

## Evolution of vulnerability to marine inundation in Caribbean islands of Saint-Martin and Saint-Barthélemy

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Kelly Pasquon, Julien Gargani, Gwenael Jouannic. Evolution of vulnerability to marine inundation in Caribbean islands of Saint-Martin and Saint-Barthélemy. International Journal of Disaster Risk Reduction, 2022, 78, pp.103139. 10.1016/j.ijdrr.2022.103139. hal-03706545v1

## HAL Id: hal-03706545 https://hal.science/hal-03706545v1

Submitted on 27 Jun 2022 (v1), last revised 1 Jul 2022 (v2)

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1	Evolution of vulnerability to marine inundation in Caribbean islands of Saint-
2	Martin and Saint-Barthélemy
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12	
13	Abstract
14	

The islands of Saint-Martin and Saint-Barthélemy in the French West Indies are regularly affected by 15 hurricanes and marine inundations. In this study, we investigated the influence of economic, 16 17 demographic, and urban planning strategies on the construction of buildings located in areas 18 exposed to coastal flooding, using a quantitative analysis based on satellite images and aerial photos 19 from 1954 to 2017. Our results indicated that the number of buildings in coastal flooding areas is higher in Saint-Martin than in Saint-Barthélemy. The number of buildings constructed in marine 20 21 inundation risk areas have increased during the last decades, owing to the tax reduction policies 22 implemented for investment in French overseas territories that favor the development of new 23 constructions in these islands and promote demographic growth. Inheritance of economic policy 24 during the 1980-2010 period is responsible for the present state of vulnerability to marine inundation. A recent decrease (by 45 %) in the constructions per year in the marine inundation risk 25 areas observed in Saint-Martin from 2011 to 2017 could have been influenced by (1) the approval of 26 the Natural Hazards Prevention Plan in 2011 and (2) population stagnation since 2007. Prevention 27 28 plan was implemented late, after many buildings had already been built in marine inundation areas. 29 The reduced prevention plan efficiency is due to the difficulty to conciliate risk mitigation, economic 30 interests and political agenda. 31 32 33 Keywords: Coastal Urbanization, vulnerability, prevention plan, Saint-Martin, Saint-Barthélemy, marine inundation 34 35 36 1. Introduction 37

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Our study focused on coastal vulnerability to marine inundation in the Saint-Martin and Saint-Barthélemy islands (Fig. 1). Saint-Martin and Saint-Barthélemy are two Caribbean islands in the North of the French West Indies where cyclonic risk is present. The economy of these islands is dominated by tourism [1,2,3,4,5]. Notably, the tourist attractions are located on the coast near the beach in marine inundation risk areas.

Hurricanes are known to generate damages by various ways: (i) wind [6], (ii) rainfall [7], and (iii)
marine inundation [8]. Wind can cause direct (e.g., houses, building, streets, infrastructure) or
indirect (e.g., by projection of various objects, debris, uprooted trees) damage, destroy agricultural

47 land [9], and thus pose direct/indirect risks to life [10,11]. Marine inundation and waves destroy 48 houses and roads on the coast [8]. Marine inundation is increased by low atmospheric pressure 49 during major hurricane. Erosion [12] and landslides [7] can be observed during cyclonic events. In the 50 future, frequency and intensity of natural disasters are expected to increase along the coast, owing 51 to climate change and sea level rise [9].

52 In low-laying coastal areas in Caribbean islands, the vulnerability to marine inundation is particularly 53 high due to the high frequency of hurricane occurrences and intense coastal urbanization [13]. 54 Tsunamis caused by distant earthquakes or submarine/subaerial volcanic eruptions or major 55 submarine landslides is also a potential risk. During the last decades, coastal urbanization has 56 increased in Saint-Martin [14] and Saint-Barthélemy but no quantitative data exist. Coastal 57 urbanization is characterized by building construction and also by infrastructure development. Supply 58 chain, such as road, harbor, and electricity infrastructures, are often located on the coast of islands 59 [15], where marine inundation risk is high.

60 After the Luis and Lenny hurricanes in Saint-Martin, damaged hotels on the coast were visible for 61 more than a decade [16]. Damages on dwellings caused by natural hazards are seldom identified as part of geoheritage, valuable in education. These are considered as "stigmata", "scars" or "warts" 62 63 that it would be preferable to make disappear. Owing to the frequent occurrence of hurricanes in the 64 last decade, improving risk and crisis management is necessary in the French Caribbean islands to 65 anticipate and mitigate the impacts of future events [17]. Notably, without anticipation and 66 prediction, recovery from such disasters will only be focused on the speed of restoration [18]. Post-67 disaster restoration consists of not only constructing buildings that are resistant to multiple hazards 68 but also enhancing social development [19,20,21]. Even if the experience of past hurricanes could 69 improve the reaction and preparation of the inhabitants of these islands [22], the "culture of risk" 70 [23] can not decrease the vulnerability of such locations.

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From all the type of vulnerability that can be discussed, such as vulnerability to environmental changes [24,25] or to natural disasters [26,27,28], which cause biophysical [29,30,31] or social impacts [32,33,34,35,36,37,38], this study concentrates on a quantitative analysis of marine inundation vulnerability.

Studies on vulnerability of coastal areas to marine inundation are essential to better protect populations from future extreme events, and several such studies have been conducted on Saint-Martin [8,13] and Saint-Barthélemy [12,39]. Previous studies concluded that Saint-Martin is highly vulnerable due to its social and economic history [13,14]. However, due to a lack of quantitative measurements of the number of buildings in the marine inundation risk areas at different period of time, the cause of vulnerability to marine inundation in Saint-Martin and in Saint-Barthélemy could not be explained accurately.

The objective of this study is to better quantify and qualify the vulnerability of the islands of Saint-Martin and Saint-Barthélemy to marine inundation. Therefore, our approach is limited to a single type of hazard affecting these islands and does not take into account other types of natural hazards (e.g., strong winds, earthquakes, runoff, landslide, and tsunami). A potential approach is to study only a specific aspect of vulnerability and construct an indicator of vulnerability specifically for a situation.

90 Previous studies have indicated that post-disaster crisis and mistakes in areas that experience marine 91 inundation could be related to the lack of risk prevention and the processes of urbanization [40]. In 92 cases of river flooding, prevention-plan efficiency has been criticized by previous studies [41,42], but 93 their real impact against marine inundation in French overseas territories is an open question. In 94 2011, a Natural Hazards Prevention Plan that regulates and constrains the urban planning rules in 95 sectors exposed to natural hazards has been established and implemented in Saint-Martin [43], but 96 not in Saint-Barthélemy. Studying the Saint-Martin and Saint-Barthélemy islands is particularly 97 interesting because we can compare the real impact of a prevention plan on the evolution of 98 construction in areas subject to natural hazards on two islands located 20 km away from each other, 99 with comparable size (53 km<sup>2</sup> and 23 km<sup>2</sup>), which have been exposed to the same hurricanes.

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101 In this study, we have described the urban evolution of Saint-Martin and Saint-Barthélemy from 102 1954, when their urbanization levels were almost similar and the number of inhabitants were 103 identical [44], to 2017, when some significant discrepancies in their organization levels and 104 population existed, just before Hurricane Irma occurred. A quantitative observation of new buildings 105 in marine inundation risk areas in Saint-Martin and Saint-Barthélemy could improve discussions 106 about their respective vulnerabilities to marine inundation with respect to time, along with the cause 107 of vulnerability evolution. Furthermore, we have discussed how social, economic, politic, and 108 environmental changes may have influenced urbanization evolution in the marine inundation risk 109 areas requalifying physical and social distinctions. Finally, we have discussed the efficiency of the 110 prevention plan for marine inundation mitigation established in 2011 in Saint-Martin.

