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Adaptation of Residential Buildings to Coastal Floods: Strategies, Costs and Efficiency

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8.1 Introduction

The 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. (2011, 2012) highlighted how buildings can trap people during floods. They showed that: (i) 100% of the drowning occurred when the flood level exceeded 1 m, (ii) 90% of the drowning occurred inside buildings located within 400m of the flood defences that failed during the storm, and (iii) 78% of the drowning occurred inside the single-storey houses.

In response, the French government implemented the 'black zone' policy, which identified 1628 buildings in the areas of extreme flood risk for demolition at a cost of €315.7 million (Cour des Comptes, 2012). This policy was severely criticised because of its lack of methodological transparency, high costs, and lack of engagement of local communities (Mercier and Chadenas, 2012). In addition, this policy did not result in any appreciable reduction in human vulnerability to flood hazards along the French coast as it was only implemented in the areas that were flooded in 2010 (Pitié and Puech, 2010; Pitié et al., 2011). In summary, this policy was perceived as a 'knee-jerk' reaction, lacked a cost-benefit analysis and devoid of any scientific underpinning.

The French Atlantic coast is particularly susceptible to floods. For instance, it is predicted that a centennial flood could submerge 354,079 ha (CETMEF et al., 2009). In this area there are 535,500 permanent inhabitants (MEDDE, 2012b) and 136,711 residential buildings (CETMEF et al., 2009),

22% of which are single-storey constructions (MEDDE, 2012b). Flood risks will probably increase under the effects of global warming that will result in sea-level rise (Chapter 1, IPCC, 2013; Nicholls, 2011). The official projection for the French Atlantic coast announces a rise of 0.60 m of sea level for 2100 (MEDDTL, 2011). Under a projection of sea-level rise of 1 m the French Atlantic coast will comprise 58% of potentially flooded areas (CETMEF et al., 2009). There is a trend for an increase of storms frequency along the French Atlantic coast due to climate change (Goeldner-Gianella, 2013; Vinet, 2010).

Two consequences could be related with future sea-level rise:

- A flood similar to Xynthia could be produced by a less intense storm.
- A storm similar to Xynthia could generate a more dangerous flood.

In this context of potential increase of coastal floods under a changing climate in zones where existing residential buildings are vulnerable for people, its adaptation becomes essential to prevent death by drowning inside the buildings. According to Nicholls (2011), adaptation strategies are well known: protection, accommodation and retreat. However, these strategies have different costs and efficiency to reduce vulnerability of buildings for people. To address these problems, in this chapter we propose a global framework to evaluate potential fatalities in relation to coastal floods and, on the basis of these results, determine the cost-efficiency of adaptation strategies. The framework implements the VIE index methodology to identify buildings where people could be trapped and drowned during floods (Creach et al., 2015). Thus, the proposed methodology will help the decision-makers to establish the most cost-effective adaptation strategies to protect the human life from flood risks in the future.

Section 8.2 will present the methodology to estimate the VIE index. This methodology will be applied to evaluate the vulnerability of existing buildings and the risk reduction related to the implementation of the adaptation strategies presented in Section 8.3. The proposed framework will be illustrated by two study cases in Section 8.4.

8.2 VIE Index: A Tool to Identify Buildings Which Could Expose Their Occupants to Death

8.2.1 Methodology Description

The VIE index is based on four major criteria which contributed to the people being trapped inside the residential buildings during the storm Xynthia (Vinet et al., 2011, 2012) (Fig. 8.1):

- CR1: Potential water depth inside buildings.
- CR2: Distance to flood defences.
- CR3: Architectural typology of buildings, since single-storey constructions are more likely to trap people than multi-storey buildings where people could escape upstairs.
- CR4: Proximity to a rescue point to facilitate evacuation.

Each criterion is rated from 0 (no vulnerability) to 4 (high vulnerability). Creach et al. (2015) proposed Eq. (8.1), validated through statistical analysis (Section 8.2.2) to identify highly vulnerable buildings (Fig. 8.1).

$$VIE = \begin{cases} 0 & \text{if CR1} = 0 \\ \frac{2}{3}CR1 + \frac{1}{3}CR4 + CR2 + CR3 & \text{elsewhere} \end{cases} \quad (8.1)$$

The results range from 0 (no vulnerability) to 12 (maximum vulnerability). The results of the index evaluation are classified into four levels of vulnerability:

- Class A (green, $VIE = 0$): buildings are not exposed to floods and so do not endanger people.
- Class B (orange, $VIE \in [1-5]$): buildings are of a suitable design to reduce risk to people during floods. The level of vulnerability for people is low.
- Class C (red, $VIE \in [5-8]$): the vulnerability of buildings to floods is high but nonlethal excepting for children, older, or disabled people.
- Class D (black, $VIE \in [8-12]$): the vulnerability of buildings to floods is very high and could result in fatalities in the case of floods.

8.2.2 Statistical Validation

The method was validated by comparing the locations of deaths during storm Xynthia for La Faute-sur-Mer town in France (Creach et al., 2015). La Faute-sur-Mer was the most impacted municipality during this event with 29 deaths, all inside the buildings. The calculation of the VIE index shows that, for a total of 2695 buildings, 48%, 33%, 8%, and 11% were, respectively, in Classes D (black), C (red), B (orange), and A (green) (Creach et al., 2015). Thus, about 50% of residential buildings were identified as posing a lethal risk to occupants in case of flood.

