (2)), validated through statistical analysis, to demarcate buildings that pose the greatest risk in terms of trapping people during floods (Figure 1):

$$\text{VIE} = \left(\text{Cr1}* \frac{2}{3} + \text{Cr4} * \frac{1}{3}\right) + \text{Cr2} + \text{Cr3} \tag{2}$$

The results range from 0 (no vulnerability) to 12 (maximum vulnerability). To map the results of the index, they are divided into four classes which represent different levels of vulnerability:

- Green class (VIE index = 0): buildings are not exposed to floods and therefore do not endanger people;
- Orange class (VIE index = 1–5): buildings are of a suitable design to reduce risk to people during floods. The level of risk for people is low;
- Red class (VIE index = 5–8): the risk for people is high but non-lethal if appropriate action is taken, except for older, younger, or disabled people;
- Black class (VIE index = 8–12): the risk for people is very high and could result in fatalities in the case of flooding.

The VIE index method has been validated through statistical analysis [11]. The first results were then validated by comparison with the locations of deaths during Storm Xynthia [11]. The calculation of the VIE index shows that 83% of fatalities occurred in buildings classified "black", while 17% of the fatalities fell within the "red" class. Thus, this shows the good ability of VIE index method to identify buildings in which death may occurs in the case of a coastal flood.

2.3. A Derived Method for Evaluating the Risk of Fatalities inside Buildings during Floods

From the methods and their limitations reviewed in Section 2, a derived method for assessing fatalities is proposed which involves the following:

- Focusing on vulnerability more than on hazards;
- Using data about fatalities that occurred inside buildings during Storm Xynthia;
- Incorporating the VIE index method to assess the vulnerability of buildings for people.

We included the FRP framework because of its holistic approach [30–32,34] and the mortality function method [17] for its simplicity in calculating a mortality fraction for areas of equal vulnerability. In contrast with Kolen et al.'s paper [6], where they applied the rule of thumb of 1% deaths during coastal floods for Storm Xynthia (see Appendix A), we calculated a specific mortality fraction for each area, which assumed that the probability of death varied according to the building's vulnerability to flooding. Though only a single event, the data for Storm Xynthia [3,4] enabled us to calculate the following in a determinist way:

- A relationship between fatalities related to Storm Xynthia and buildings which posed the greatest risk to people, as determined by the VIE index [11]. This allowed us to estimate a parameter close to the FRP framework's area vulnerability.
- A relationship between the age of deceased people and the total number fatalities. This allowed us to estimate a parameter close to the FRP framework's people vulnerability.

These two parameters are then used to estimate a mortality fraction.

Another important aspect of Storm Xynthia was the importance of secondary houses (i.e., houses which are held by people who do not live there throughout the year and which are mainly used for leisure during holiday times) in the coastal municipalities impacted by the storm, which had a major influence on the number of exposed people. This is an additional parameter to be estimated for assessing the exposed population.

In summary, we propose an add-on methodology that assesses fatality risk, taking into account the two previously mentioned aspects for the assessment of the mortality rate (Figure 2).

2.3.1. Lessons Learned from Storm Xynthia's Fatalities

The circumstances regarding deaths inside buildings during Storm Xynthia are listed in Table 3, according to previous detailed work by Vinet et al. [3,4]. This shows that 29 of the 41 deaths by drowning occurred inside buildings in the municipality of La Faute-sur-Mer.

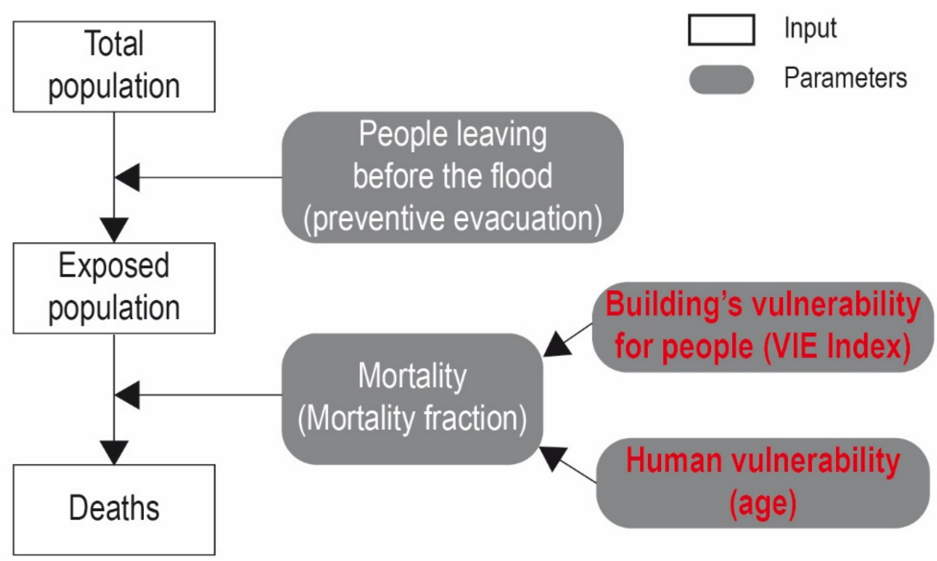

Figure 2. Proposed factors influencing the number of fatalities inside buildings due to flooding (adapted from [21]). Text in red corresponds to new parameters we propose using for calculation of the mortality fraction.

Table 3. Synthesis of death circumstances inside buildings during Storm Xynthia with regard to VIE index results.

		Number of Deaths	% of Total (29 Deaths)
Total Number of Deaths		**29**	**100%**
Deaths distribution depending on vulnerability class	Black	24	83%
	Red	5	17%
Deaths distribution depending on age	Under 15	3	10%
	15–60	4	14%
	Above 60	22	76%
Deaths distribution depending on occupation	Principal houses	20	69%
	Secondary houses	9	31%

From the VIE index, people residing in a house in a black zone are at substantially greater risk of fatality than those in a house in a red zone. According to Devaux et al. [50], 1661 out of 1996 flooded buildings in the municipality of La Faute-sur-Mer were likely to expose their occupants to a risk of death, according to the VIE index [7]. Of these 1661 buildings, 63% (1027 buildings) were "black" zone buildings and 37% (604 buildings) were "red" zone buildings, according to the definitions of the VIE index. However, 83% of the deaths were located inside "black" zone buildings according to Table 3, compared with just 17% inside "red" zone buildings. According to these results, "orange" zone buildings are not considered to be likely to expose their occupants to a risk of death, because their vulnerability level should allow people to escape (upstairs or to a shelter close to the house).

In addition, elderly or very young people are at greatest risk of being drowned. In 2006, the census reported that 45% of the inhabitants of La Faute-sur-Mer were above the age of 60 [51]. Crucially, over 76% of deaths occurred in people older than 60 (Table 3). By contrast, people aged 15–60 years represented 45% of the population in 2006. However, only 14% of the total number of deaths related to Storm Xynthia affected this age group (Table 3).

Four deaths of people aged from 15–60 were located inside black zone houses, thus confirming the risks associated with this classification of building. For the red zone buildings, 33% of the deaths of people aged under 15 and 18% of people aged above 60 occurred, which also confirms the danger of this classification of building. From these data, the probability of death relating to age and building type could be estimated.