111 The aim of this study is to understand how vulnerability to marine inundation areas evolved with 112 time in two Caribbean islands. We show using a quantitative approach that population growth and 113 past political decisions played a significant role on vulnerability increase. The local prevention plan 114 has limited effectiveness in reducing inundation risk.

- 115
- 116 **2. Case study**
- 117

Since 1648, the island of Saint-Martin has been divided into two parts: a Dutch part called Sint Maarten, and a French part called Saint-Martin. Whereas Sint Maarten is outside the territory of the European Union, Saint-Martin is inside. The French part covers 53 km<sup>2</sup>, with 35,941 inhabitants in 2017 [44,45], and the Dutch part covers an area of 37 km2, with 37,000 inhabitants in 2018 [44]. The surface area of Saint-Barthélemy is 24 km<sup>2</sup> and the total population was 10,124 inhabitants in 2018.

123 In 2007, Saint-Martin and Saint-Barthélemy changed their status from municipalities administratively 124 attached to Guadeloupe to two relative autonomous French overseas regions (article 74 of the 1958 125 French Constitution). Consequently, the two local authorities decide and apply the rules with respect 126 to urban planning, construction, and housing [46]. However, the French State remains competent to 127 lay down rules in several areas, including the organization of justice, military forces, public security, 128 and the environment (including natural hazards prevention). Notably, the two islands have the same 129 tax exemption laws, favoring investments, especially in the construction of new buildings (Pons law 130 since 1986; Paul law in 2001; Giradin law in 2003; Scellier outre-mer law in 2009; and Pinel law in 131 2015) [2,16,42]. In 2012, the island of Saint-Barthélemy strengthened its autonomy by obtaining the 132 status of an overseas country and territory. As a result, since 2012, Saint-Barthélemy has been 133 outside the territory of the European Union (EU) and thus, it is responsible for its environmental 134 competence (including natural hazards prevention).

During the last decade, the social, economic, and political trajectories of Saint-Martin and Saint-Barthélemy were not similar [14,13]. Notably, the population growth was significantly higher in Saint-Martin than Saint-Barthélemy [44]. Furthermore, in 2016, the Gross Domestic Product of Saint-Barthélemy was more than twice that of Saint-Martin [12,45,47], inverse proportional with population, as observed in other cases [48]. The social and historical differences, could have played a role in the political strategies and economic activities [13,14]. Historical processes are fundamental to understanding how conditions of risks emerge and persist over time [49,50,51,52].

The landscapes of Saint-Martin and Saint-Barthélemy are composed of old volcanic hills. Several areas having a low topography can be observed and several lagoons are also present. These islands are affected by hurricanes; the hurricanes Luis (1995) and Lenny (1999) caused serious damage to these islands [16,53,54]. The climate of these islands is tropical, with a mean temperature of 27 °C and mean rainfall of 800 mm/yr [55]; the wet season extends from June to November.

147 In 2017, Hurricane Irma (classified as category 5 on the Saffir-Simpson scale) generated strong winds, 148 with a mean velocity of 287 km/h [56], and caused coastal flooding along the coast [38,8]. Eleven 149 inhabitants died during this event [57]. A decrease of social and economic activities occurred after 150 hurricane Irma [58]. In 2018, a report from the French National Assembly based on insurers' data 151 reports [59] estimated that the compensation paid by insurance companies to reimburse the damage 152 caused by Irma was 1.164 billion euros for Saint-Martin (50 % for homes, 45 % for business premises, 153 4 % for cars, 1 % for boats) and 839 million euros for Saint-Barthélemy (61 % for homes, 36 % for 154 business premises, 3 % for cars, >1 % for boats). In 2021, the estimated compensation to be paid to 155 the victims by the insurance companies amounts to 2.10 billion euros for the two islands [60]. These 156 numbers must be qualified because the penetration rate of insured goods is very low on these two 157 islands, only 40 % of the population on Saint-Martin and 60 % on Saint-Barthélemy have home 158 insurance [9], compared to the rate of 97 % in metropolitan France [61].





Figure 1. A) Topographic map of West Indies (source : GeoMapApp); B) Map of marine inundation
depth on French part of Saint-Martin, based on impacts of Hurricane Irma and DTM; and C) Map of
marine inundation depth on French part of Saint-Barthélemy, based on impacts of Hurricane Irma and
DTM.

165

## 166 **3. Methods**

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In this study, we coupled the maps of marine inundation with the buildings' localization in Saint-Martin (French side) and Saint-Barthélemy to study the evolution of urbanization between 1954 and 2017 (before Irma hurricane) in the (1) entire territory and (2) marine inundation risk areas. The island of Saint-Martin is shared between two countries: at the North, a French territory that will be called "Saint-Martin" in this study, and at the South, a Dutch territory that will be called Sint Maarten (Fig 1).

174

## 175 **3.1 Building maps**

176 In this study, aerial photography from the French National Institute of Geography [IGN, 177 https://remonterletemps.ign.fr/] were used to construct urbanization maps for different years for 178 monitoring the evolution of new building construction in Saint-Martin and Saint-Barthélemy. There 179 were 776 aerial photos of Saint-Martin and 431 of Saint-Barthélemy. These aerial photos were 180 recorded during 12 photographic campaigns for Saint-Martin and 9 for Saint-Barthélemy, between 181 1947 and 2010. The time span between photographic campaigns was irregular, with gaps ranging 182 between 2 months and 15 years, and the satellite images were recorded since 2010 (Pleiades images, 183 20 cm/pixels). In this study, the monitoring was conducted from 1954 until 2017, before the occurrence of Hurricane Irma. To compare data from Saint-Martin and Saint-Barthélemy, we
 presented only the results where photographic campaigns or satellite images were
 contemporaneous in both territories: 1954, 1969, 1989, 1999, 2010, and 2017.

QGIS (Geographic Information System) was used to visualize and overlay aerial photos and building
maps. The aerial photos were initially not geo-referenced. It was necessary to superimpose them
with a georeferenced image.



Figure 2. Aerial photographs of Anse Marcel, Saint-Martin for: A) 1947, B) 1954, C) 1969, D) 1979, E)

- 193 1984, F) 1984 G) 1989, H) 1999, I) 2004, J) 2010, and K) 2017; L) Maximum marine inundation depth
- 194 *impact on buildings located in Anse Marcel in 2017*
- 195
- 196 3.2 Statistical data, uncertainty and standardization
- 197 This historical database allowed us to interpret the evolution of urbanization and reconstruction of
- buildings on the island of Saint-Martin and Saint-Barthélemy between 1954 and 2017 (before

Hurricane Irma). Comparison between the two islands is possible because datasets are similar (resolution, year). In total about 19,185 buildings were surveyed in 6 aerial campaigns for both islands and more than 150,000 descriptions have been made. Notably, only buildings having a surface area greater than 20 m<sup>2</sup> were counted, to avoid any bias in relation with variations in the image accuracy/resolution of old data. This choice permit to reduce error in the counting and to obtain a more homogeneous estimation at the various times. Furthermore, in the islands considered, there are no complex architecture, such as very close buildings as in dense urbanized areas.

206 Due to the limited number of aerial photography and satellite imagery, short-term (<6 years) 207 fluctuations cannot be observed with this data set and only time step of around 10-15 years were 208 monitored. Linear evolutions between two successive times were represented in several figures. 209 Yearly averaged values or linear interpolation representation were presented. In both cases, this is a 210 simplification of real evolution. Linear interpolation smooth real evolution. Mean annual values 211 estimated over several year hide fluctuations during this period. If 3500 new buildings have been 212 constructed in 20 years (from 1969 to 1989, for example), the resulting average number of new 213 buildings per year is equal to 3500/20 = 175 buildings per year. The value of 175 will be reported in 214 the graph each year, from 1969 to 1989. Presenting the number of building per year instead of the 215 number of building permit to standardize the counting independently of the time step between to 216 consecutive data.