The results presented in Fig. 8.2 are in agreement with the location of deaths. Fig. 8.2 shows that 83% of fatalities were inside the buildings in Class D (black), while 17% of the fatalities were in Class C (red). This confirms that buildings in the black or red classes could expose their occupants to a risk of death in case of floods. The number of deaths during storm Xynthia (29 persons) seems to be small considering that 1305 buildings were

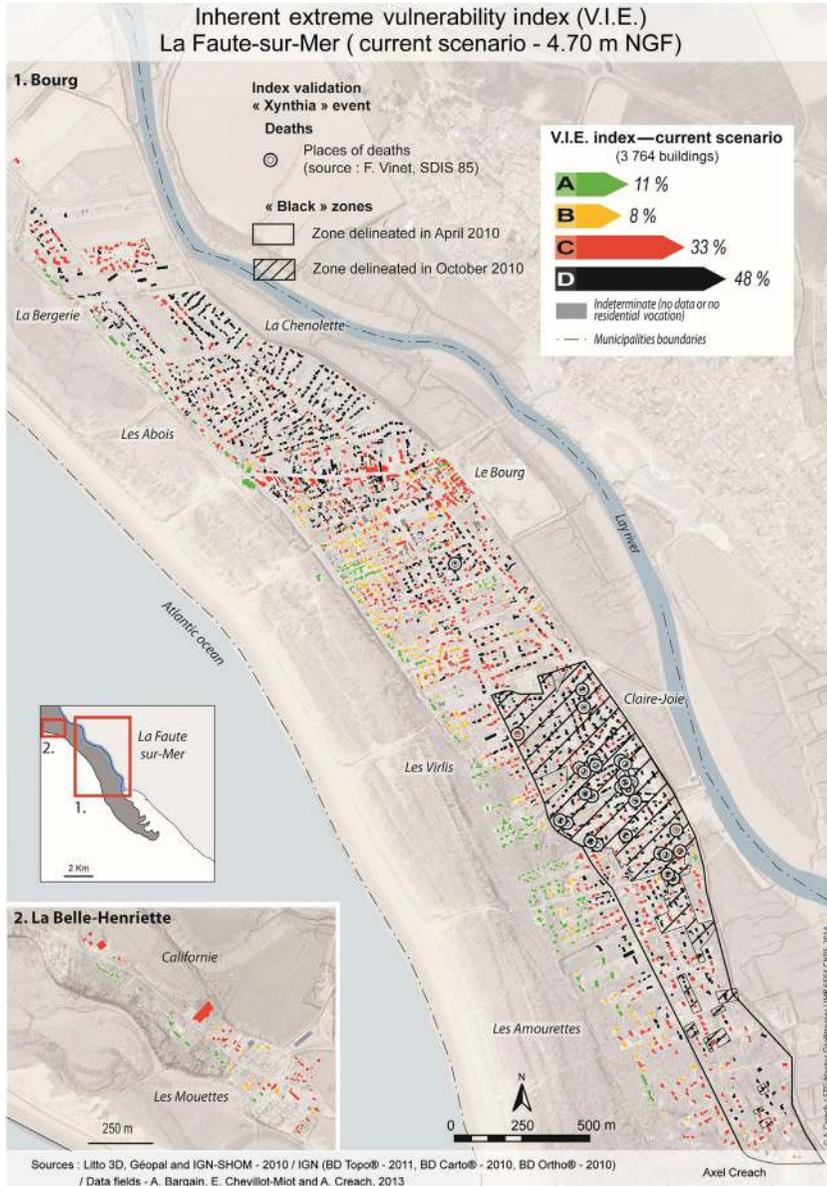


Fig. 8.2 Results of the VIE index for La Faute-sur-Mer municipality and the location of deaths linked to storm Xynthia. (Reprinted by permission from *Natural Hazards/Springer, The use of a micro-scale index to identify potential death risk areas due to coastal flood surges: lessons from Storm Xynthia on the French Atlantic coast*, Creach et al., © 2015).

identified in the Class D by the VIE index. This is explained by the fact that 85% of residential buildings are secondary houses (INSEE, 2014) and were probably unoccupied during the storm.

Fig. 8.2 also shows two areas of high vulnerability located in the south (where the deaths were located) and in the north. During Xynthia, the northern area was not subjected to high water depths thus reducing the number of fatalities compared to the southern area. However, the northern area was still identified as potentially dangerous by experts, because of its proximity to the Lay River (Pitié and Puech, 2010). Surprisingly, this north area was not included in the black zone policy (Pitié and Puech, 2010).

8.3 Adaptation Strategies

Various adaptation strategies could be implemented to reduce the vulnerability of houses during coastal flood events. Table 8.1 summarises the classification of structural adaptation strategies found in the literature which could be applied to the buildings (Klein et al., 2001; Nicholls, 2011; Paskoff, 2004). Moreover, preventive warning and evacuation could be considered as an accommodation strategy crucial to prevent fatalities (Priest et al., 2007; Lumbroso and Vinet, 2011; Kolen et al., 2013; Lumbroso and Davison, 2016). In this way, this chapter considers *protection*, *retreat* and two accommodation strategies (*housing architectural adaptation* and *preventive warning*)

Table 8.1 Adaptation Strategies for Housing Subjected to Coastal Flood Risks

Adaptation Strategy	Scheme
<p><i>Protection:</i> Construction of a protective structure that reduces the probability of floods in a particular zone.</p>	
<p><i>Retreat:</i> Moving an exposed building to safe zones (MEDDE, 2012a). This strategy was adopted after storm Xynthia via the “black areas policy”</p>	
<p><i>Accommodation:</i> Minimisation of flood impact by renovating housing at the original location</p>	

Adapted from Nicholls, R., 2011. Planning for the impacts of sea level rise. *Oceanography* 24(2), 144–157.

and evacuation). The following sections will describe these adaptation strategies including their costs and effects on VIE index assessment.

8.3.1 Protection: Dike Reinforcement and Raising

8.3.1.1 Objectives and Implementation

This strategy aims at artificially maintaining the position of the shoreline by the construction of dikes or protective walls that reduce the likelihood of floods (Klein et al., 2001; Nicholls, 2011; Paskoff, 2004). Nevertheless, there are three failure mechanisms of these protection structures: (i) structural failure, (ii) overtopping, and (iii) degradation. Despite criticisms regarding its high costs (Jonkman et al., 2013) and the false sense of security that they provide to people living behind these structures (Vinet, 2010), this strategy is popular in developed countries (Klein et al., 2001).