A final point concerned the occupation of principal and secondary houses. From a total of 3737 buildings in 2006 [51], 86% were secondary houses, and only 14% were principal houses. Storm Xynthia occurred during a holiday weekend, and it is probable that several principal houses were unoccupied while several secondary houses were occupied. Table 4 shows that 69% of deaths occurred in principal houses while 31% were located inside secondary houses. This finding has important implications for estimating the exposed population.

Table 4. Results of the mortality fraction by building vulnerability class and age of population.

VIE Index Typology	Age Category	Mortality Fraction
Black class	Under 15 $\left(F_D^{B-15}\right)$	2.61%
	15–60 $\left(F_D^{B\ 15-60}\right)$	1.20%
	Above 60 $\left(F_D^{B+60}\right)$	5.38%
Red class	Under 15 $\left(F_D^{R-15}\right)$	2.22%
	15–60 $\left(F_D^{R\ 15-60}\right)$	0%
	Above 60 $\left(F_D^{R+60}\right)$	2.04%

Based on these different observations, we focused on the most vulnerable zone (red and black classes), and a mortality fraction was proposed for each situation using Equation (3):

$$F_D^{i,j} = \frac{N^{i,j}}{N_{EXP}^{i,j}} \quad (3)$$

where $i = \{B, R\}$ refers to the building vulnerability class (black or red class), $j = \{-15, 15\text{–}60, +60\}$ is the age of the population, $F_D^{i,j}$ is the mortality fraction according to the building vulnerability class and the age of the inhabitants, $N^{i,j}$ is the potential number of deaths for each situation, and $N_{EXP}^{i,j}$ is the corresponding exposed population.

Detailed calculations of the mortality fraction for each situation are given in Appendix B, and the results are summarized in Table 4 and Appendix C (lines 15–20). It needs to be said that black buildings could lead to death for all, whereas red class buildings are relatively safe except for the young and the elderly, who can have difficulties moving inside a flooded house.

2.3.2. Estimating a Global Mortality Fraction per Municipality ($F_D^{MUNICIPALITY}$)

Based on these mortality fractions, a specific mortality function per municipality, called $F_D^{MUNICIPALITY}$, is calculated, which includes the following:

- Age of the local population according to census data;
- Proportion of black and red houses according to the VIE index results.

As shown by Equation (4), each mortality fraction is multiplied by the proportion of each age category. Then, the proportions between the black and red houses are included:

$$\begin{aligned} F_D^{MUNICIPALITY} = & \left[\left(F_D^{B,-15} * P^{-15}\right) + \left(F_D^{B,15-60} * P^{15-60}\right) + \left(F_D^{B,+60} * P^{+60}\right)\right] * P^B \\ & + \left[\left(F_D^{R,-15} * P^{-15}\right) + \left(F_D^{R,15-60} * P^{15-60}\right) + \left(F_D^{R,+60} * P^{+60}\right)\right] * P^R \end{aligned} \quad (4)$$

where $F_D^{B,-15}$ is the mortality fraction for people aged under 15 in black zone houses, P^{-15} is the proportion of people aged under 15 in the municipality population, $F_D^{B,15-60}$ is the mortality fraction for people aged 15–60 in black zone houses, P^{15-60} is the proportion of people aged 15–60 in the municipality population, $F_D^{B,+60}$ is the mortality fraction for people aged above 60 in black zone houses, P^{+60} is the proportion of people aged above 60 in the municipality population, P^B is the proportion of black zone houses among dangerous buildings (red and black houses), $F_D^{R,-15}$ is the mortality fraction for people aged under 15 in red zone houses, $F_D^{R,15-60}$ is the mortality fraction for people aged 15–60 in red zone houses, $F_D^{R,+60}$ is the mortality fraction for people aged above 60 in red zone houses, and P^R is the proportion of red houses among dangerous buildings (red and black zone houses).

This method enables having a more accurate assessment of the mortality fraction for each city. For example, a city with mostly red zone houses and people aged 15–60 will have a low mortality fraction.

2.3.3. Estimating the Exposed Population per Municipality (N_{EXP})

To estimate the most exposed population per municipality in the case of coastal flooding, the fatality risk in relation to building vulnerability to flooding needs to be emphasized. In particular, this concerns the occupants of both the red and black zone houses as classified by the VIE index. This number is estimated using the total number of the potentially deadliest buildings and the average number of people per household, as defined by census data.

The importance of secondary houses will be integrated into the population estimation. This is achieved using census data in which the proportion of principal and secondary houses is collected. For each of them, an average occupation rate based on data from Storm Xynthia is proposed, which is 69% for principal houses and 31% for secondary houses (Table 4). This results in a global occupation rate for the deadliest buildings. This is then multiplied by the average people per household and gives Equation (5):

$$N_{EXP}^{MUNICIPALITY} = [(P_{PH} * T_{PH}) + (P_{SH} * T_{SH})] * N^{RB} * N_{HF} \quad (5)$$

where $N_{EXP}^{MUNICIPALITY}$ is the population potentially exposed to a risk of death per municipality in the case of coastal flooding, P_{PH} is the proportion of principal houses in the municipality, T_{PH} is the estimated occupation rate of principal houses (69%), P_{SH} is the proportion of secondary houses in the municipality, T_{SH} is the estimated occupation rate of secondary houses (31%), N^{RB} is the number of black and red buildings identified by the VIE index, and N_{HF} is the average number of people per household of the municipality.

This formula allows the proportion of the deadliest houses (which could vary from one municipality to another) to be considered, as well as secondary houses which could radically increase the number of people at risk of fatality. In the case of La Faute-sur-Mer, according to the formula, a total of 1182 people were exposed to flooding during Storm Xynthia (Appendix B).

2.3.4. Assessing the Potential Number of Deaths (N)

Using Equation (4) ($F_D^{MUNICIPALITY}$) and Equation (5) ($N_{EXP}^{MUNICIPALITY}$), the potential number of deaths (N) for each municipality, depending on its specific characteristics on the basis of the formula of Jonkman et al. [17], was calculated (Equation (1)). For the specific case of La Faute-sur-Mer, the application of the formula yielded a total of 29 potential deaths, which is an accurate result in light of the data on fatalities in this municipality.

The strength of this method is that it allows for the inclusion of parameters pertaining to the vulnerability of houses, which could vary from one municipality to another (altimetry and architectural type of buildings). The method also accounts for the importance of secondary houses, which could be an important parameter to assess the exposed population in the case of some touristic municipalities exposed to coastal floods.

3. Results

The results of both the VIE index and potential fatality assessment were calculated for seven municipalities on the French Atlantic coast [7,52]. Three of them are located in Baie de l'Aiguillon, and they were directly impacted by Storm Xynthia: La Faute-sur-Mer

(29 deaths), L'Aiguillon-sur-Mer (no deaths), and Charron (3 deaths). The others are located on Noirmoutier Island, which was impacted little by the storm, but the configuration of human settlement is similar to the municipalities impacted in 2010 [52,53] and has been impacted by coastal floods in the past [54,55].