Analysis is relevant only for factors that have an impact over several years. The quantitative data presented in this study are used to describe the relations that exist between parameters such as the number of buildings, the number of buildings in marine inundation areas and the number of inhabitants. The buildings could be inhabited, inhabited part of the year or abandoned. Linear correlations are proposed and used to describe quantitatively the relation between parameters. More precisely, a linear correlation, with standard error to evaluate uncertainty, is proposed to describe the relation between: (1) the number of buildings and the number of buildings in marineinundation areas, (2) the number of buildings and the number of inhabitants.

225

## 226 **3.3 Hurricane Irma marine inundation map**

227 The French Ministry of Environment and local authorities of Saint-Martin and Saint-Barthélemy, 228 commissioned a team of flood experts from the Cerema (Center for studies and expertise on risks, 229 environment, mobility, and spatial planning) to model new maps of the cyclonic hazards posed by 230 marine inundation. These two maps were built on the basis of field surveys that considered the 231 highest water levels, following the marine inundation generated by Hurricane Irma in Saint-Martin 232 and Saint-Barthélemy. These maps classified the marine inundation depth into five areas 233 corresponding to the maximum sea-level height (above the standard sea level) observed in 234 September 2017 after Hurricane Irma (Figs. 1B, 1C). The number of buildings in each areas were 235 estimated, along with the total number of buildings observed in the marine inundation risk areas 236 during six different periods (1954, 1954–1969, 1969–1989, 1989–1999, 1999–2010, and 2010–2017). 237 A building that is in part in the marine inundation risk area and in part outside is considered in the 238 marine inundation risk area. In a second time, the counting was performed fo different thickness of 239 inundation (0-0.5 m, 0.5-1 m; 1-2 m; 2-3 m; +3 m). A building that is a part of two different categories 240 of expected water thickness was counted in each category. Around 30 % of buildings overlay two 241 categories. Consequently, the sum of building in the different categories was higher than the total 242 number of buildings in the marine inundation risk areas. However, the number of buildings in marine 243 inundation risk area plus the number of buildings outside marine inundation risk area is equal to the 244 number of buildings in the islands. The total number of buildings in marine inundation risk areas 245 helped us to analyze quantitatively the causes of urban expansion on the coast, and the comparison

of the number of houses between different categories allowed us to discuss risk apprehension andspace availability.

## **3.4 Correlation with social, economic, political, and environmental events**

The evolution of the number of construction of buildings in marine inundation risk areas was compared with the population growth to discuss possible causal link. Data about population growth were collected by the French National Statistical Institute (INSEE) [44] and are available since 1954. Economic indicators, such as the number of tourist that arrived in harbors and airports, were collected by the IEDOM [47,45]. Data on the political changes, especially laws that favored tax reduction and construction investments in Saint-Martin and Saint-Barthélemy, were obtained from the Journal Officiel de la République Française (JORF). Interviews with stakeholders, as well as local and national authorities, were conducted on the field in April 2019 and December 2019. Data about environmental events, and more precisely hurricanes, were obtained from different databases, and scientific publications and their local effect were also obtained interviewing the locals.

## **4. Results**

## **4.1. Urbanization from 1954 to 2017**



Figure 3. Graphs for the French part of Saint-Martin and the island of Saint-Barthélemy from 1954 to
2017 (before Hurricane Irma): A) Graph of evolution of population (INSEE)[44] and number of total
buildings, and B) Graph of growth in buildings per year (on average)

## 271 4.1.1. Saint Martin Island

272 Before 1954, only few urban areas were built on this island. The neighborhoods consisted of less 273 than 200 buildings (with a mean value of 100 buildings). The island was sparsely anthropized and 274 numerous natural areas were presents.

From 1954 to 1969, 1040 buildings were constructed on the island. This is equivalent to 69 buildings
constructed per year during 1954–1969 (Fig. 3B). Urbanization and embankments increased at
Marigot and Sandy Ground. The Sandy Ground channel was dug to connect a lagoon to the sea. In
1969, a total of 1840 buildings were present on Saint-Martin (Fig. 3A).

Between 1969 and 1989, 3560 new buildings were constructed on the island. This means that 178
buildings were constructed per year during this period (Table1). A large number of new buildings
developed at Terres Basses, Cul-de-Sac, Quartier d'Orléans, Sandy Ground and the periphery of
Marigot. Four marinas were built: two in Marigot, one in Anse Marcel, and one in Oyster Pond.
Grand-Case Airport was also built during this period. In 1989, 5400 buildings were present on the
island.

# Table 1. Evolution of number of buildings and population on Saint-Martin and Saint-Barthélemy between 1954 and 2017

			Annual r	ate of building	Average nur	nber of people per
Year	I	Population	con	struction	b	uilding
	Saint-					
	Martin	Saint-Barthélemy	Saint-Martin	Saint-Barthélemy	Saint-Martin	Saint-Barthélemy
1954	4001	2176	/	/	5.0	2.8
1954–1969	5061	2351	69	31	2.8	1.9
1969–1989	28519	5038	178	105	5.3	1.6
1989–1999	29112	6854	225	155	3.8	1.4
1999–2010	36979	8938	265	179	3.5	1.4
2010–2017	35941	9567	167	91	3.1	1.3

<sup>296</sup> 

297

Between 1989 and 1999, 2250 new buildings were observed. Each year, around 226 buildings were constructed. New embankments were visible mainly near Marigot. Marinas were developed and an industrial harbor was created at the north of Marigot. We also observed signs of densification in all the neighborhoods, but no new neighborhoods were created. A total of about 7650 buildings were visible on the island in 1999 (Fig. 3A).

Between 1999 and 2010, 2910 buildings were constructed on the island. Thus, during this period around, ~265 buildings were built by year (Table 1). Urbanization was increasing throughout the island. An industrial zone developed near the airport of Grand Case ac well as of the industrial harbor near Marigot, and in 2010, approximately 10,560 buildings were present. Finally, between 2010 and 2017 (before Hurricane Irma), 1170 new buildings were constructed, equivalently to 165 buildings per year. The densification process continued throughout the island, mainly on the coast, reaching approximately 11,730 buildings (with an area of more than 20 m<sup>2</sup>) in 2017 (Fig. 3).

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313 4.1.2 Saint-Barthélemy Island

Saint-Barthélemy was poorly urbanized before 1954 and Gustavia harbor was the main constructed area. The number of buildings in Saint-Barthélemy began to increase in 1954. In 1954, 770 buildings were present on the island (Table 1). Notably, Gustavia is the oldest urbanized area of the island, with 168 buildings observed in 1954. This represented 25 % of the total buildings observed in 2017.

Between 1954 and 1969, Saint-Jean Airport was in construction. The Shell Beach near Gustavia harbor was enlarged and embankments were developed. The number of construction increased: 472 new buildings were constructed. This is equivalent to ~31 buildings built per year. No environmental modifications were observed in the lagoon areas. In 1969, 1242 buildings were present on the island. From 1969 to 1988, 1993 news buildings were constructed on the island, with an average of 105 buildings constructed per year. One of the lagoon area was almost covered with buildings built on the embankments. The eastern part of Saint-Jean lagoon was also covered with buildings, and the

airport was constructed. In 1988, a total of 3234 buildings were observed on the island (Fig. 3).

Between 1988 and 1999, 1554 news buildings were constructed, which is equivalent to 155 buildings constructed per year. In 1999, 4788 buildings were present on the island, and the western part of the Saint-Jean lagoon was completely covered with buildings.

Between 1999 and 2010, 1969 new buildings were constructed on the island, which is equivalent to 179 buildings constructed per year (Fig. 3B). In 2010, 6655 buildings were present on Saint-

Barthélemy (Fig. 3) and in 2017, the number increased to 7394 buildings. Between 2010 and 2017,
around 91 buildings were constructed each year (Fig. 3A, Table 1).