This chapter considers only the adaptation of existing protection facilities to overcome sea-level rise due to climate change. In France, since 2015 and the introduction of the GEMAPI law (GESTion des Milieux Aquatiques et Prévention des Inondations, i.e., Water Environment and Floods Prevention Management), local authorities are now responsible for management of flood defences. This poses a significant challenge to the local authorities because prior to 2010, 3000 km of existing flood defences were not managed or maintained properly (Lumbroso and Vinet, 2011).

8.3.1.2 Costs

Dollet and Sylla (2015) quantified reinforcement and raising costs for a segment of a dike located in Noirmoutier Island in France. A 120 cm raise of the dike crest was estimated as sufficient to overcome the maximum expected sea level for actual conditions of 4.20 m NGF ('nivellement général de la France', i.e., ordnance datum). This raise also includes an extra protection (80 cm) to mitigate future sea-level rise. The new altitude of the dike will be then 5 m NGF.

The total cost of this work was estimated at €500 per m of dike, plus an annual maintenance allowance equivalent to 2% of the investment (€10 per m of dike). Although this value is similar to others found in the literature (Goeldner-Gianella et al., 2015), it is important to highlight that these costs vary depending on the initial state of the structure, required dike raise, and/or availability and proximity of construction materials.

8.3.1.3 Impact on VIE Index Calculation

This strategy affects the second criterion CR2 of the VIE index which concerns the distance between flood defences and buildings. This study considers that flood defences are reinforced and therefore its probability of collapse is less important. Consequently, a value of 0.5 is subtracted to the mark of CR2 by considering that the defence is in a good functional state. In contrast, raising flood defences could increase the surprise effect in case of failure and therefore increase flood vulnerability for houses and their occupants.

8.3.2 Retreat

8.3.2.1 Objectives and Implementation

In some cases, implementation of protective strategies for high-risk exposure levels becomes very expensive and accommodation strategies cannot guarantee a significant decrease in vulnerability. Consequently, it is necessary to relocate vulnerable buildings outside of high-level hazard areas.

This measure has been previously implemented for housing and facilities placed in zones where coastal erosion is unavoidable (Klein et al., 2001). Regarding the marine flood risk, this approach is still new in France, that is, the “black areas policy” was the first example of the application of this strategy after the Xynthia event. In the context of sea-level rise due to climate change, this strategy should become widely employed in the future, as proposed in the French national strategy for shoreline management (MEDDE, 2012a).

The implementation of this type of strategy requires the purchase and destruction of the more exposed buildings and facilities. Although retreat is expensive in the short-term, it should eliminate future flood consequences. Like protection measures, this strategy also concerns mainly public authorities and is carried out by friendly takeovers or expropriations.

8.3.2.2 Costs

Housing retreat costs after the Xynthia event are not considered in this study. Therefore, the costs for this adaptation strategy are estimated based on available information as the sum of the purchase and demolition costs. The purchase costs in coastal zones are mainly influenced by land pressure that differs for each construction. To account for these variations, this study estimates a mean cost per m² for La Guérinière town in France from information available in three specialised websites (<http://www.meilleursagents.com/prix-immobilier>, <http://prix-immobilier.drimki.fr>, and <http://Efficity.com>). Data for seven towns located around La Guérinière zone indicate a mean purchase cost of

€2366/m² with a standard deviation of €555/m². The surface area of the buildings to be demolished is multiplied by this mean cost to estimate the purchase cost.

Demolition costs are estimated at €20,000 per building considering the information available in the website: <http://www.renovationetravaux.fr/cout-demolition-maison-prix-devis>. Considering the additional costs such as land restoration or installation in new retreat areas could complete retreat costs but they are not considered herein.

8.3.2.3 Impact on VIE Index Calculation

This strategy has no direct impact on any of the VIE index criteria. In this study, buildings identified in Class D (black) are considered too dangerous and consequently, it is supposed that they will be demolished.

8.3.3 Accommodation 1: Housing Architectural Adaptation

8.3.3.1 Objectives and Implementation

This strategy focuses on adapting buildings to reduce occupants' vulnerability to coastal flood events. The different types of solutions can be classified into two categories:

- *measures that reduce or avoid potential flood zones*: for example, the increase of the first floor level by using of stilts, construction of mounds around the building, use a floating foundation, etc.; and
- *measures that provide a safe zone in case of a flood*: for example, the addition of a refuge floor, conversion of loft, etc.

The implementation of these solutions depends on both the use and temporality of the construction. For example, the first category would be more suitable for new buildings while the second one could be more appropriate for the existing or secondary constructions. The present study only considers architectural adaptation of existing buildings. It will then focus specifically on the construction of a refuge floor, as proposed by the French repository for flood prevention in existing houses (MEDDE and METL, 2012) (Fig. 8.3).

Considering that 17% of deaths occurred in single-storey buildings during the Xynthia event (Vinet et al., 2011, 2012), the implementation of this adaptation strategy could be cost-effective. However, it should be noted that it does not completely eliminate the risks for occupants in case of a coastal flood. In some cases they could be trapped on the ground floor despite the presence of a refuge. The application of the strategy concerns mainly private individual initiatives but it may also be supported by public financial incentives.

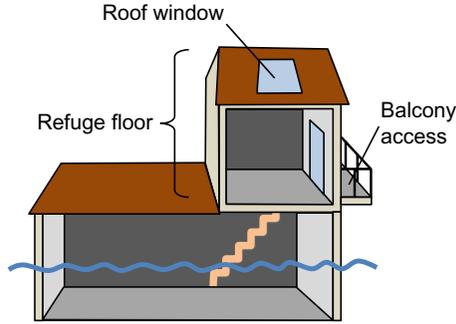


Fig. 8.3 Example of creation of a refuge floor. (According to MEDDE and METL, 2012).