The results of these previous studies show good validation of the model for the three studied municipalities impacted by Storm Xynthia (see Section 2.2.2), as well as confirming that it was highly risky places with black houses representing levels of 48%, 28%, and 1% in La Faute-sur-Mer, l'Aiguillon-sur-Mer, and Charron, respectively [7]. This was due to recent allotments of single-story type buildings constructed in the lower parts of these municipalities. On the other hand, the municipalities of Noirmoutier Island showed a low level of black houses which was always under 4%, except for in La Guérinière (20%) [52]. In general, buildings in flood-prone areas on the island are located relatively far from the sea (500 m or more).

Here, we focus on the case of La Guérinière, since it is the most exposed municipality of Noirmoutier Island [52]. However, data and detailed calculations of potential fatalities are given for each of the seven municipalities in Appendix C.

3.1. Study Site

Noirmoutier Island is in the central part of the French Atlantic coast (Figure 3). It is a low-lying island with an area of 49 km^2 and with 68% of its territory located beneath the level of the storm surge associated with Storm Xynthia [53]. To protect it from the sea, a network of 24 km of flood defenses was established on the east coast of the island, while the west coast is protected by a sandy barrier [56]. La Guérinière is in the central part of the island, namely on its narrowest part (800 m between the west and east coasts). It is the smallest municipality of the island with an area of 7.8 km^2, and 80% of its territory could potentially be flooded [50], therefore making it the most exposed town on the island. Its position increases the risk of coastal floods. In addition, in the event of failure of the eastern flood defenses (5-m elevation flood defenses) or the sandy barrier (5.5-m elevation), the resulting damage would be catastrophic.

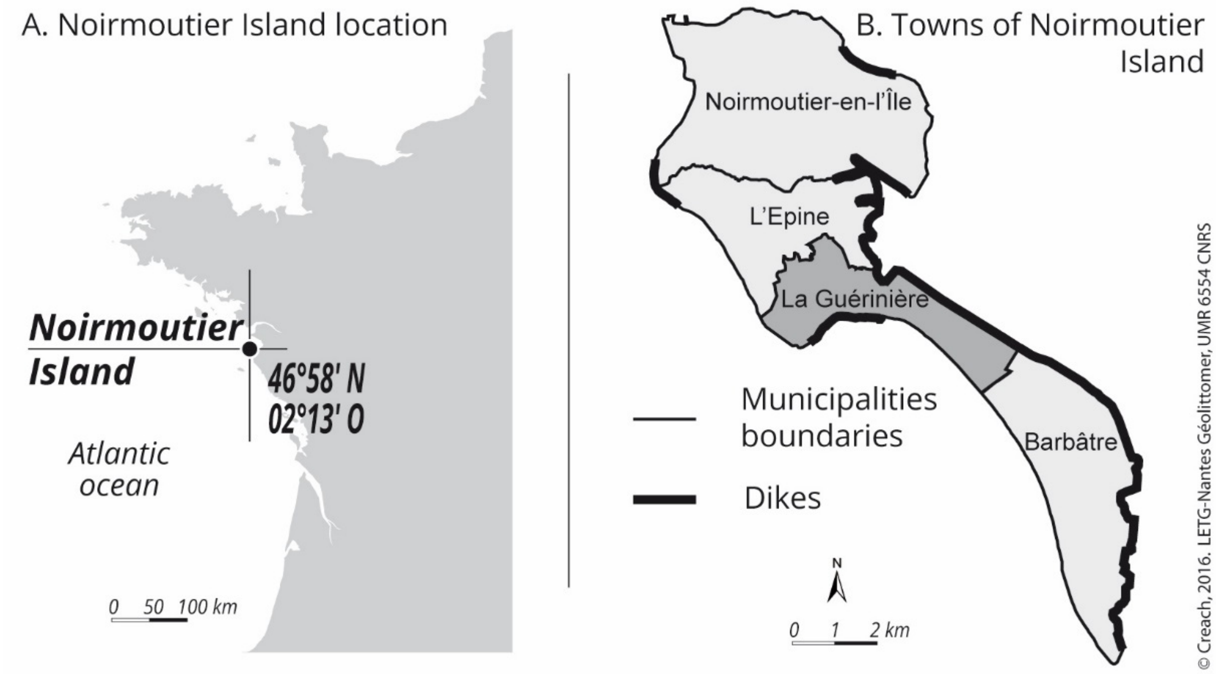

Figure 3. Location of the town of La Guérinière (source: [57]).

Today, Noirmoutier is noted for its leisure activities [58]. In the last 40 years, the number of buildings increased by 162%, and the population increased by 19% [57], with most of this urbanization occurring in low-lying areas. Thus, should a centennial flood occur, one half of the residential buildings of the island would be at extreme risk of flooding [52].

With a total of 1460 inhabitants in 2011 [51], La Guérinière is the smallest municipality of the island with 15.5% of the island's total population. However, the number of residential buildings has increased by 144% since 1968 [51], and they represent 17% of the total number of residential buildings on the island (2817 of 16,438 buildings). Of these buildings, 74% are secondary homes, while the average is 66% on the island [51]. For a centennial-scale flood, 63% of the residential buildings of La Guérinière could be flooded [52] (Table 5).

Table 5. VIE index results for La Guérinière municipality (adapted from [57]). Non-identified buildings correspond to those for which the VIE index cannot be calculated due to missing data (i.e., architectural type unknown) or which are not residential buildings.

Class	Number of Buildings	% of Buildings among "Total Identified Buildings"
Green class	1034	37%
Orange class	329	12%
Red class	885	31%
Black class	569	20%
Total identified buildings	2817	100%
Non-identified buildings	1251	ø
Total buildings	4068	ø

Although only 3% of the area of Noirmoutier was flooded during Storm Xynthia [50], and though no major storms have impacted the island since the 1950s, major floods have occurred in the past [55,59]. For example, the storm of 1937 is known to have flooded a large part of the island even though no deaths occurred, probably because of the lower population density [55]. Even though Noirmoutier Island was not recently impacted by coastal floods, it remains at risk, since low-lying areas are heavily urbanized.

3.2. VIE Index Results

The VIE index results for La Guérinière were presented in two recent publications, with one presenting the results for the whole of Noirmoutier Island for two flood scenarios [52] and the other focusing on the case of La Guérinière and presenting four different flood scenarios [57]. In this section, the "medium scenario", which corresponds to a centennial return period, is selected for analysis. As recommended by the French Ministry for the Environment, this scenario needs to be used for regulatory documents for urban planning in flood-prone areas [60]. It needs to be based on either the highest known historical sea level or on the results of a centennial flood numerical model [60]. For Noirmoutier Island, the sea level measured in the harbor of Noirmoutier-en-l'Île was used. It was measured to be 4.20 m NGF (French legal altimetric datum). It needs to be said that only the water depth was used to specify the hazard, as the VIE index focuses on vulnerability inside buildings, with the proximity to coastal defenses being a way to estimate high rising water inside.

Calculation of the VIE index requires several steps for each criterion, which are linked to different maps. Here, we refer to Creach's [61] atlas to review each map of the process. It should be noted that the results presented here refer to buildings for which the VIE index has been calculated ("total identified buildings" given in Table 5), which could defer from the total number of buildings in the territory as most of them are not residential buildings (e.g., garages or garden sheds) or sometimes data are missing (i.e., architectural typology).