333

## 334 4.1.3 Comparison between Saint-Martin and Saint-Barthélemy

The number of buildings constructed on both the islands increased between 1954 and 2017. The evolution was similar even if Saint-Barthélemy showed a lower number of buildings than Saint-Martin (Fig. 3). The rate of increase in building construction is higher from 1954 to 2010, than from 2010 to 2017. The highest construction rate was between 1999 and 2010 for the two islands (Fig. 3B), but the highest growth of new constructions was between 1969 and 1989 for both islands.

Since 1967, Saint-Martin and Saint-Barthélemy portrayed different population evolution. The population of Saint-Martin increased from 4001 inhabitants in 1954 to 35,941 in 2017 (Fig. 5A). This represents an increase of 900 %. On Saint-Barthélemy, the population increased from 2176 inhabitants in 1954 to 9,567 inhabitants in 2017 (Fig. 5A). This corresponds to a growth of around 450 %. The evolution of population in Saint-Martin and Saint-Barthélemy was thus, contemporaneous.

The main difference between the two islands was relative to the number of inhabitants in 1989. In 1989, the ratio between the population and the number of buildings was of 5.3 for Saint-Martin and of 1.5 for Saint-Barthélemy, indicating the different urban and social trajectories of the two islands.

349

## 350 4.2 Construction in marine inundation areas from 1954 to 2017

The surface of marine inundation risk areas was more than three time higher in Saint-Martin than Saint-Barthélemy (i.e., 5 km<sup>2</sup> vs 1.5 km<sup>2</sup>, respectively). This area represents 9.56 % of the total surface of Saint-Martin (i.e. 5 km<sup>2</sup> of 53 km<sup>2</sup>) and 6.53 % of the total surface of Saint-Barthélemy (i.e. 1.5 km<sup>2</sup> of 24 km<sup>2</sup>) (Fig. 4). The surface potentially affected by marine inundation was higher in Saint-Martin than Saint-Barthélemy, whatever the water level categories. However, the difference between the amounts of inundated surfaces of Saint-Martin and Saint-Barthélemy was small (3 % of the total island surface). The water level category from 1 m to 2 m covered the largest area and is dangerous for children and adults, and could damage buildings.

360 361



Figure 4. Percentages of submersible land area for Saint-Martin and Saint-Barthélemy for different
 water level categories

From 1954 to 2017, there was an increase in the buildings constructed in the marine inundation risk areas of both islands (Fig. 5A). The number of buildings in these areas was greater in Saint-Martin than Saint-Barthélemy. Standardizing the number of buildings in marine inundation risk areas by the

369 coastal inundated area, there were 652 buildings/km<sup>2</sup> in Saint-Martin and 709 buildings/km<sup>2</sup> in Saint 370 Barthelemy, in 2017 when Hurricane Irma hit.

371 In Saint-Barthélemy, the percentage of buildings constructed in coastal flooding areas showed a 372 tendency to increase between 1954 and 1969, followed by a decrease until 2017 (Fig. 5B). In Saint-373 Martin, the percentage of buildings built in coastal flooding areas increased significantly (i.e. about 8 374 % from 23 % to 31 %) between 1969 and 1989, followed by a decreasing trend. Around 25-30 % of 375 the buildings on Saint-Martin were constructed in areas exposed to marine inundation, whereas only 376 10–15 % of the buildings on Saint-Barthélemy were constructed in areas exposed to this risk. This 377 discrepancy was prominent from 1969 to 1989. The decrease in the percentage of buildings in 378 marine inundation risk areas was due to higher growth of buildings outside the marine inundation 379 areas.

Concerning the mean number of buildings constructed per year from 1954 to 2017 in coastal flooding areas, several trends were observed in our study. At Saint-Martin, the number of constructions exposed to marine inundation increased from 1969 to 1989. Between 1969 and 2010, the average number remained approximately constant; in Saint-Martin, this number decreased after 2010 (Fig. 5C). The peak number of new buildings was achieved between 1999 and 2010 in Saint-Martin. At Saint-Barthélemy, the trend was less clear; the construction rate increased from 1954 to 1999, after which, it was almost constant.

387

388



Figure 5. Urban evolution in marine inundation risk areas in Saint-Martin and Saint-Barthélemy from 1954 to 2017 (before Hurricane Irma): A) Number of buildings constructed in areas of marine inundation, B) Percent of buildings present in marine submersible area relative to the total number of buildings on the whole island, and C) Average number of buildings constructed in the submersible area per year

396 At Saint-Martin, the categories 1 (water depth 0–0.5 m) and 2 (water depth 0.5–1 m) had the highest 397 number of constructions between 1969 and 1989. Categories 3 (water depth 1–2 m), 4 (water depth 398 2-3 m), and 5 (water depth +3 m) showed the highest number of constructions in the flooding area, 399 from 1989 to 1999 (Fig. 6). For Saint-Barthélemy, categories 1, 2, and 3 showed higher number of 400 constructions from 1999 to 2010, whereas category 4 showed maximum constructions, between 401 1999 and 2017, and finally category 5 (almost not represented) showed a peak from 1969 to 1989 402 (Fig. 6). The higher number of construction in marine inundation risk areas were located in the lowest 403 water depth level (0-1 m) corresponding to a moderate risk, in comparison to the highest water 404 level (+2 m).

405

<sup>395</sup> 



Figure 6. Average annual number of new buildings located in flood risk areas of Saint-Martin and
Saint-Barthélemy, from 1954 to 2017 (before Hurricane Irma), for different water levels: A) in 1969; B)
in 1989; C) in 1999; D) in 2010; and E) in 2017..

## **5. Interpretation and discussion**

Despite their similarities, Saint-Martin and Saint-Barthélemy have historical, economic, and social
differences: (i) in 2016, the Growth Domestic Product was 40000 euros/capita in Saint-Barthélemy,
whereas it was 16000 euros/capita in Saint-Martin [45,47]; (ii) since 1986, the population growth was

significantly higher in Saint-Martin than Saint-Barthélemy [44,47], even if it was almost similar in
1960; (iii) the protection of populations against natural hazards benefited from a Natural Hazard
Prevention Plan (called Plan de Prévention des Risques Naturels, PPRN in French [62]) implemented
in 2011 in Saint-Martin but not in Saint-Barthélemy; and (iv) the economic strategies of both islands
were different (quality/quantity and luxurious/mass for Saint-Barthelemy vs. Saint-Martin) [55,63],
even if the strategies were based exclusively on tourism development.

423

## 424 **5.1** Tax exemption laws and construction

425 During the 1960's, there was an increase in the population and building construction, 426 attributed to the interest of rich North American citizens for new investments and 427 residences in the Caribbean islands [64,65,66]. Before 1969, people built their home only where there was a maximum of 1m of water in case of inundation (50 cm in Saint-Martin). 428 Population growth began in 1986, after the French government decided to develop 429 430 economical activities in French overseas territories [2,64,53] and the increase in the number of buildings was almost contemporaneous. A detailed evolution of the number of 431 432 construction over time showed that it increases after 1984 (Table 2), and more particularly, 433 after 1986. After 1989, dwellings were built also in areas where water height could reach 1 to 3 m. 434

435

The number of inhabitants in Saint-Martin increased significantly after 1986, favored by tax
exemption laws that stimulated the construction of new buildings for the development of
the tourist industry (legislation from the Pons law of 1986 onwards) [21]. The purpose of this
tax exemption law for individuals and companies was to stimulate the economic
25

440 development of the island [52,53,67]. The Pons Law ratified in 1986 [68] allowed individuals 441 and real estate developers to deduct a large part of their real estate investments in overseas French territories for a period of 5 years for companies and 10 years for individuals. This law 442 led to the construction of numerous second homes, tourist accommodations, and hotels, but 443 also indirectly led to the development of housing for construction and tourist workers and 444 445 their families. From 1982 to 1989, there was an increase from 8000 to 28,000 inhabitants at 446 Saint-Martin [44]. Migration from other Caribbean islands, especially from Haiti, was 447 substantial at Saint-Martin [55,67]. Part of the new inhabitants worked to build touristic infrastructures and residences or work as tourism employees [55]. Notably, a peak in new 448 constructions was achieved between 1999 and 2010 (Table 1). For the higher risk areas 449 450 (depth >2m), the number of new construction slightly decreased after 1999 (i.e. after 451 Hurricane Luis and Lenny; Figure 6).