8.3.3.2 Costs

The solution takes into account the recommendations of the French ministry for flood prevention in relation to the existing housing (MEDDE and METL, 2012). It consists of constructing a refuge floor with the following characteristics: (i) surface area varying from 9 to 20 m², (ii) a floor level higher than 4.2 m above the sea level, and (iii) external access (roof, window, or balcony) allowing evacuation by helicopter or boat (Fig. 8.3). On the basis of these requirements, Festuot and Guillaume (2015) estimated that the minimum construction cost of a refuge floor of 20 m² is €19,000. However, this cost may vary depending on the type of existing foundation and structure as well as the selection of construction materials. Potential benefits include the use of the new space as an active part of the house and the increase of the economic value of the residential building.

8.3.3.3 Impact on VIE Index Calculation

The measure of housing architectural adaptation has impacts on the third criterion CR3 of the VIE index (architectural configuration of the house). The single-storey buildings identified in red and black classes in the initial results will be adapted by building a refuge floor.

8.3.4 Accommodation 2: Preventive Warning and Evacuation

8.3.4.1 Objectives and Implementation

This strategy aims to facilitate preventive evacuation in case of an alert of a coastal flood. Kolen et al. (2013) affirmed that such an evacuation would significantly reduce human fatalities during storm Xynthia. Moreover, Chadenas et al. (2013) showed that prevention could be greatly improved for coastal floods in France; however, no real-time monitoring of coastal

surges and warning was available during storm Xynthia (Lumbroso and Vinet, 2011).

Nevertheless, the effectiveness of an evacuation depends on: (i) the number of people who effectively evacuate, which can be extremely variable (Priest et al., 2007); and (ii) the time available between the beginning of the alert and the occurrence of the storm event as well as the evacuation logistics (Parker et al., 2009).

A successful warning and evacuation, in case of a coastal flood, requires people to have awareness of flood risk and preliminary preparation has been undertaken. This necessitates that appropriate guidelines are issued regarding evacuation procedures and drills conducted frequently. The difficulty with such a measure is maintaining risk awareness as an ongoing process.

This strategy could be implemented at two levels:

- *Implementation of preventive measures from population information and education:* this task could be carried out by disseminating regulatory documents for information and prevention (e.g., risk prevention plans) and conducting evacuation drills regularly. These actions would facilitate the successful evacuation of inhabitants in case of an alert.
- *Deployment of evacuation equipment and/or construction of refuge structures:* since the total evacuation of an area is unrealistic, provision of compulsory household equipment such as the ‘standby emergency kit’ (<http://www.developpement-durable.gouv.fr/Kit-d-attente-des-secours-pendant.html>) are useful to localise and provide timely help to people during a flood event. On the other hand, specific structures like shelter platforms could also be installed for use as a refuge. Various types of refuge platforms have been already implemented elsewhere (Creach, 2015).

The application of this strategy depends primarily on public authorities. Nevertheless, several private facilities such as holiday centres have already built refuge platforms (Creach, 2015).

8.3.4.2 Costs

This study considers the implementation of information and educational measures as well as the construction of a refuge shelter platform. Preventive actions are defined at the municipal level. The costs of the production and dissemination of documents and evacuation training for the Flood Prevention Action Plan for La Rochelle (France) are €357,000 (CdA La Rochelle, 2013). An update every five years is envisaged to maintain risk awareness.

The installation of the shelter platforms is compulsory in certain holiday centres and campgrounds. According to one company that constructed and

installed them in France (TDEM company), the cost of a platform with a capacity of 150–200 people is about €80,000. This cost varies depending on the size and additional equipment of the platform (staircases, lifts, etc.). Finally, the cost of the ‘standby emergency kit’ is estimated at €250 taking into account the list of equipment recommended by the Ministry of Ecology.

8.3.4.3 Impact on VIE Index Calculation

This adaptation measure impacts the fourth criterion (CR4) of the VIE index (proximity to a rescue point to facilitate evacuation). The number of platforms to install is estimated by supposing that each house should be located at least at 200m of a natural or artificial shelter or safe haven.

8.4 Case Studies

The main objective of this section is to illustrate how the VIE index could be used to identify houses with higher flood risk and then to use this information to estimate the cost–efficiency of the adaptation strategies. The first case study (Section 8.4.2) will focus on the assessment of cost–efficiency for the four adaptation strategies described previously. For this case study, it is supposed that the adaptation strategies are applied separately and compared for La Guérinière town. The second case study (Section 8.4.3) will illustrate how these adaptation strategies could be combined to improve its cost–efficiency for La-Faute-Sur-Mer town.

8.4.1 Basic Considerations

8.4.1.1 Considered Coastal Flood Scenarios

This study analyses the vulnerability of houses for people and costs of the adaptation strategies for four scenarios of coastal floods: frequent, medium, medium including sea-level rise in 2100, and extreme. These scenarios have been defined on the basis of studies made by the French administration to formulate and implement the Flood Directive (European Commission, 2007). Table 8.2 provides the sea water levels for each scenario estimated in (DREAL Pays de la Loire, 2014) for Fromentine town. These values are considered herein because Fromentine town is also placed in the Atlantic coast close to La Guérinière and La-Faute-Sur-Mer towns.

Table 8.2 Coastal Flood Scenarios (DREAL Pays de la Loire, 2014)

Scenario	Return Period	Sea Water Level at Fromentine Town
Frequent	10 years	3.6 m NGF
Medium	100–300 years	4.2 m NGF
Medium + SLR ^a	Same as above +0.6 m	4.8 m NGF
Extreme	1000 years or more	5.2 m NGF

^aSLR: Sea-level rise.