La Guérinière has a total amount of 1783 residential houses located under 4.20 m NGF and which could be flooded in a centennial flood (Table 5). It represents 24% of the total number of potentially inundated buildings of the island, and 75% of them in La Guérinière could be submerged by a water depth >1 m, which is considered a level of extreme danger for people [17,30,62]. A 1-m water level would result in 28% of the buildings on the island being inundated. While 40% of the coast of the island is artificial, few buildings are close to flood defenses. Less than 23% could be directly affected by high rising water if the flood defenses failed. However, in La Guérinière, where the island is the narrowest, 56% of residential buildings are particularly vulnerable to a dike failure (Cr2). The architectural typology (Cr3) shows that 60% of the potentially inundated buildings of La Guérinière are single-story, with the average on the island being 64%. Finally, since Noirmoutier Island is a low-lying territory, there are few natural shelter areas (i.e., above the maximum water level). In La Guérinière, these correspond to the sandy barrier. Additionally, 35% of La Guérinière's buildings (Cr4) are less than 100 m from a natural shelter area (average of 25% on Noirmoutier Island), while 14% are located more than 200 m away (average of 9% on Noirmoutier Island).

The calculation of the VIE index confirmed that La Guérinière is the most exposed municipality of Noirmoutier Island. At the island scale, the exposure of residential buildings for people is not particularly high; the green class (no vulnerability of the buildings for people) is 54%, the red class is 26% (potential risk of death due to individual behavior or vulnerable people), and the black class is 5% (potential death due to the vulnerability of the building for people). In La Guérinière, according to Table 5, 37% of residential buildings are in the green class, 12% are in the orange class, and most importantly, 31% are in the red class, while 20% are in the black class. Therefore, there is a considerable risk of death for people living in 52% of the residential buildings of La Guérinière, compared with 31% for the whole island. The black class is far more representative than the other municipalities, as this class reaches a maximum of 4% on Noirmoutier-en-l'Île and less than 1% on L'Epine and Barbâtre. On Noirmoutier-en-l'Île, it comprises 291 buildings, whereas in La Guérinière, it is 569.

As shown in Figure 4, most of the black houses are relatively close to the southwest coast, where the sandy barrier is narrow, less elevated, and thus poorly protected by flood defenses. These houses are also of a single-story type, which does not allow for vertical evacuation, contrary to the surrounding red houses which are located at the same altimetry but offer multiple stories. A rapid rise of water is possible, meaning there is insufficient time for people to evacuate, except if a preventive evacuation is carried out or if it is possible to escape upstairs. On the other hand, buildings at the two ends of La Guérinière are located on the barrier (green class) or are protected by it, and therefore the rise in water level would be slower (red or orange class).

3.3. Potential Fatalities

From the VIE index results, and with reference to the census data which are given in Appendix C, it is possible to estimate the potential number of deaths in relation to floods.

3.3.1. Estimating the Mortality Fraction (F_D)

The mortality fraction was calculated from the age of the population, the proportion of potentially lethal houses (red and black VIE index classes), and the integrated mortality fraction (Appendix C). The age composition of the population for 2011 (to allow comparison with Storm Xynthia's context of 2010) and the proportion of red and black houses among the potentially lethal houses are given in Appendix C (from line 6 to 9 and lines 3 and 4, respectively).

Derived from Equation (4) and according to the data from Appendix C, we have Equation (6):

$$\begin{aligned} F_D^{LaGueriniere} &= [(0.261 * 0.138) + (0.120 * 0.482) + (0.538 * 0.379)] * 0.39 \\ &+ [(0.222 * 0.138) + (0 * 0.482) + (0.204 * 0.379)] * 0.61) = 0.018 \end{aligned} \quad (6)$$

This indicates a mortality fraction of 1.82%, which is less than that for La Faute-sur-Mer (2.45%). The difference is explained by the potentially lethal black zone houses, which are less represented in La Guérinière (39%) than in La Faute-sur-Mer (60%). Thus, in proportion, fewer buildings will expose the occupants to an extreme risk of death.

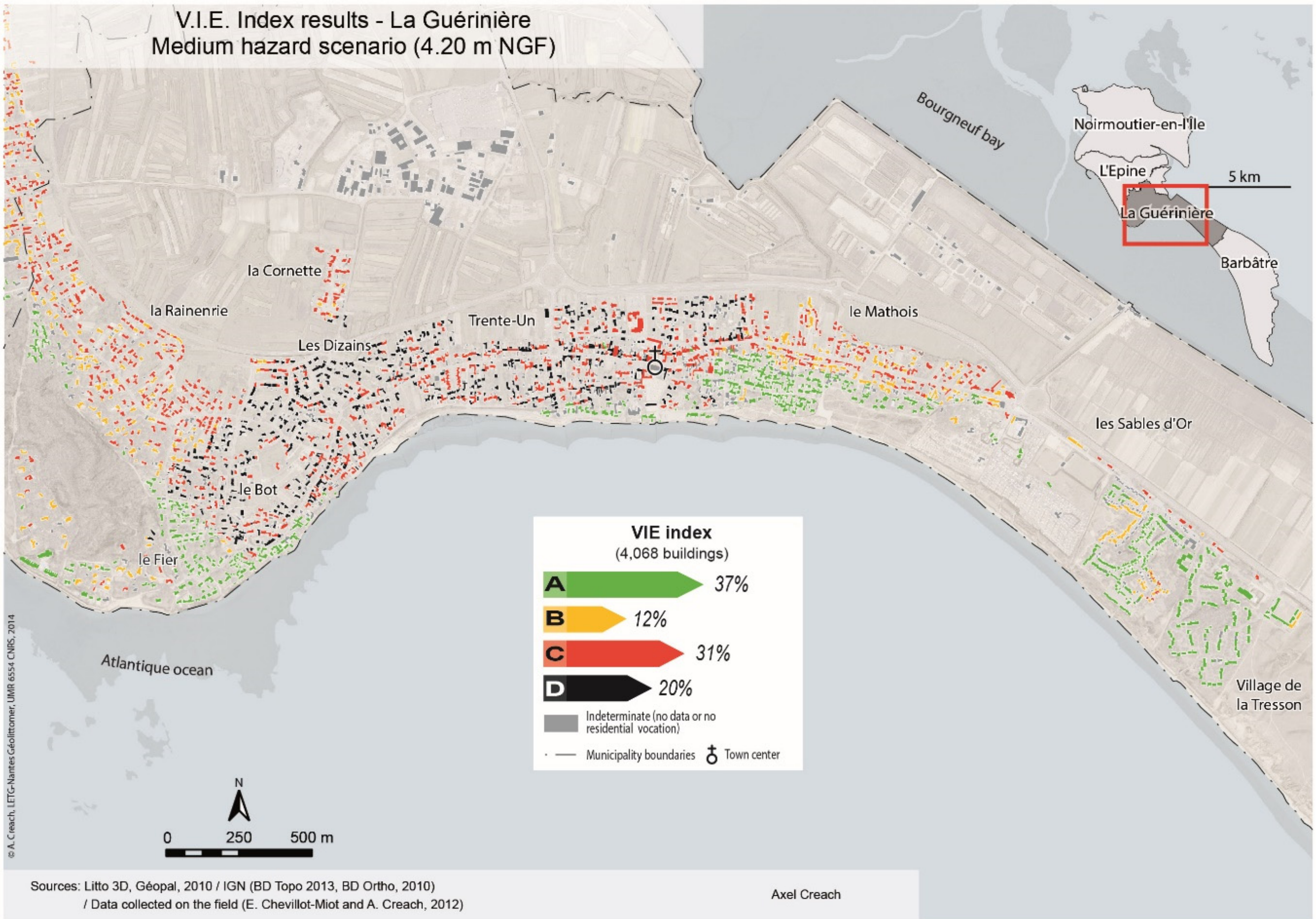

Figure 4. VIE index results for La Guérinière municipality (adapted from [57]).

