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

3  
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12  
13 **Abstract**

14  
15 The islands of Saint-Martin and Saint-Barthélemy in the French West Indies are regularly affected by  
16 hurricanes and marine inundations. In this study, we investigated the influence of economic,  
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  
20 higher in Saint-Martin than in Saint-Barthélemy. The number of buildings constructed in marine  
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  
25 inundation. A recent decrease (by 45 %) in the constructions per year in the marine inundation risk  
26 areas observed in Saint-Martin from 2011 to 2017 could have been influenced by (1) the approval of  
27 the Natural Hazards Prevention Plan in 2011 and (2) population stagnation since 2007. Prevention  
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,  
34 marine inundation

35

36

## 37 **1. Introduction**

38

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

44 Hurricanes are known to generate damages by various ways: (i) wind [6], (ii) rainfall [7], and (iii)  
45 marine inundation [8]. Wind can cause direct (e.g., houses, building, streets, infrastructure) or  
46 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  
62 part of geoheritage, valuable in education. These are considered as “stigmata”, “scars” or “warts”  
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.

71

72

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

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

84 The objective of this study is to better quantify and qualify the vulnerability of the islands of Saint-  
85 Martin and Saint-Barthélemy to marine inundation. Therefore, our approach is limited to a single  
86 type of hazard affecting these islands and does not take into account other types of natural hazards  
87 (e.g., strong winds, earthquakes, runoff, landslide, and tsunami). A potential approach is to study  
88 only a specific aspect of vulnerability and construct an indicator of vulnerability specifically for a  
89 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.

100

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

118 Since 1648, the island of Saint-Martin has been divided into two parts: a Dutch part called Sint  
119 Maarten, and a French part called Saint-Martin. Whereas Sint Maarten is outside the territory of the  
120 European Union, Saint-Martin is inside. The French part covers 53 km<sup>2</sup>, with 35,941 inhabitants in  
121 2017 [44,45], and the Dutch part covers an area of 37 km<sup>2</sup>, with 37,000 inhabitants in 2018 [44]. The  
122 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; Girardin 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).