8.4.1.2 Flood Modelling, Assumptions, and Limitations

Based on the sea water levels presented in Table 8.2, the potentially flooded areas were determined employing a static flood model (Breilh et al., 2013). This model uses high-resolution topographic datasets (Lidar Litto-3D) (IGN and SHOM, 2012) and considers that inland areas located below sea level are inundated within a range of 100 m of the seashore. The difference between sea level and the ground level of the house is used to estimate the potential water level in case of floods. This method is relatively simple but has two main limitations: (i) the house ground level is derived from LiDAR datasets; however Cooper et al. (2013) identified several uncertainties for LiDAR datasets particularly in marshes and urbanised areas, and (ii) it is assumed that the LiDAR ground level corresponds to the ground level of the house. If both the aspects are accounted for, there will be in some cases a difference of 20–60 cm with respect to the real ground level of the house inducing some errors for the assessment of the real water level. Consequently, infield data would be necessary to improve the accuracy of the vulnerability assessment.

8.4.1.3 Discount Rates

There is some uncertainty about the discount rate, particularly for climate change economic assessments [see Chapter 1 or Bastidas-Arteaga and Stewart, 2015, 2016 for a further discussion]. France used a discount rate of 8% to evaluate public investments from 1985 to 2005. However, following the 2005 Lebègue report (Lebègue et al., 2005), the ‘Commissariat Général au Plan’ has recommended a 4% discount rate for short-term investments and a lower discount rate of 2% for cash flows occurring after more than 30 years (Gollier, 2012). These discount rates were revised in 2013 by the ‘Commissariat Général à la Stratégie et à la Prospective’ recommending 2.5% and 1.5% discount rates for short-term (lifetime less than 70 years) and long-term investments, respectively (Quinet, 2013). Quinet (2013) also

recommends carrying out a sensitivity analysis with a 4.5% discount rate to compare new and old approaches. The present study considers a 2% discount rate as recommended by the ‘Commissariat Général à la Stratégie et à la Prospective’ in 2005 in the Lebègue report (Lebègue et al., 2005).

8.4.2 Case Study 1: VIE Index for Adaptation Measures Applied Separately

8.4.2.1 Site Description

Noirmoutier is a French Atlantic island (area of 49km²) located in the Vendée department (Fig. 8.4). The island is in a low-lying area currently protected by 24km of flood defences on the east coast and by a sand barrier on the west coast (Fattal et al., 2010). Without this protection, around 68% of the island would have been under water during storm Xynthia (Creach et al., 2016).

Since 1968, the population of the island has increased by 19%, meanwhile, the urbanisation has increased by +162% during the same period (Creach et al., 2017). This important growth is mainly due to the construction of leisure residential houses which represented 50% of the urbanised area in 2011 (INSEE, 2014). Leisure housing is mainly located in low-lying areas (Creach et al., 2016) and today one-half of these constructions are located in potential flood areas.

Noirmoutier island was not severely affected by storm Xynthia in 2010 with only 3% of the territory flooded (Devaux et al., 2012). Since the 1950s,

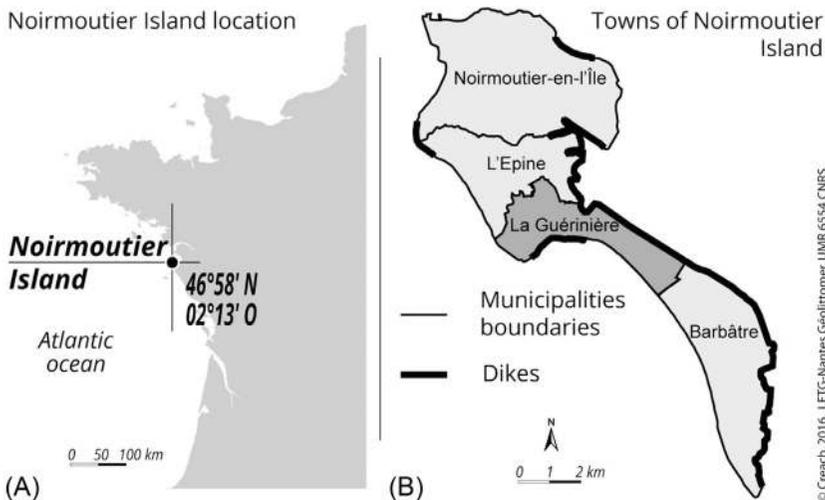


Fig. 8.4 Location of La Guérinière town.

no major floods have occurred. A large part of the island was flooded in 1937; however, the relatively unpopulated nature of the island at that time resulted in minimal impacts on human life and infrastructure (Garnier et al., 2012). Taking into account the natural risk of floods for this island, the additional risk related to sea-level rise and its present urbanisation, it is important to evaluate the potential consequences of extreme events occurring today and in the future.

This section focuses on one of the most vulnerable towns of the island called La Guérinière. La Guérinière covers 7.8 km² (16% of the island) with 80% of its territory located below the sea water level attained during storm Xynthia (4.20 m NGF) (Devaux et al., 2012). The town is in the narrowest part of the island (less than 800 m between the west coast and the east coast) which increases the risk of coastal floods (see Fig. 8.4). On the east coast, La Guérinière is protected by flood defences which are 5 m high (following renovation in 2014) (Fig. 8.4). On the west coast, the town is isolated from the Atlantic Ocean by a sand barrier which is high and wide on the north and the south, but narrow and less elevated in the central part of the town (approximately 5 m high and 50 m wide) and supported by a seawall.

The town had 2667 houses with 1460 inhabitants in 2011 (INSEE, 2014). The number of houses has increased by 144% since 1968 and presently 73% are located under the seawater level reached during storm Xynthia (Creach et al., 2017).

8.4.2.2 VIE Index Without Adaptation Measures

The VIE index was calculated for each flood scenario for 2817 houses identified in 2012. Results are showed in Table 8.3. As expected, vulnerability of houses for people depends on the intensity of the hazard. The proportion of non-floodable houses (Class A) decreases from 47% to 26% from the frequent to the extreme scenario. On the other hand, the proportion of houses that could expose their occupants to a fatality risk (Class D) increases from 16% to 29% from a frequent to an extreme event.