Concerning the age of the population, the elderly are less represented in La Guérinière (38%) than in La Faute-sur-Mer (45%), but the representation of young people is large (14% in La Guérinière, relative to La Faute-sur-Mer (10%)).

La Guérinière is the municipality with the highest mortality fraction of Noirmoutier Island (1.5% in Noirmoutier-en-l'Île, 1.2% in Barbâtre, and 1.1% in L'Epine). This is mainly because of the importance of black buildings among potentially lethal houses; these represent 39% of houses in La Guérinière but only 19% in Noirmoutier-en-l'Île, 2% in Barbâtre, and 0.2% in L'Epine. Thus, the probability of dying inside a residential house in La Guérinière is higher than in the other municipalities of Noirmoutier Island.

3.3.2. Estimating the Exposed Population (N_{EXP})

According to Equation (5), the exposed population was estimated from the average number of people per household, which is given in line 14 of Appendix C (2.1 inhabitants per household). Appendix C also shows the proportion of principal houses (line 11; 26%) and secondary houses (line 12; 74%) and the occupation rate (Table 4 and Appendix C, lines 21 and 22, respectively, at 69% for principal houses (T_{PH}) and 31% for secondary houses (T_{SH})), and the number of potentially lethal houses (line 5; 1454 (N^{RB})):

$$N_{EXP}^{LaGueriniere} = [(0.26 * 0.69) + (0.74 * 0.31)] * 1454 * 2.10 = 2146.65 \quad (7)$$

Equation (7) gives a total of 1247 of people potentially exposed to flooding. The fact that this number is smaller than the number of potentially lethal houses is due to the importance of secondary houses, which represent 74% of the buildings of La Guérinière. This number of potentially exposed people is slightly higher than the number of people exposed to Storm Xynthia in La Faute-sur-Mer (1182 according to Equation (A3) in Appendix B). The number of potentially exposed people in La Guérinière is the highest for Noirmoutier Island but not as high as elsewhere (1118 in L'Epine, 1054 in Noirmoutier-en-l'Île, and 1022 in Barbâtre). This difference is mainly due to the slightly higher number of potentially lethal houses in La Guérinière (1454) than in the other locations (1228 in L'Epine, 1220 in Noirmoutier-en-l'Île, and 1214 in Barbâtre).

3.3.3. Number of Potential Fatalities (*N*)

By applying the formula for the mortality function method (Equation (1)) using (1) the mortality fraction calculated for La Guérinière ($F_D^{La\ Gueriniere}$ = 1.8%) and (2) the number of potentially exposed people ($N_{EXP}^{La\ Gueriniere}$ = 1247), the potential number of deaths could be estimated using Equation (8):

$$N^{La\ Gueriniere} = F_D^{La\ Gueriniere} * N_{EXP}^{La\ Gueriniere} = 1.8\% * 1247 = 22.71 \quad (8)$$

In the case of a centennial flood in La Guérinière, 23 fatalities could be recorded inside houses. This is lower than the number of deaths that occurred in La Faute-sur-Mer during Storm Xynthia (29 deaths recorded). As explained previously, this is the result of the mortality fraction being lower in La Guérinière ($F_D^{La\ Gueriniere}$ = 1.8%) than in La Faute-sur-Mer ($F_D^{La\ Faute-sur-Mer}$ = 2.45%).

The other municipalities on the island may also experience fewer fatalities in the case of a centennial flood (16 in Noirmoutier-en-l'Île, 12 in L'Epine, and 12 in Barbâtre) because of a lower mortality fraction but also an exposed population (Appendix C, line 25).

This result confirms that La Guérinière is the municipality most at risk of fatalities on Noirmoutier Island, even if it is not as exposed as La Faute-sur-Mer.

4. Discussion

Regarding the VIE index, the key limitations are discussed in the work of Creach et al. [7]. Different uncertainties are responsible for overestimation of the number of flooded houses. These include (1) the use of a "static" method to estimate the potential water depth, (2) no consideration of flood defenses to reduce water depth (as recommended by the French Ministry for Environment (see [62])), and (3) estimation of the water depth in relation to the local topography. It is an evaluation of the worst scenario possible. If a building is likely to be flooded, even though the probability is low, it needs to be considered at risk of inundation. The precautionary principle needs to be considered when protecting human life.

The novelty for fatality assessment is to identify those buildings in which deaths are most likely, which allows for proposing adaptation strategies to reduce their vulnerability. However, there are several specific limitations to the approach proposed in this paper. First, it is a deterministic approach, as the mortality fractions are only estimated from Storm Xynthia. This limitation is evident when considering that the mortality fraction is 0 for people aged 15–60 in red houses (Table 4), because no deaths were recorded in this case during Storm Xynthia [3,4]. In fact, deaths are less likely to occur in red houses for "healthy" people [1,4], but there is still a degree of risk. It was similarly necessary to consider principal and secondary houses because they represent more than 50% of the residential buildings in the studied coastal municipalities [51]. Despite the availability of accurate data about the number of secondary houses, even though there are general data proposed at the municipality scale, it is difficult to estimate the population exposed to a risk of flooding. The number of people occupying secondary houses can vary because of holiday periods, which themselves are seasonal. Only very fine resolution studies would permit the elucidation of details concerning the exact location and number of occupied secondary houses, but this would require numerous interviews [63,64] or new considerations about the occupancy of residential houses throughout the year, with this type of research still being in progress for the French Atlantic coast [64]. In fact, the hypothesis we used could be seen as an upward occupancy in regard to the most frequent season for coastal floods to occur on the French Atlantic coast [59]. Winter is not the period at which residential homes are the most occupied.

Analysis of more past flood events is clearly needed to validate the methodology and to refine the mortality fractions. For instance, the 1953 storm in the Netherlands [65], Canvey Island in the UK [21,26], and Hurricane Katrina in the USA [2] are well-documented storms for which data concerning deaths inside buildings are available. Therefore, the application of the methodology presented in this paper is a first step which can be adapted and applied to the French Atlantic coastal municipality, as they exhibit similar characteristics in terms of the degree of urbanization, architectural typology, number of secondary houses, and population. In addition, the current lack of accurate data, both on fatalities related to Storm Xynthia and census information, as well as other parameters that could influence the number of fatalities (e.g., gender or health condition), have not been considered [1]. Finally, there is also a disparity between the accuracy of the outputs given by the VIE index, which can permit the identification of each residential house based on its vulnerability and ranking from fatality assessments, which provide an estimation of the potential number of deaths at the municipality scale. This is because of difficulties such as the lack of available high-resolution spatial data in France. This is particularly true for other parameters such as the building type, size, and function (i.e., principal or secondary house) as well as the number of occupants and their ages and genders.