452



Figure 7. Number of buildings B in Saint-Martin and Saint-Barthélemy in relation with the number of inhabitants P. The coefficient of proportionality is  $\alpha \approx 0.27$  in Saint-Martin and  $\alpha \approx 0.7$  in Saint-Barthélemy, with a standard error of 7.617% (± 0.02089) and 4.106%, (± 0.02882), respectively.

454

Data collected in this study indicates that the number of buildings (*B*) is proportional to the number of inhabitants (*P*), with  $B = \alpha P$  and  $\alpha$  a constant (see Fig. 7). The significant increase in the number of inhabitants per building in Saint-Martin during the period 1969–1989 (Table 1) could be due to the construction of hotel compared to the increase in the number of inhabitants and to the higher number of person in workers' houses.

The mean number of construction per year decreased after 2010 in Saint-Martin and Saint-Barthélemy (Figure 3 and Table 1), even when there were local differences in Anse Marcel in Saint-Martin (Table 2). After 1990, overall, construction for residents and tourist accommodation 467 continued to increase on both the islands. This is due to the fact that in 2001 and 2003, two laws 468 successively continued the tax exemption efforts initiated by the Pons Law, with the aim of economic 469 recovery: the Paul Law and the Girardin Law (the latter is also called the "Overseas Program"). These 470 laws encouraged new rental property investments, with more restrictive conditions, such as 471 prohibitions on renting property to a member of one's tax household, than the Pons Law [16]. A 472 succession of tax exemption schemes followed this period: the Scellier overseas law in 2009, Duflot 473 law in 2014, and the Pinel Law in 2015. All these laws helped maintain the development of urban 474 planning initiated on the island in 1986 by the Pons law. Nevertheless, all these tax laws, 475 implemented on both islands, were less favorable for construction investment after 2010, to prevent 476 construction in the risk areas.

477

478	Table 2. Number of building in Anse Marcel, Saint-Martin, f	from 1947 to 2017
-----	---	-------------------

	Cumulated number of	Number of new	New buildings per	
Year	building	buildings	year	
1947	0	0	0	
1954	0	0	0	
1969	0	0	0	
1984	0	0	0	
1989	23	23	5	
1999	33	10	1	
2004	34	1	0	
2010	50	16	3	
2017	75	25	4	

480 The population increase in Saint-Barthélemy was slower than that in Saint-Martin and is 3.5 time 481 smaller in Saint-Barthélemy than in Saint-Martin in 2018 (Figure 3 and Table 1). This could be due to 482 (i) the smaller size of Saint-Barthélemy [48,56], (ii) difficulty to access Saint-Barthélemy by plane and 483 boat, in comparison to the accessibility of Saint-Martin [55,63,64], and (iii) different political and 484 economic strategies of Saint-Barthélemy and Saint-Martin. Notably, we observed that Saint-485 Barthélemy favored luxurious touristic infrastructures, such as villas and small luxurious hotels 486 [55,63,64] and "entre-soi" (homogeneous community of wealthy people) [66,69]. Residents and 487 political authorities decided to control urban development at Saint-Barthélemy to reduce potential 488 negative effects of mass tourism [63,64]. The increased administrative autonomy from the French 489 government, along with the tax exemption, allowed Saint-Barthélemy to attract many rich residents 490 and companies [66].

491

#### 492 **5.2** Tax exemption laws and construction in marine inundation risk areas

493 From 1954 to 2017, the two islands have experienced an increase in the number of buildings in the marine inundation risk area (Table 3). Until 1986, many coastal areas were not inhabited or 494 495 urbanized (Fig. 2). While this increase was progressive in Saint-Barthélemy, it was abrupt in Saint-496 Martin. Despite an approximately similar number of buildings in the marine inundation risk area in 497 1954, a difference >300 % was observed in 2017 between the two islands. This divergence occurred 498 especially during the last decades (1980–2010), when the number of construction per year in marine 499 inundation risk areas was 3–4 times higher in Saint-Martin than Saint-Barthélemy (Fig. 5C) for a 500 population that was around 3 times more. Considering that tax exemption laws were the same in 501 Saint-Martin and Saint-Barthélemy, the difference in the number of construction per year could not 502 be explained as the effect of these specifics laws.

503

## 505 Table 3. Number of building (B) and number of buildings in marine inundation risk areas ( $B_{MIRA}$ ) in

- 506 Saint-Martin and Saint-Barthélemy
- 507

Vern	$\mathbf{N}_{\mathbf{r}}$		Number of building in marine		
Year	Number of	Number of buildings (B)		inundation risk areas (BMIRA)	
	Saint-Martin	Saint-Barthélemy	Saint-Martin	Saint-Barthélemy	
1954	800	777	182	136	
1969	1807	1237	400	226	
1989	5381	3149	1672	532	
1999	7661	4896	2292	739	
2010	10565	6284	3007	932	
2017	11593	7120	3262	1064	

509

The temporal correlation between the implementation of tax exemption laws and the increase in the number of buildings in marine inundation risk areas suggested a potential link. Tax exemption laws in French overseas territories were not specifically implemented to increase the urbanization of the coast or promote construction in the marine inundation risk areas. Nevertheless, investments in businesses, especially in restaurants, hotels, and residences for tourists, favored construction close to the sea.

516

517



Figure 8. Number of buildings in marine inundation risk areas  $B_{MIRA}$  in relation with the total number of buildings B in Saint-Martin and Saint-Barthélemy. The coefficient of proportionality is  $\beta \approx 0.287$  in Saint-Martin and  $\beta \approx 0.15$  in Saint-Barthelemy, with a standard error of 1.82% (± 0.00523) and 1.943%, (± 0.002943), respectively.

518

The results obtained in this study indicated that the number of buildings in the marine inundation risk areas  $B_{MIRA}$  is proportional to the number of total buildings B, with  $B_{MIRA} = \beta B$  (see Fig. 8). Consequently,  $B_{MIRA}$  was proportional to the number of inhabitants P portrayed by the equation:  $B_{MIRA} = \beta B = \beta \alpha P$  (see Fig. 9). Notably, population growth was favored by economic growth resulting from local tax exemption laws. We observed an indirect causal link between the implementation of tax exemption laws (Pons law, 1986 [18]) and the increase in the number of buildings in marine inundation risk areas.



Figure 9. Number of buildings in marine inundation risk area  $B_{MIRA}$  versus number of inhabitants P for Saint-Martin and Saint-Barthélemy. The coefficient of proportionality ( $\beta \alpha$ ) is equal to  $\approx 0.08$  in Saint-Martin and to 0.10 in Saint-Barthélemy, with a standard error of 6.29% (± 0.004982) and 2.9%, (± 0.003111), respectively.

538

## 539 **5.3 Influence of touristic flux on construction in marine inundation risk areas**

The increase of new construction in Saint-Martin and Saint-Barthélemy is simultaneous with population growth on these islands. Previous studies have suggested that the increase in the building construction on the islands was due to tourism development [5,14,55]. In general, tourist influx increases only after tourist infrastructures, such as hotel and residence, but also airport and harbor,are built [14,55,63].