8.4.2.3 VIE Index for the Adaptation Strategies

Tables 8.4–8.7 summarise the VIE indexes for all adaptation strategies. It is noted that each adaptation strategy has a different performance depending on the flood scenario. In a global manner, retreat is the most efficient measure because all the houses considered as the most dangerous (Class D) are demolished. Therefore Table 8.4 shows that Class D is empty. However, from political, economical, and social points of view, it is harder to

Table 8.3 VIE Index without Adaptation Measures for La Guérinière

	Frequent Event (3.60 m NGF)		Medium Event (4.20 m NGF)		Medium Event + SLR (4.80 m NGF)		Extreme Event (5.20 m NGF)	
Class A	1,312	47%	1,034	37%	890	32%	690	26%
Class B	304	11%	329	12%	313	11%	267	10%
Class C	732	26%	885	31%	908	32%	911	35%
Class D	469	16%	569	20%	706	25%	758	29%
Total of identified houses	2,817	100%	2,817	100%	2,817	100%	2,626	100%
Non-identified ³	1,251	31%	1,251	31%	1,251	31%	1,442	35%
Total	4,068	100%	4,068	100%	4,068	100%	4,068	100%

³Indeterminate: no data or no residential vocation.

Table 8.4 VIE Index for Retreat Adaptation Strategy for La Guérinière

	Frequent Event (3.60 m NGF)		Medium Event (4.20 m NGF)		Medium Event + SLR (4.80 m NGF)		Extreme Event (5.20 m NGF)	
Class A	1,312	56%	1,034	46%	890	42%	690	37%
Class B	304	13%	329	15%	313	15%	267	14%
Class C	732	31%	885	39%	908	43%	911	49%
Class D	0	0%	0	0%	0	0%	0	0%
Total of identified houses	2,348	100%	2,248	100%	2,111	100%	1,868	100%
Non-identified ³	1,251	35%	1,251	36%	1,251	37%	1,442	44%
Total	3,599	100%	3,499	100%	3,362	100%	3,310	100%

³Indeterminate: no data or no residential vocation

Table 8.5 VIE Index for Housing Architectural Adaptation Strategy for La Guérinière

	Frequent Event (3.60 m NGF)		Medium Event (4.20 m NGF)		Medium Event + SLR (4.80 m NGF)		Extreme Event (5.20 m NGF)	
Class A	1,312	47%	1,034	36%	890	32%	690	26%
Class B	631	22%	701	25%	618	22%	588	22%
Class C	848	30%	975	35%	966	34%	906	35%
Class D	26	1%	107	4%	343	12%	442	17%
Total of identified houses	2,817	100%	2,817	100%	2,817	100%	2,626	100%
Non-identified ³	1,251	31%	1,251	31%	1,251	31%	1,442	35%
Total	4,068	100%	4,068	100%	4,068	100%	4,068	100%

³Indeterminate: no data or no residential vocation.

Table 8.6 VIE Index for Protection Adaptation Strategy for La Guérinière

	Frequent Event (3.60 m NGF)		Medium Event (4.20 m NGF)		Medium Event+SLR (4.80 m NGF)		Extreme Event (5.20 m NGF)	
Class A	1,312	47%	1,034	37%	890	31%	690	26%
Class B	364	13%	382	14%	320	11%	268	10%
Class C	889	31%	1,015	35%	1,085	39%	1,106	42%
Class D	252	9%	386	14%	522	19%	562	22%
Total of identified houses	2,817	100%	2,817	100%	2,817	100%	2,626	100%
Non-identified ^a	1,251	31%	1,251	31%	1,251	31%	1,442	35%
Total	4,068	100%	4,068	100%	4,068	100%	4,068	100%

^aIndeterminate: no data or no residential vocation.

implement when considering the destruction of 16% (frequent event) to 29% (extreme event) of residential buildings (King et al., 2014).

The second most efficient measure is housing architectural adaptation (Table 8.5). It reduces the number of dangerous houses (Class D) from 95% (for a frequent event) to 42% (for an extreme event) with respect to the reference values provided in Table 8.3. The protection measure (Table 8.6) decreases the number of dangerous houses from 46% (frequent event) to 26% (extreme event). Finally, the warning and evacuation measures appear to be less efficient (Table 8.7), but their efficiency increases with the intensity of the coastal flood hazard. For example, for a frequent event, it reduces the quantity of Class D houses by 2.3%, whereas the reduction reaches 14% for an extreme event.

Table 8.7 VIE Index for Preventive Warning and Evacuation Adaptation Strategy for La Guérinière

	Frequent Event (3.60 m NGF)		Medium Event (4.20 m NGF)		Medium Event+SLR (4.80 m NGF)		Extreme Event (5.20 m NGF)	
Class A	1,312	47%	1,034	37%	890	32%	690	26%
Class B	304	11%	362	13%	378	13%	314	12%
Class C	743	26%	914	32%	931	33%	970	37%
Class D	458	16%	507	18%	618	22%	652	25%
Total of identified houses	2,817	100%	2,817	100%	2,817	100%	2,626	100%
Non-identified ^a	1,251	31%	1,251	31%	1,251	31%	1,442	35%
Total	4,068	100%	4,068	100%	4,068	100%	4,068	100%

^aIndeterminate: no data or no residential vocation.