Applying the method to other past floods could also allow for addressing another limitation of the proposed method: building collapses are not considered, as no collapse occurred during Storm Xynthia [4]. However, this is usually integrated in such studies [20], as it could amplify the risk of death [39].

Despite these limitations, the proposed methodology is suited for low-lying areas protected from the sea by walls or sandy barriers, which vast territories along the French Atlantic coast or in Netherlands and UK have. It could be proposed as an add-on to the LSM, the FRP, and the mortality functions methods. It allows one to identify buildings which are safe or unsafe, depending on the exposed population in an agent-based model, and it could add another input to the FRP method and allow one to address a specific mortality fraction, depending on the building typology, other than those currently estimated by the mortality functions method. Moreover, it should be seen as a useful experimental tool for enabling decision makers to reduce the vulnerability of buildings and to protect people from future floods, which could increase with the sea level's rising due to climate change. The achievability of this goal is enhanced by the possibility of undertaking cost–benefit analyses. Overall, it provides a complementary approach to existing fatality assessment methods by considering the risk of death inside buildings.

5. Conclusions

The methodology presented herein is useful for considering how fatalities may result from people being trapped in buildings during coastal floods. The primary example of Storm Xynthia showed how the building type, configuration, and location could considerably increase the risk of death [3,4].

The VIE index [7] provided a method of assessing which buildings posed the greatest risk to occupants during times of flooding. This index is based on four criteria, which were identified as predominant in the estimation of human vulnerability during Storm Xynthia: (1) potential water depth inside buildings, (2) distance to flood defenses, (3) the architectural typology of the buildings, and (4) proximity to a rescue point. These criteria are used to assign a rating to houses which present the greatest risks to people. The results are divided into four vulnerability classes (green to black), of which two represent a potentially lethal situation for occupants: (1) the red class, where death risk is more related to at-risk behavior or vulnerable people, and (2) the black class, where the configurations and locations of people contribute more to the risk of fatalities during periods of flooding.

From the assessment of the vulnerability of houses for people, a deterministic quantification of the death risk was proposed using the mortality function method developed by Jonkman et al. [17] and data from Storm Xynthia. This method estimates the probability of death (F_D) among an exposed population (N_{EXP}). According to Jonkman et al. [17], the probability of death occurring depends on the hazard characteristics. In this paper, the probability of death was shown to have been conditioned not just by the zone (i.e., the "black class") of the occupied houses but also the age of the occupants. Based on the conditions under which fatalities occurred during Storm Xynthia [3,4], a mortality fraction of the deaths was estimated depending on the vulnerability of the houses for people (red or black class) and the age of the population (under 15, 15–60, and above 60 years). By integrating census data and the VIE index results at the municipality scale, it is possible to estimate a specific probability of death for people. Then, the exposed population is calculated depending on the average number of households living in dangerous houses (red and black classes of the VIE index) considering the combined effects associated with the principal and secondary houses. This allows the potential number of deaths to be calculated.

The model gives good results, with the VIE index highlighting the high vulnerability of buildings in La Faute-sur-Mer and L'Aiguillon-sur-Mer—the most impacted towns during Storm Xynthia—for which the death toll was counterbalanced by numerous secondary houses unoccupied at the time of the flood. The method has also been applied to Noirmoutier Island, which was not impacted by Storm Xynthia, but with similar characteristics regarding buildings' locations and configurations. However, the expected deaths there are less important due to a less important mortality fraction. This is due to the fact that, in general, buildings are located farther from the sea, so their vulnerability level is lower.

Despite several limitations of the deterministic approach, specifically the need for more data regarding the circumstances of death, and the fact that it is impossible to assess the exact number of deaths, the estimate provided by the methodology is a first step toward a complementary approach that links with other existing methods for assessing fatalities in relation to floods and which is suited for urbanized coastal flood-prone areas protected from the sea by sandy barriers or walls. Moreover, the present methodology could be used for evaluation with cost-efficiency analysis (CEA) for building mitigation strategies. This may be a very useful tool for decision makers to save lives by identifying the best adaptation strategies to reduce vulnerability to coastal floods, the magnitude and frequency of which are expected to increase in response to rising sea levels [16,66].

6. Patents

- Different fatality assessment methods due to floods exist but do not integrate building characteristics;
- The VIE index framework allows one to assess a building's vulnerability for people;
- Coupled with census data, it allows one to evaluate a specific mortality fraction per municipality;
- This derived fatality assessment method is useful for working on a building's adaptation.

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Appendix A. Estimation of the 1% Value of Deaths in the Case of Storm Xynthia

Jonkman [35] and Jonkman et al. [17] proposed the generic value of 1% of deaths (F_D) among an exposed population (N_{EXP}) in case of flooding, and it was successfully applied in the case of Storm Xynthia by Kolen et al. [6]. Considering the number of deaths (N = 29) and an exposed population (N_{EXP}) estimated to be 3000 people, the mortality fraction (F_D) is equal to 1%, as shown below (Equation (A1)):

$$F_D = \frac{N}{N_{EXP}} = \frac{29}{3000} = 0.01 \quad \text{(A1)}$$

However, the value of N_{EXP} can be criticized. It corresponds approximately to the combined population of La Faute-sur-Mer and L'Aiguillon-sur-Mer, which are neighboring and were both impacted by Storm Xynthia. The total population of the two municipalities was 3291 in 2006 and 3001 in 2011 [51]. However, the deaths were only recorded in La Faute-sur-Mer; its population was 1008 inhabitants in 2006. Thus, Equation (A2) yields

$$F_D = \frac{N}{N_{EXP}} = \frac{29}{1008} = 0.0288 \quad \text{(A2)}$$

Here, the mortality fraction (F_D) is close to 3%. It could be improved by considering that not every building was flooded, and thus certain municipal areas were not affected. The exposed population was clearly lower, and if so, the mortality fraction was higher. Thus, we consider that the value of 1% was not sufficient in this case.

This contrasts with other values used in the literature. For instance, for the 1953 storm at Canvey Island (UK), the mortality fraction was estimated to be 0.4% [36], and in The Netherlands, it was proposed to have a mortality fraction of 0.3% for coastal floods [27].

Appendix B. Calculation of the Mortality Fraction Depending on Building Vulnerability and the Age of Casualties for La Faute-sur-Mer

To estimate a mortality fraction using the VIE index, which considers red or black houses and the ages of people, we used the data from Storm Xynthia (see Section 2.3.1). The results are given in Table 4. In this appendix, we give details on the calculation of each mortality fraction (F_D) according to data from Storm Xynthia for the La Faute-sur-Mer municipality (29 deaths) as derived from Equation (2). We needed to estimate the number of people impacted (N_{EXP}) to do so.

Census data used for the calculation are given in Appendix C (lines 6–14).