545 Notably, the two islands have an economy dominated by tourist activities [2,4,5,55,63,66,70]. Saint-546 Martin/Sint Maarten experiences more tourist arrivals every year than Saint-Barthélemy [45,47]. 547 While Saint-Martin has not restricted the development of tourism, Saint-Barthélemy decided to limit 548 the number of cruise arrivals and developed an urban planning strategy to limit the number of rooms 549 available for rent and increased the rental prices [4,55,62,63,66]. This strategy, which was developed 550 from 1980 to 2010, influenced the island's successive evolution significantly [66]. Notably, old 551 construction on the islands of Saint-Martin and Saint-Barthélemy (from 1980 to 2010) attributed a 552 strong heritage value to the island.

553

554 The decrease in the number of construction per year after 2010 in Saint-Martin could not be related 555 to the decrease in the tourism flux to the island (Fig. 10) [45]. The mean number of passengers that 556 arrived in Saint-Martin per year in the harbor and airport was higher during 2010–2018 than 2000– 557 2009 (107200 and 87600, respectively) [45]. The same trend was observed in Sint Maarten [45]. 558 Consequently, tourist flux evolution is not directly responsible for the decrease in the number of new 559 construction after 2010. The mean number of rooms per year available as rentals at Saint-Martin 560 significantly decreased from 2000-2009 to 2010-2018 (Fig. 11), from 2000 rooms to 1494 rooms per 561 year, respectively [45]. This decrease of 25 % has been interpreted as an overcapacity of rooms 562 proposed as rentals, because hotels were only partly occupied at Saint-Martin [45]. In Saint-Martin, 563 several hotels were transformed to apartments. In Saint-Barthélemy, a slight reduction was observed 564 in the hotel and residence rooms available for daily or weekly rentals during the same period [47].

The apparent reduction in the official number of rooms available (Fig. 11) and the simultaneous increases in the touristic flux (Fig. 10) could appear contradictory. In 2011, Airbnb activity began in

Saint-Martin, and more than 2700 apartment and home rentals per month were proposed in 2017 [5]. These new housing opportunities not always appeared in official statistics and could explain the apparent decrease of room availability in Saint-Martin. A reduction in the mean duration of vacations could also explain this drop. In Saint-Barthelemy, more than 300 lodging are available in 2022 via the same platform.



573 Figure 10. Evolution of annual number of tourists on the French part of Saint-Martin (source: [40])



Figure 11. Evolution of official annual number of hotel rooms for rental in Saint-Martin and SaintBarthélemy. Source: [45,47].

## 578 **5.4 "Free space" availability and environmental protection**

Available spaces are limited on small islands, and there is a potential of saturation of coastal areas by buildings. It could be suggested that the progressive reduction of free areas for construction could have reduced the number of constructions per year. Nevertheless, in the case of Saint-Martin, we observed "free spaces" (i.e. without construction) in coastal areas, as well as in the internal part of the island. For example, the western part of Nettlé Bay in Saint-Martin had no new constructions in 2020. During our study, several areas at the north of the Orient Bay, along with Happy Bay and Friar's Bay, were still unconstructed.

586 In our study, difficulty to build in marine inundation risk areas could not be directly related to the 587 reduction of unconstructed areas. In 1986, in addition to the implementation of the Pons Law, the 588 Littoral Law has been implemented. The applications of this law in French overseas territories 589 regulate the development in the zone known as the fifty geometric steps (81.20 m) from the sea [71], 590 even if the region has illegal constructions [16]. This zone, which belongs to the public domain (e.g., 591 [72]) is i) inalienable, which means that the state cannot sell it to private individuals (however, such a 592 sale has become possible under certain conditions since 1996); and b) imprescriptible, which allows a 593 prolonged installation by a private individual in this zone does not confer any property rights over the 594 construction. In Saint-Martin, despite this law, numerous constructions have been built in this 595 regulated zone, with or without authorization, in almost all the districts of the island. In application 596 of this law, a French institute of coastline protection (i.e. Conservatoire du littoral) has bought 597 coastal areas in this region and limited new constructions.

In Saint-Barthélemy, local owners seem to favor conservative behavior and protect their way of life,
instead of selling their property [58,59]. The Saint-Barthélemy administration, in agreement with the
residents, provides authorization to construct new buildings sparingly [64,66].

Notably, the reduction in new construction in Saint-Martin and Saint-Barthélemy during the last decade could result from a strategy of mitigating urbanization of the islands, after decades of neglecting environmental protection in this region. Environmental protection is also a way to protect the way of life [20] and health interest. Recent studies highlight that waste management as well as electricity and water production are specific problems in an insular context that increase vulnerability [18,58,73].

607

#### 608 **5.5 Effect of past cyclonic events on construction in marine inundation risk areas**

Hurricanes Luis (1995) and Lenny (1999) have damaged Saint-Martin and Saint-Barthélemy [16,53].
However, after they occurred, from 1999 to 2010, the number of buildings constructed in the marine
inundation risk areas still increased on both the islands. It must be taken into account that (1) during

Lenny and Luis hurricanes, marine inundation was less, in comparison with Hurricane Irma [23]; wind and heavy rain generated during Luis and Lenny hurricanes resulted in severe damage to life and property [16,53]. (2) Regulations for construction in areas exposed to natural hazards have been implemented only in 2011 in Saint-Martin and previous construction rules (Land Use Plan regulation, a restriction to construct in the first 18 m from the sea) did not have a significant impact on limiting the construction of new buildings in these areas. (3) The population evolution of Saint-Martin via demographic growth or tourism [14,21], could be attributed to several factors.

After Hurricane Luis, several damaged buildings were no more used. For example, a hotel has been abandoned. The ruins of the hotel are always counted in the buildings' number because it is not always possible using aerial photos and satellite images to determine if a building is really abandoned and during how many years. During a field study conducted in 2019 after Hurricane Irma, we observe that buildings seriously damaged (i.e. without roof at the first floor) were still inhabited at the ground floor. Our observations during a field study suggest that 10-15 buildings were abandoned after Hurricanes Luis and Lenny. This has no effect on new building counting.

For Saint-Martin, some constructions in the risk areas were not built with sturdy construction materials, thus, not adhering to para-cyclonic rules/standards [23], and most (60 %) were not insured for damages caused to property and life [9]. Sea walls were not engineered (height, width, depth,...) to be efficient to resist and protect against Irma-like marine inundation (Figure 12). After a disaster, the reconstruction is often slow and the building are sometimes constructed with unsuitable material and technology [10,42]. The reduction of new buildings in areas with potentially > 2 m of marine inundation is too small to conclude on a potential effect: further studies are necessary.



Figure 12 : Presence of a small sea wall (1-2m height, 30m long). The buildings was
damaged during Hurricane Irma. Oriental Bay, Saint-Martin, December 5<sup>th</sup> 2019.

633

For Saint-Barthélemy, even if some constructions are in areas exposed to marine inundation, they
are built better: generally the owners built them with sturdy construction materials, while respecting
the para-cyclonic standards [55,66]. Additionally, these buildings benefit from financial support
(insurance and higher income) to rebuild faster [9].

641

## **5.6 Influence of prevention plan on construction in marine inundation areas**

The possibility that hurricanes can destroy private and public infrastructures along the coast and deeply disorganize socio-economic structures was not sufficiently anticipated in previous studies in French overseas territories before Hurricane Irma [74]. Several decades of rules (Land Use Plan regulation – Plan d'Occupation des Sols in French, 2002; "Littoral protection" law [71,75]) were not able to limit or decrease the vulnerability of these islands. During this period, part of the constructionon the coast were built without authorization and property documents [16,70].

From 1970 to 2010, the number of buildings constructed was 2–4 times higher in Saint-Martin than Saint-Barthélemy, with the population being ~3.5 times higher. After 2010, the annual number of construction in the marine inundation risk areas was only 1.8 times higher in Saint-Martin than Saint-Barthélemy, with the population being more than 3 times higher.