8.4.2.4 Cost-Efficiency of Adaptation Strategies

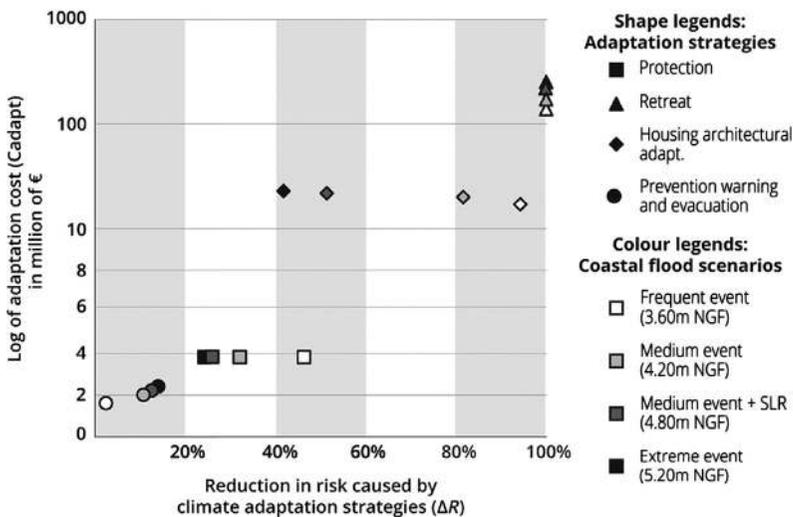
Costs of adaptation (C_{adapt}) are also calculated including investment and maintenance costs for a lifetime of 100 years. The reduction in risk caused by climate adaptation strategies (ΔR) is estimated in terms of the ability of the adaptation measure to reduce the number of dangerous houses in Class D as:

$$\Delta R = \frac{nb_{\text{with adap}} - nb_{\text{without adap}}}{nb_{\text{without adap}}} \times 100\% \quad (8.2)$$

where $nb_{\text{with adap}}$ and $nb_{\text{without adap}}$ are respectively the number of houses in Class D with and without considering the adaptation strategy.

Fig. 8.5 shows costs and corresponding risk reduction for the considered adaptation strategies and flood scenarios for La Guérinière. It is observed that the costs of adaptation strategies are very different: from about €2 million (for preventive warning and evacuation) to more than €100 million (for retreat). Protection is around €4 million while housing architectural adaptation is between €16 and €22 million.

Considering the risk reduction, it can be noted that retreat is the most efficient adaptation strategy ($\Delta R = 100\%$) for all flood scenarios. The efficiency of housing architectural adaptation and protection strategies decreases for larger hazard intensities. The ΔR for housing architectural adaptation diminishes from 95% to 42%. This means that this strategy is appropriate for dealing with



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Fig. 8.5 Adaptation costs and corresponding risk reduction for adaptation strategies applied to La Guérinière.

current flood scenarios but it is not effective for reducing future risks related with climate change. The efficiency of the protection strategy is smaller than 50% for frequent events and could decrease up to 23% for extreme events. For the preventive warning and evacuation strategy ΔR is very low but increases from 2% (frequent scenario) to 14% (extreme scenario). This could be explained by the fact that additional refuge platforms are implemented for extreme events. This will reduce the distance between exposed population and houses and then increase the efficiency of the measure. Overall results show that, independently from the flood scenario, the strategies could answer to different political choices: saving money (economical choice, it concerns protection) to safety first (safety choice, it concerns retreat).

8.4.3 Case Study 2: VIE Index for Combined Adaptation Measures

8.4.3.1 Site Description

Hinkel et al. (2013) stated that climate change adaptation cannot be based on a unique solution but on a mix of strategies. In Section 8.4.2 we found that each strategy has a different cost and risk reduction performance. Nevertheless, what would be the efficiency of preventive warning and evacuation and housing architectural adaptation together to protect humane life? Or would this mix of strategies reduce the number of houses to be relocated? To provide some partial responses to these challenges, this section includes combined adaptation strategies for La Faute-sur-Mer town.

La Faute-sur-Mer is located on a small strip of coastal land and 80% of its 6.8 km² territory could potentially be flooded (Creach, 2015); and some low-lying areas are protected from the Lay River by a dike (Fig. 8.2). In addition, urbanised areas have grown by 262% between 1968 and 2006 (Creach, 2015). In 2006, there were 3737 residential buildings (INSEE, 2014) among which 85% are leisure residential houses (INSEE, 2014) and 70% are single-storey houses (Creach, 2015).

La Faute-sur-Mer was the most impacted municipality by storm Xynthia (29 people died). After storm Xynthia, the French government bought and demolished 552 houses for a total cost of €160 million (Cour des Comptes, 2012). This 'black zones' policy could be referred to as a retreat of the most dangerous buildings (Class D).

8.4.3.2 Results of VIE Index

Fig. 8.2 showed that about 50% (1305 over 2695 houses) of the houses in La Faute-sur-Mer could expose their occupants to extreme vulnerability

(Class D) in case of coastal flood similar to Xynthia. To reduce this vulnerability, the four adaptation strategies presented in Section 8.3 were considered. This analysis also includes the implemented ‘black zones’ policy and two alternatives mixing the adaptation strategies proposed above:

- Alternative 1: it combines preventive warning and evacuation and housing architectural adaptation. The objective is to avoid the retreat of houses in the flood prone area but facilitating evacuation of people during a flood.
- Alternative 2: it combines preventive warning and evacuation, housing architectural adaptation and retreat. It is the same scenario described above but the most dangerous houses are relocated. The goal is to minimise the risk of death for Class D houses in cases where housing architectural adaptation is not efficient.

The VIE index for each adaptation strategy and a medium coastal flood hazard is given in Table 8.8. It is observed that adaptation strategies decrease the percentage of houses in Class D from 48% up to 0%. The higher reductions correspond to the cases of retreat and both alternatives combining the different adaptation strategies.

8.4.3.3 Cost-Efficiency of Adaptation Strategies

Costs of adaptation (C_{adapt}) and the reduction in risk caused by climate adaptation strategies (ΔR) are estimated by following the same considerations given in Section 8.4.2.4. The results of the analysis are presented in Table 8.9. It is noted that protection and preventive warning and evacuation are the less interesting measures because its risk reduction is less than 7% for an investment of €3.9 million. Retreat is the most expensive measure (€320.5 million), two times higher than ‘black zones’ policy (€160 million), but with a $\Delta R = 100\%$. This could be explained by the fact that ‘black zones’ policy concerned only the south part of La Faute-sur-Mer while there are also dangerous houses on the north part of the town (see Fig. 8.2). Housing architectural adaptation provides a ΔR higher than 70% with a cost 10 times cheaper than retreat.