It should be noted that all buildings identified by the VIE index were not flooded during Storm Xynthia (due to the limitations discussed in Section 4). Table A1 shows the number of buildings effectively flooded, which needed to be used for estimating the mortality fractions from Storm Xynthia. Among the flooded buildings, 63% were black houses, and 37% were red houses.

Table A1. Differences between buildings theoretically (according to VIE index results) and effectively flooded during Storm Xynthia.

	Theoritically Flooded (According to VIE Index) for Storm Xynthia	Effectively Flooded for Storm Xynthia	% Effectively or Theoretically Flooded
Red class	885	604	68.2%
Black class	1305	1027	78.7%
Total	2190	1631	74.5%

Appendix B.1. Estimating the Impacted Population (N_{EXP})

Since we know the number of deaths (29), the context of the casualties (Table 4), and the number of effectively flooded buildings (1631) [9], it is possible to apply Equation (4) as follows (Equation (A3)):

$$N_{EXP}^{La\ Faute-sur-Mer-Xynthia} = [(P_{PH} * T_{PH}) + (P_{SH} * T_{SH})] * N^{RB} * N_{HF} = 1181.7 \quad \text{(A3)}$$

where N_{EXP} is the population potentially exposed to a risk of death in the case of a coastal flood, P_{PH} is the proportion of principal houses in the municipality (=13.4%), T_{PH} is the occupation rate of principal houses (69%), P_{SH} is the proportion of secondary houses in the municipality (85.9%), T_{SH} is the occupation rate of secondary houses (31%), N^{RB} is the number of black and red buildings identified by the VIE index and flooded during Storm Xynthia (1631), and N_{HF} is the average household of the municipality (2.02).

The result showed a total number of 1182 persons exposed to death risk during Storm Xynthia.

Appendix B.2. Mortality Fraction for People Aged under 15 Living in Black Houses

Based on the results from Equation (A3) ($N_{EXP}^{La\ Faute-sur-Mer-Xynthia}$ = 1181.7), it was possible to estimate the number of those aged under 15 who were exposed to the flood during Storm Xynthia that were living in black houses. This number was driven by the proportion of people under 15 in the municipality population (P^{-15} = 10.3%, line 7 from Appendix C) and the proportion of black houses effectively flooded during the storm (P^B = 63%). This gives Equation (A4):

$$N_{EXP}^{B-15} = \left(N_{EXP}^{La\ Faute-sur-Mer-Xynthia} * P^{-15}\right) * P^B = (1181.7 * 0.103) * 0.63 = 76.7 \quad \text{(A4)}$$

The result gives a total number of 77 people aged under 15 who were exposed to the flood in that were black houses during Storm Xynthia (N_{EXP}^{B-15}). Among them, two deaths were recorded (N^{B-15}). The mortality fraction (F_D^{B-15}) is given by Equation (A5):

$$F_D^{B-15} = \frac{N^{B-15}}{N_{EXP}^{B-15}} = \frac{2}{76.7} = 0.0261 \quad \text{(A5)}$$

The mortality fraction for people under 15 in black houses (F_D^{B-15}) was 2.61% according to the data from Storm Xynthia in La Faute-sur-Mer.

Appendix B.3. Mortality Fraction for People Aged 15–60 Living in Black Houses

The people aged 15–60 represented 44.7% of the local population in 2006 (P^{15-60}; line 8 from Appendix C). The total number of the exposed population (N_{EXP} = 1181.7) and the proportion of black houses effectively flooded during the storm (P^B = 63%) are given in Equation (A6):

$$N_{EXP}^{B15-60} = \left(N_{EXP}^{La\ Faute-sur-Mer-Xynthia} * P^{15-60}\right) * P^B = (1181.7 * 0.447) * 0.63 = 332.8 \quad \text{(A6)}$$

The result gives a total of 333 people aged 15–60 who were exposed to flooding during Storm Xynthia (N_{EXP}^{B15-60}). Among them, four deaths were recorded (N^{B15-60}). The mortality fraction (F_D^{B15-60}) is given by Equation (A7):

$$F_D^{B15-60} = \frac{N^{B15-60}}{N_{EXP}^{B15-60}} = \frac{4}{332.8} = 0.0120 \quad \text{(A7)}$$

The mortality fraction for people aged 15–60 who were in black houses (F_D^{B15-60}) was 1.20% according to the data from Storm Xynthia in La Faute-sur-Mer.

Appendix B.4. Mortality Fraction for People Aged above 60 Living in Black Houses

People aged above 60 represented 45% of the local population in 2006 (P^{+60}; line 9 from Appendix C). Using the total number of people exposed in the population (N_{EXP} = 1181.7) and the proportion of black houses effectively flooded during the storm (P^B = 63%) gives Equation (A8):

$$N_{EXP}^{B+60} = \left(N_{EXP}^{La\ Faute-sur-Mer-Xynthia} * P^{+60}\right) * P^B = (1181.7 * 0.449) * 0.63 = 334.3 \quad \text{(A8)}$$

This indicates that a total of 334 people aged above 60 were exposed to flooding during Storm Xynthia (N_{EXP}^{B+60}). Among them, 18 deaths were recorded (N_{EXP}^{B+60}). The mortality fraction (F_D^{B-15}) is given by Equation (A9):

$$F_D^{B+60} = \frac{N^{B+60}}{N_{EXP}^{B+60}} == \frac{18}{334.3} = 0.0538 \quad \text{(A9)}$$

The mortality fraction for people aged above 60 in black houses (F_D^{B-15}) was 5.38% according to data from Storm Xynthia in La Faute-sur-Mer.

Appendix B.5. Mortality Fraction for People Aged under 15 Living in Red Houses

People aged under 15 comprised 10.3% of the local population in 2006 (P^{-15}; line 7 from Appendix C), and those effectively flooded red houses during Storm Xynthia represented 37% (P^R). We could estimate the number of people aged under 15 effectively exposed to flooding (N_{EXP}^{R-15}) using Equation (A10):

$$N_{EXP}^{R-15} = \left(N_{EXP}^{La\ Faute-sur-Mer-Xynthia} * P^{-15}\right) * P^R = (1181.7 * 0.103) * 0.37 = 45.03 \quad \text{(A10)}$$

This gives a total of 45 people aged under 15 who were exposed to flooding in red houses during Storm Xynthia (N_{EXP}^{R-15}). Among them, one death was recorded (N^{R-15}). The mortality fraction (F_D^{R-15}) is given by Equation (A11):

$$F_D^{R-15} = \frac{N^{R-15}}{N_{EXP}^{R-15}} = \frac{1}{45.03} = 0.0222 \quad \text{(A11)}$$

The mortality fraction for people aged under 15 in red houses (F_D^{R-15}) was 2.22% according to data from Storm Xynthia in La Faute-sur-Mer.