653 In 2011, a natural hazard prevention plan was established in Saint-Martin to protect the population 654 from different possible risks (called Plan de Prévention des Risques Naturels - PPRN). This plan 655 establishes standards for constructions in areas where a natural hazard was documented. Natural 656 hazard prevention plans concern: 1) floods, 2) debris flows, 3) earthquakes, including liquefaction, 657 and 4) hurricanes, including winds and marine inundation. These hazards are mapped according to 658 three intensity levels: low, medium, and strong. The objective of this plan is to limit urbanization 659 according to the intensity of the risk. New construction in the sectors exposed to a strong risk is 660 forbidden, and new buildings in sectors at low and medium risk are authorized under the condition 661 of respecting certain construction standards. Notably, measures to reduce vulnerability are 662 mandatory for existing buildings, depending on the intensity of the hazard (e.g., existence of a refuge 663 room in the house to protect against strong winds).

The mean number of buildings constructed in marine inundation risk areas each year was 65 during the 2000–2010 in Saint-Martin; this decreased to 36 after 2011, representing a reduction of around 45 %. Contemporaneously, the number of new buildings constructed at Saint-Barthélemy was stable at around 20 each year. In Saint-Barthélemy, no prevention plan was established, which allowed us to draw comparisons to Saint-Martin, which implemented such as plan in 2011.

669

670 Taking into account the fact that Saint-Martin has more than three times more inhabitants than 671 Saint-Barthélemy (35,000 vs 10,000) [45,47], the fact that there is only 1.8 times more buildings 672 constructed during 2010–2017 in Saint-Martin could suggest that the prevention plan implemented 673 in Saint-Martin was efficient to reduce the construction of buildings in marine inundation risk areas. 674 Nevertheless, the cumulative number of buildings in the marine inundation risk areas has not 675 decreased in Saint-Martin (3007 in 2010 vs. 3262 in 2017; Fig. 5A), suggesting that the prevention 676 plan established in 2011 has not contributed significantly to the decrease in the construction in the 677 risk areas, while only resulting in a slow rate of construction.

678

#### 679 **5.7 Vulnerability and marine inundation risk**

680 The vulnerability of the islands to marine inundation  $V_{MI}$  progressively increased with the number of 681 buildings in the marine inundation risk areas  $B_{MIRA}$  (i.e.  $V_{MI} = \gamma B_{MIRA}$ ). The number of buildings in 682 marine inundation risk areas  $B_{MIRA}$  represented a potential indicator for the vulnerability to marine 683 inundation of these territories. This method could slightly overestimate vulnerability in areas where 684 buildings were abandoned without being demolished as in Saint-Martin or Anguilla. A coefficient ( $\gamma$ ) 685 taking into account the specific features of the buildings constructed in marine inundation risk areas 686 of Saint-Martin and Saint-Barthélemy, such as the function of the building, its size, price, and 687 quality/resistance to marine inundation, could improve the estimation of vulnerability to marine 688 inundation.

689

690

Figure 9 indicates that the B<sub>MIRA</sub> values for Saint-Martin and Saint-Barthélemy could be determined
by the number of inhabitants (P). This trend is similar in Saint-Martin and Saint-Barthélemy, and thus,

an increase in the population of Saint-Barthélemy should increase the number of buildings in the
 marine inundation risk areas, thereby increasing the vulnerability of this island.

695 This could be observed in the case of Saint-Martin after tax exemption laws were implemented to 696 increase investments in the construction of new buildings and where local administration has not 697 discouraged urban expansion. Theoretically, a demographic increase in the French Caribbean islands 698 in the next decades should generate a vulnerability increases to marine inundation, if no significant 699 change to mitigate it is adopted. This theoretical law is also in agreement with the stabilization of 700 vulnerability in Saint-Martin observed since 2010, contemporaneously with the stagnation in the 701 number of its inhabitants. Notably, following this period, a decrease in the construction of new 702 buildings (around 45 %) in Saint-Martin was observed not only in the marine inundation risk areas 703 (Fig. 5) but also on the whole island (Fig. 3). Small population fluctuations in Saint-Martin seem to 704 have not influenced decreases in vulnerability but slowed down the increase; however, this trend 705 must be analyzed over a longer duration. Notably, the implementation of prevention plans in coastal 706 areas may not be the main reason of reduction in the construction in marine inundation risk areas.

707 The inheritance of past-construction (for construction between 1986 and 2010) affects the present 708 vulnerability of Saint-Martin. The duration of high-level vulnerability caused by the significant 709 number of constructions in marine inundation risk areas will last several decades, considering a 710 building's life-time is several decades (Fig. 12). In Saint-Barthélemy, despite the significant reduction 711 in the construction of new buildings on the whole island (Fig. 3), the construction of new buildings in 712 the marine inundation risk areas has been rather consistent and constant (Fig. 5), suggesting that 713 coastal areas are also particularly exposed to urbanization and that vulnerability to inundation risk is 714 still increasing. After standardization by the area "desirable" for construction next to the sea as well 715 as by the number of inhabitants, Saint-Barthelemy is not more virtuous than Saint-Martin (0.071 buildings/km<sup>2</sup>/inhabitants vs 0.018 buildings/km<sup>2</sup>/inhabitants, respectively). Notably, decision to 716

- reduce vulnerability to marine inundation could take a long time, e.g., the high level of vulnerability
- of the region was highlighted by Hurricane Irma in 2017 [10,13,17,42,43].
- 719



- 720 721 Figure 13. Evolution of vulnerability in (A) Saint-Martin and (B) Saint-Barthélemy; marine inundation
- 722 risk areas (MIRA)

## 724 5.8. Systemic vulnerability and risks

The relative nature of the notion of vulnerability invites reflection on the temporal scales of these concepts, because goods, people, or society cannot be defined as vulnerable *per se*. For example, concrete roof are more resistant than metal roof during category 5 hurricanes. Nevertheless, reconstruction of concrete roofs in a seismic zone instead of metal or wooden roofs in Saint-Martin after hurricane Irma, without compliance with specific seismic regulations (Eurocode 8) do not reduce vulnerability. Consequently, permanent reduction of vulnerability could be complex. 731 Processes other than the increase of construction in marine inundation areas could explain the 732 islands' vulnerability to marine inundation risk areas (Fig.13), which includes social inequality [42], a 733 reduced "culture of risk" of inhabitants after 20 years without huge hurricanes [23], problems in risk 734 management, and lack of resistant para-cyclonic constructions [10]. Vulnerability to marine 735 inundation indicator presented in this study cannot be interpreted without taking into account social, 736 economic, and historical contexts [52]. The role of population increase, tax exemption laws, touristic 737 flux, environmental constrain, and prevention plans on vulnerability to marine inundation have been 738 discussed in our study (Fig. 13). Vulnerability to marine inundation and natural hazard are only part 739 of the vulnerability factor. Abrupt increase in population, specialization of economy on a reduced 740 number of sectors, social inequality, illiteracy, and unemployment are some of the weaknesses of 741 these territories, especially in Saint-Martin [10,14,42,45,52,70]. However, the interrelation between 742 social, economic, environmental, and politic trajectories in Saint-Martin and Saint-Barthélemy are 743 complex [10,3,14,49] and their accurate description is beyond the scope of this study.