Concerning combined adaptation strategies, Alternative 1 is 11% more expensive than architectural adaptation alone but provides a larger ΔR compared to this single strategy. Alternative 2 provides the same ΔR than retreat but is 76% less expensive. These results indicate that combining adaptation strategies is paramount to reduce the adaptation costs and increase the risk reduction.

Table 8.8 VIE Index for Different Adaptation Strategies, Including Two Alternative Scenarios, on La Faute-sur-Mer Municipality for a Medium Coastal Flood

	VIE Index															
	(Medium Event—4.70 m NGF)	'Black Zones' Policy	Protection	Housing Architectural Adaptation	Preventive Warning and Evacuation	Retreat	Alternative 1	Alternative 2								
Class A	289	11%	289	11%	289	11%	289	11%	289	11%						
Class B	216	8%	216	10%	172	6%	399	15%	230	9%	216	16%	422	17%		
Class C	885	33%	749	35%	1,016	38%	1,626	60%	920	34%	885	64%	1,811	67%	1,811	72%
Class D	1,305	48%	891	42%	1,218	45%	381	14%	1,256	47%	0	0%	173	6%	0	0%
Total of identified houses	2,695	100%	2,145	100%	2,695	100%	2,695	100%	2,695	100%	1,390	100%	2,695	100%	2,522	100%
Non-identified ^a	1,069	28%	964	31%	1,069	28%	1,069	28%	1,069	28%	1,069	43%	1,069	28%	1,069	30%
Total	3,764	100%	3,109	100%	3,764	100%	3,764	100%	3,764	100%	2,459	100%	3,764	100%	3,591	100%

^aIndeterminate: no data or no residential vocation.

Adapted from Creach, A., 2015. "Cartographie et analyse économique de la vulnérabilité du littoral atlantique français face au risque de submersion marine (2 volumes)." Université de Nantes.

Table 8.9 Adaptation Costs and Corresponding Risk Reduction for Adaptation Strategies Applied to La Faute-sur-Mer Under a Medium Coastal Flood

Adaptation Strategy	Adaptation Cost (in € million)	ΔR (%)
'Black zones' policy	160	31.7
Protection	3.9	6.7
Housing architectural adaptation	31.9	70.8
Preventive warning and evacuation	3.9	3.7
Retreat	320.5	100
Alternative 1	35.7	86.7
Alternative 2	76.4	100

8.5 Summary

Sea-level rise and vulnerability of the existing residential buildings would increase the risk of death in case of future floods. To prevent these fatalities, adaptation is an essential solution. However, the cost and efficiency of available adaptation strategies are difficult to evaluate. Therefore, this chapter presented a global framework that aims to assess vulnerability of buildings for people under different flood scenarios including climate change. It is based on the VIE index and is useful to identify buildings which need to be adapted in priority. Four different adaptation strategies were illustrated in the chapter; protection, retreat, housing architectural adaptation, and preventive warning and evacuation. The proposed methodology was used to compare their costs and risk reduction.

Two case studies showed that retreat is one the most efficient but expensive alternatives to reduce vulnerability of buildings for people. In addition, it was observed that a combination of adaptation strategies could reduce risks and adaptation costs. The results highlighted that the proposed framework could be used as a decision-making tool to compare or optimise the performance and costs of adaptation strategies under various flood scenarios.

8.6 Potential Design and Practice Evolutions

Adaptation of the coastal areas subjected to flood risks is not an easy task for decision-makers. For example, after storm Xynthia, the lack of standardised procedures including a comprehensive methodology to evaluate and compare various adaptation strategies conducted to the implementation of a costly, ineffective and criticised 'black zones' policy.

The standardised procedures should include building adaptation to reduce vulnerability for people in a context of sea-level rise due to climate change. Building adaptation could reduce the vulnerability of buildings but there will be a remaining risk. For instance, 5 of the 41 deaths related to storm Xynthia occurred inside multistorey houses where people were trapped at the ground floor (Vinet et al., 2011).

Human factors including flood risk awareness and acceptability should also be considered when formulating adaptation strategies. The acceptability of the ‘black zones’ policy for the local population is an example in France where people rejected to leave their houses after the storm Xynthia (Mercier and Chadenas, 2012). Acceptability could be created by explaining to local communities about the potential consequences of flood for various scenarios and proposing to them several adaptation strategies to deal with.

A final aspect that should be considered when formulating ‘acceptable’ adaptation strategies is to propose alternative economical models. Nowadays governments or insurers provide the main source of funding to implement adaptation measures after a flood event. However, one could imagine that all the involved actors (governments, insurers and owners) participate preventively for cofunding the implementation of adaptation strategies. For instance, a cofunding scheme with financial incentives from the government and reduction of insurance fees could motivate the owners to invest in the construction of a refuge floor. This solution in turn will increase the living space of the house generating cobenefits for the owner.

8.7 Open Research Questions

The proposed methodology is a useful decision-making tool to reduce the vulnerability of buildings and to protect people from future floods. To be fully operational the framework needs to be improved in the following directions:

- Consideration of dynamic effects on flood modelling and ageing and failure mechanisms for defences.
- Quantification and propagation of uncertainties related to the hazard, the adaptation strategies and the cost-efficiency analysis.
- Calibration of the VIE index with databases different from the storm Xynthia. For instance, databases in the Netherlands (Di Mauro and Lumbroso, 2008), UK (Gerritsen, 2005) and the USA (Jonkman et al., 2009)

- Consideration of acceptability on the formulation of adaptation strategies.
- Formulation of innovative funding schemes where all the involved actors could participate actively and preventively in the whole process.

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