Appendix B.6. Mortality Fraction for People Aged 15–60 Living in Red Houses

Using the total number of the exposed population (N_{EXP} = 1181.7), the proportion of people aged 15–60 (P^{15-60} = 44.7%; line 8 from Appendix C), and the proportion of red houses effectively flooded during the storm (P^R = 37%), we could estimate the exposed population of people aged 15–59 living in red houses (N_{EXP}^{R15-60}) using Equation (A12):

$$N_{EXP}^{R15-60} = \left(N_{EXP}^{La\ Faute-sur-Mer-Xynthia} * P^{15-60}\right) * P^R = (1181.7 * 0.447) * 0.37 = 195.5 \quad \text{(A12)}$$

This gives a total of 196 people aged 15–60 exposed to flooding in red houses during Storm Xynthia (N_{EXP}^{R15-60}). Among them, no deaths were recorded (N^{R15-60}). The mortality fraction (F_D^{R15-60}) is given by Equation (A13):

$$F_D^{R15-60} = \frac{N^{R15-60}}{N_{EXP}^{R15-60}} = \frac{0}{195.80} = 0.0 \quad \text{(A13)}$$

The mortality fraction for people aged 15–60 living in red houses (F_D^{R15-60}) was 0% according to data from Storm Xynthia in La Faute-sur-Mer.

Appendix B.7. Mortality Fraction for People Aged above 60 Living in Black Houses

Using the total number of the exposed population (N_{EXP} = 1181.7), the proportion of people aged above 60 (P^{+60} = 45%; line 9 from Appendix C), and the proportion of red houses effectively flooded during the storm (P^R = 37%), we could estimate the exposed population of people aged above 60 living in red houses (N_{EXP}^{R+60}) using Equation (A14):

$$N_{EXP}^{R+60} = \left(N_{EXP}^{La\ Faute-sur-Mer-Xynthia} * P^{+60}\right) * P^R = (1181.7 * 0.449) * 0.37 = 196.3 \quad \text{(A14)}$$

This gives a total of 197 people aged above 60 exposed to flooding living in red houses during Storm Xynthia (N_{EXP}^{R+60}). Among them, four deaths were recorded (N^{R+60}). The mortality fraction (F_D^{R+60}) is given by Equation (A15):

$$F_D^{R+60} = \frac{N^{R+60}}{N_{EXP}^{R+60}} = \frac{4}{196.3} = 0.0204 \quad \text{(A15)}$$

The mortality fraction for people aged above 60 living in red houses (F_D^{R+60}) was 2.04% according to data from Storm Xynthia in La Faute-sur-Mer.

Appendix C.

Table A2. Data Used for Calculations in Section 3 (Results).

# Line		La Faute-sur-Mer #	%	L'Aiguillon-sur-Mer #	%	Charron #	%	Noirmoutier-en-l'Île #	%	L'Epine #	%	La Guérinière #	%	Barbâtre #	%
	(i)	**Building's vulnerability (calculated with VIE Index)**													
1	Buildings in flood prone area	2406	X	2337	X	491	X	2227	X	1747	X	1783	X	1775	X
2	"Orange" buildings	216	X	253	X	187	X	1007	X	519	X	329	X	561	X
3	"Red" buildings (P^R)	885	40.4%	1262	60.6%	293	96.4%	929	76.1%	1225	99.8%	885	60.9%	1189	97.9%
4	"Black" buildings (P^B)	1305	59.6%	822	39.4%	11	3.6%	291	23.9%	3	0.2%	569	39.1%	25	2.1%
5	Potentially lethal buildings (N^{RB} = #3 + #4)	2190	100%	2084	100%	304	100%	1220	100%	1228	100%	1454	100%	1214	100%
		Census data (source: INSEE [48])													
	Census's year	2006		2006		2006		2011		2011		2011		2011	
	(j)	**Population**													
6	Total population	1008	100%	2283	100%	2140	100%	4550	100%	1713	100%	1460	100%	1786	100%
7	Under 15 (P^{-15})	104	10.3%	225	9.9%	448	20.9%	614	13.5%	204	11.9%	201	13.8%	267	14.9%
8	15-60 ($P^{15\text{-}60}$)	451	44.7%	893	39.1%	1259	58.8%	2224	48.9%	802	46.8%	704	48.2%	784	43.9%
9	Above 60 (P^{+60})	453	44.9%	1165	51.0%	433	20.2%	1713	37.6%	706	41.2%	554	37.9%	735	41.2%
		Houses													
10	Residential houses total	3737	100%	2334	100%	897	100%	6984	100%	2124	100%	2667	100%	3172	100%
11	Principal houses (P_{PH})	499	13.4%	1140	48.8%	839	93.5%	2219	31.8%	846	39.8%	695	26.1%	856	27.0%
12	Secondary houses (P_{SH})	3210	85.9%	1116	47.8%	30	3.3%	4554	65.2%	1197	56.4%	1963	73.6%	2221	70.0%
13	Unoccupied houses	28	0.7%	78	3.3%	29	3.2%	211	3.0%	81	3.8%	9	0.3%	95	3.0%
		Average people per households													
14	Average people–Principal houses (N_{HF} = #6∗/#10)	2.02		2.00		2.55		2.05		2.02		2.10		2.09	
		Standard values (see Section 2.3**)**													
		Mortality fraction values (FDV) per age and building's vulnerability													
15	${F_D}^{B-15}$	0.0261													
16	${F_D}^{B15-60}$	0.0120													
17	${F_D}^{B+60}$	0.0538													
18	${F_D}^{R-15}$	0.0222													
19	${F_D}^{R15-60}$	0.0000													
20	${F_D}^{R+60}$	0.0204													

Table A2. *Cont.*

# Line		La Faute-sur-Mer		L'Aiguillon-sur-Mer		Charron		Noirmoutier-en-l'Île		L'Epine		La Guérinière		Barbâtre	
		#	%	#	%	#	%	#	%	#	%	#	%	#	%
	Occupation rate (Tx) per type of houses														
21	Tx Principal houses (T_{PH})	69.0%													
22	Tx Secondary houses (T_{SH})	31.0%													
	Mortality fraction (F_D) $F_D = [(F_D{}^{B-15} * P^{-15}) + (F_D{}^{B15-60} * P^{15-60}) + (F_D{}^{B+60} * P^{+60}) * P^B] + [(F_D{}^{R-15} * P^{-15}) + (F_D{}^{R15-60} * P^{15-60}) + (F_D{}^{R+60} * P^{+60}) * P^R]$														
23	**$F_D{}^{MUNICIPALITY}$ = [(#15 ∗ #7) + (#16 ∗ #8) + (#17 ∗ #9) ∗ #4] + [(#18 ∗ #7)+(#19 ∗ #8) + (#20 ∗ #9) ∗ #3]**	**2.4%**		**2.1%**		**0.9%**		**1.5%**		**1.1%**		**1.8%**		**1.2%**	
	Exposed population (N_{EXP}) $N_{EXP} = [P_{PH} * T_{PH}) + (P_{SH} * T_{SH})] * N^{RB} * N_{HF}$														
24	**$N_{EXP}{}^{MUNICIPALITY}$ = [(#11 ∗ #21) + (#12 + #22)] ∗ #5 ∗ #14**	**1587**		**2025**		**508**		**1054**		**1118**		**1247**		**1022**	
	Number of potential fatalities ($N = F_D{}^{MUNICIPALITY} * N_{EXP}{}^{MUNICIPALITY}$)														
25	**N = #23 ∗ #24**	**38**		**43**		**5**		**16**		**12**		**23**		**12**	

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