744

745 It has been suggested that the culture of risk is more prevalent in Saint-Barthélemy [16], and the 746 buildings on this island are constructed while considering the relevant geotechnical norms [56]. 747 Nevertheless, our study indicated that Saint-Barthélemy's vulnerability to marine inundation is not 748 lower than that of Saint-Martin, but is above all more resilient. Damage reported by insurance in Saint-Barthélemy have been estimated to be of 82.3 x 10<sup>3</sup> euros/inhabitants (i.e., 823 million euros 749 for 10,000 inhabitants) whereas it was of 33.4 x 10<sup>3</sup> euros/inhabitants (i.e., 1170 million euros for 750 751 35,000 inhabitants) in Saint-Martin [59]. The influence of wealth on the urbanization strategy in 752 marine inundation risk areas is advantageous for Saint-Barthélemy, as previously believed. Damages 753 by marine inundation during Hurricane Irma in wealthy neighborhoods of Orient Bay or Anse Marcel 754 were significant, as those observed in the poorest neighborhoods of Sandy Ground in Saint-Martin. 755 Specific paracyclonic constructions resistant to wind and to marine inundation were not 756 systematically built before Hurricane Irma in wealthy or in the poorest neighborhoods of Saint-757 Martin.

Insured damages are only part of total damages in Saint-Martin and Saint-Barthélemy, where 60 % of people have no insurance [9]. Furthermore, during hurricanes, people lose assets that have no financial value. Thus, insured damages are not efficient to evaluate the vulnerability of a territory to a specific event. Data necessary to build specific indicators and evaluate vulnerability of the region are often difficult to collect and analyze due to their heterogeneity.

763 The search for a better management of social vulnerability, and in particular the use of systemic 764 vulnerability that can better assess societal interactions and question the adaptive capacity of system 765 is crucial in such regions [76]. Moreover, it should be noted that in the absence of awareness of the 766 permanent vulnerabilities of urban systems to the vagaries of the climate, the territory will tend to 767 favor a short-term reactive resilience strategy on a piecemeal basis [77,78]. Notably, the learning 768 from past disasters must be positive and therefore, accepted in a certain sense, to serve as a 769 springboard for dynamic and proactive long-term resilience. Nevertheless, it remains complicated to 770 answer questions related to the perception of the return to a balance, owing to the different 771 perceptions between the individual/collective/territory and the levels of services provided by the 772 territory with regard to the fundamental needs of the population, which are themselves evolving.

After Hurricane Irma, a new prevention plan was decided by the French government to accelerate the reduction of vulnerability to marine inundation in Saint-Martin. For the French government, the aims of the new risk plan were to: (1) reduce potential damage and injuries in case of marine inundation, (2) inform residents and potential investors about risks involved, and finally, (3) support a faster recovery after the occurrence of a natural hazard. The revision of the Natural Hazards Prevention Plan becomes the subject of crystallization of all the tensions and fears that the

779 inhabitants express regarding the future of their property and life goals. To address this issue, the 780 local authorities of Saint-Martin reproached the State for putting a halt to tourism development on 781 the island, while some inhabitants, often among the poorest, reproached the State for favoring the 782 richest by authorizing, under certain conditions, the construction or rebuilding of hotels close to the 783 shore [79]. Demonstration against the new prevention plan occurred in December 2019 [21]. After 784 several days of rioting, the French Minister for Overseas announced the suspension of this plan in its 785 current state and its early application for a period of three months [79]. This event indicates that 786 there are social tensions resulting from the high level of inequality [70]. These tensions are observed 787 in particular on the coastal area, where natural hazards, main touristic investments, and the most 788 fragile populations (e.g. Sandy Ground) are presents. Opponents against the new prevention plan claim that working class and touristic activities will experience disadvantages, especially in Sandy 789 790 Ground and Quartier d'Orléans [4].

791 Notably, disasters generates social transformations directly or indirectly [80,81], after which 792 prevention plans, environmental policies, urban plans, and economic strategies must be modified to 793 take into account past and future hazards (Fig. 13). Hurricane Irma has not only deeply affected the 794 touristic economy of the islands, but could contributes to the transformation and reorganization of 795 Saint-Martin [20]. The deep destabilization of Saint-Martin [82] and Saint-Barthélemy after Hurricane 796 Irma suggest social and economic fragilities of these territories. Historical trajectory of these 797 territories allow us to understand the reasons of their present vulnerabilities [14,21,52]. Further 798 destabilization, whatever there are, will probably affect these territories significantly as well. Despite 799 mistakes that favored the increase of vulnerability during several decades (Fig. 13), as evidenced by 800 damages and causualities of Hurricane Irma [21], the trajectories of vulnerabilities of Saint-Martin 801 and Saint-Barthélemy are not written definitely and can be altered and changed for a better 802 outcome.

The relocation of people accommodation with their agreement outside risky areas, no new constructions in inundation risk areas, preservation of natural areas (mangrove, lagoon, sand dune and beach), promoting risk prevention by various approaches, a financial support to promote renovation for more robust housing, improved critical networks infrastructures [83], diversified economic activities (not overspecialization in tourism activities), efficient Public Service (emergency staff, emergency shelter, prevention staff, etc.), could reduce vulnerability.

811

## 812 **6. Conclusion**

813 This study about evolution of vulnerability to marine inundation shows that:

814 (1) Between 1954 and 2017, an increasing number of buildings were constructed in areas exposed to
815 marine inundation for the islands of Saint-Martin and Saint-Barthélemy (more than 3000 and 1000,
816 respectively). Notably, there was no reduction in the vulnerability during this period.

(2) The tax exemption laws have a significant influence in Saint-Martin as well as in Saint-Barthélemy
and favored a demographic growth as well as the increase of constructions in areas where marine
inundation due to hurricane could occur. The construction increase occurred also in other parts of
the island.

(3) The mean number of construction per year was around 4 times lower in Saint-Barthélemy than
Saint-Martin during 1969–1989 (15 and 63, respectively), with population that was 3 times smaller
leading to 106 buildings in marine inundation areas for 1000 inhabitants in Saint-Barthelemy instead
of 59 in Saint-Martin in 1989 (and 1.6 inhabitants per buildings in Saint-Barthelemy vs. 5.3 in SaintMartin in 1989).

(4) There is no clear evidence in our data that Luis and Lenny hurricanes may have directly caused a
reduction of new buildings construction in marine inundation risk areas, even if a small effect could
exist for new construction where potential water depth is greater than 2m.

(5) A reduction of new construction in marine inundation risk areas was observed in Saint-Martin during 2010–2017 (-45%), but not in Saint-Barthélemy. This trend was contemporaneous with the prevention plan established in 2011 in Saint-Martin. The natural hazard prevention plan established in 2011 may have influenced the reduction of the number of new constructions in marine inundation risk areas, as well as the stagnation of the population demography. Nevertheless, many buildings were constructed before the prevention plan (more than 3000 in Saint-Martin and more than 900 in Saint-Barthelemy).

(6) The vulnerability of this island did not decrease after that prevention plan was established. Thus,
the prevention plan is not enough to have an effective impact on the decrease of the absolute
number of buildings constructed in coastal flood areas.

(7) In Saint-Barthélemy, there was no prevention plan to mitigate natural hazard and no significant decrease of the number of building in marine inundation risk areas is observed during the period spanning from 2011 to 2017 (constant with ~20 building/yr). The progressive increase of new buildings in marine inundation risk areas from 8 to 20 building/yr could be due to the slow population increase from 2000 to ~10000 during this period and also because no efficient strategy to limit the increase of building in marine inundation risk areas was implemented in Saint-Barthélemy.

(8) The number of house constructed in hazard areas and its evolution is an indicator of the efficiency of the prevention plan. Notably, policy coordination of economic, social, and risk management strategies are essential for efficiency. Moreover, mistakes in urbanization and economic strategies could cause high vulnerability during several decades. Resolving the past errors in urban planning or

socio-economic problems is often a slow process, and abrupt transformations could cause futurecrises.

852	Acknowledgement: This work was supported by the French National Agency for
853	Research [ANR RELEV - ANR-18-OURA-0004]. The funding source was not involved
854	in the design and interpretation of the data in the writing of the report. We would
855	like to thanks the 5 reviewers that helped to improve the manuscript with
856	constructive comments and suggestions as well as associate editor Fantina Tedim.
857	
858	Declaration of interest: none
859	

862 **<u>References</u>** 

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