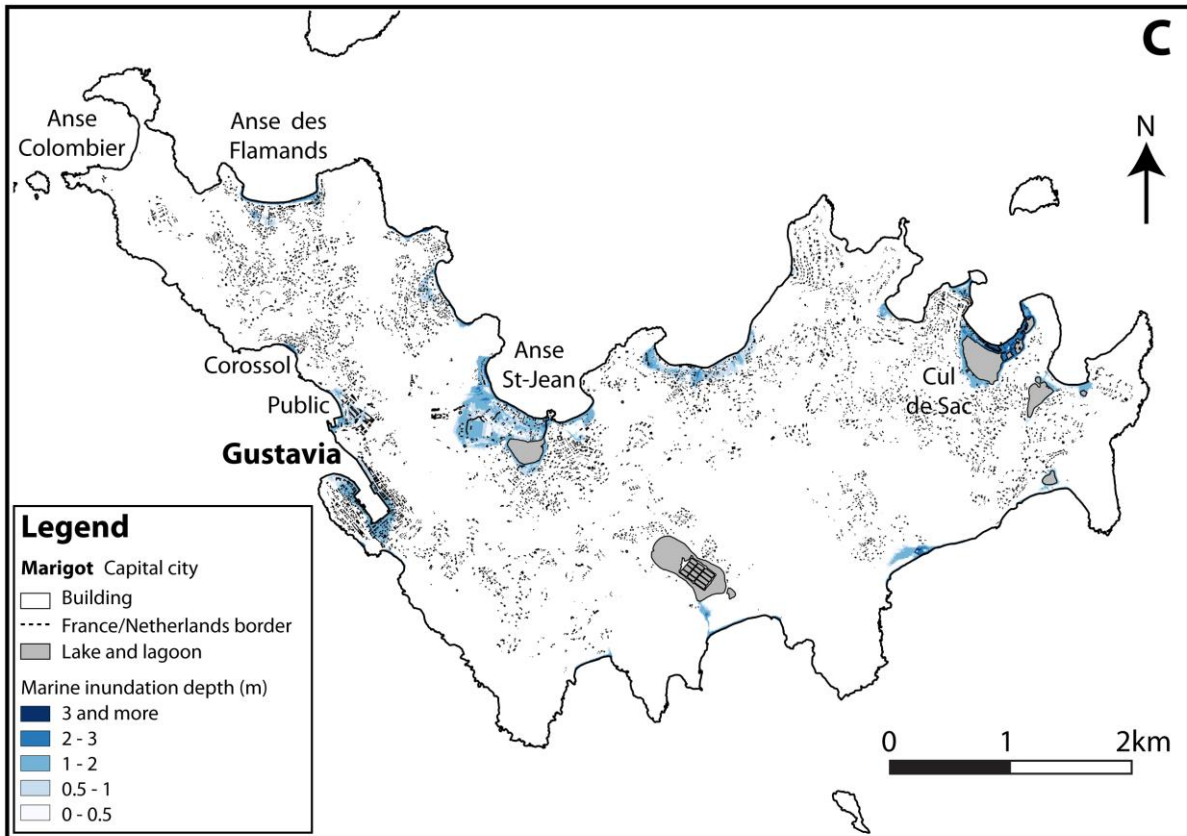
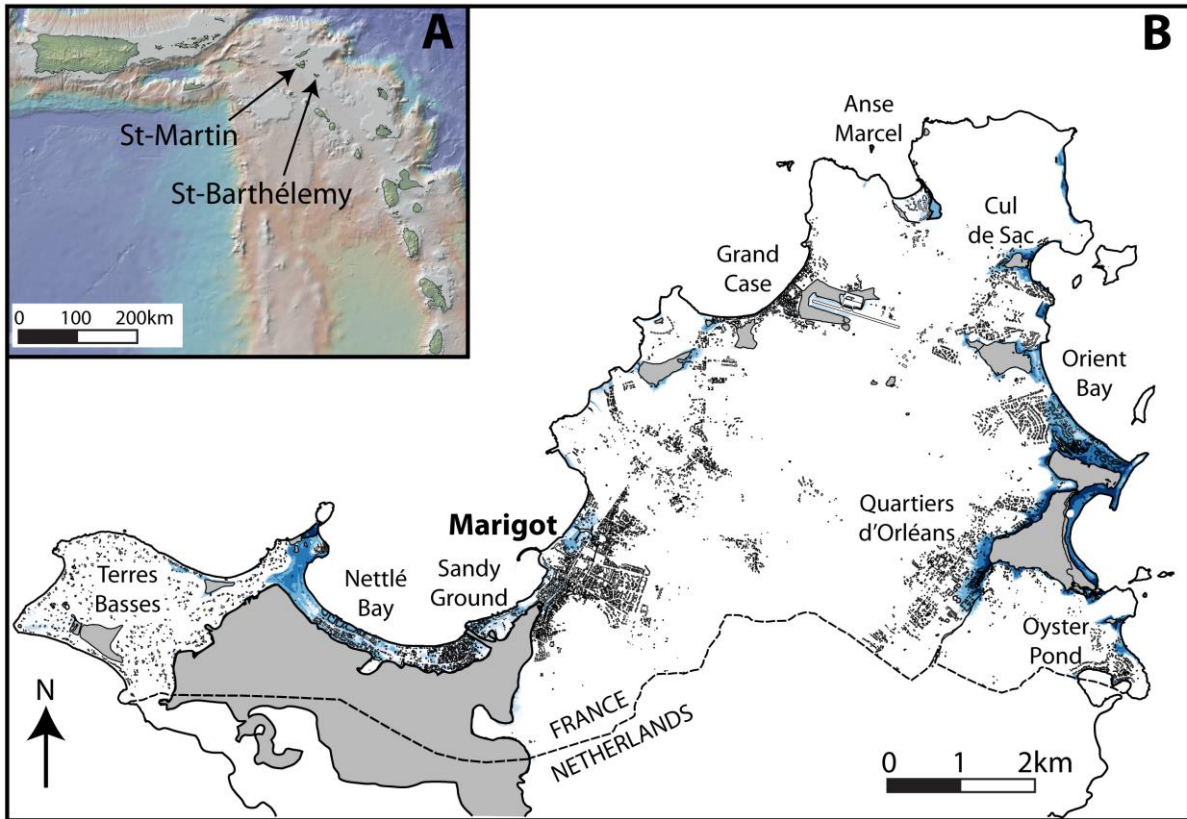
135 During the last decade, the social, economic, and political trajectories of Saint-Martin and Saint-  
136 Barthélemy were not similar [14,13]. Notably, the population growth was significantly higher in Saint-  
137 Martin than Saint-Barthélemy [44]. Furthermore, in 2016, the Gross Domestic Product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

142 The landscapes of Saint-Martin and Saint-Barthélemy are composed of old volcanic hills. Several  
143 areas having a low topography can be observed and several lagoons are also present. These islands  
144 are affected by hurricanes; the hurricanes Luis (1995) and Lenny (1999) caused serious damage to  
145 these islands [16,53,54]. The climate of these islands is tropical, with a mean temperature of 27 °C  
146 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].

159





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

165

### 166 **3. Methods**

167

168 In this study, we coupled the maps of marine inundation with the buildings' localization in Saint-  
169 Martin (French side) and Saint-Barthélemy to study the evolution of urbanization between 1954 and  
170 2017 (before Irma hurricane) in the (1) entire territory and (2) marine inundation risk areas. The  
171 island of Saint-Martin is shared between two countries: at the North, a French territory that will be  
172 called "Saint-Martin" in this study, and at the South, a Dutch territory that will be called Sint Maarten  
173 (Fig 1).

174

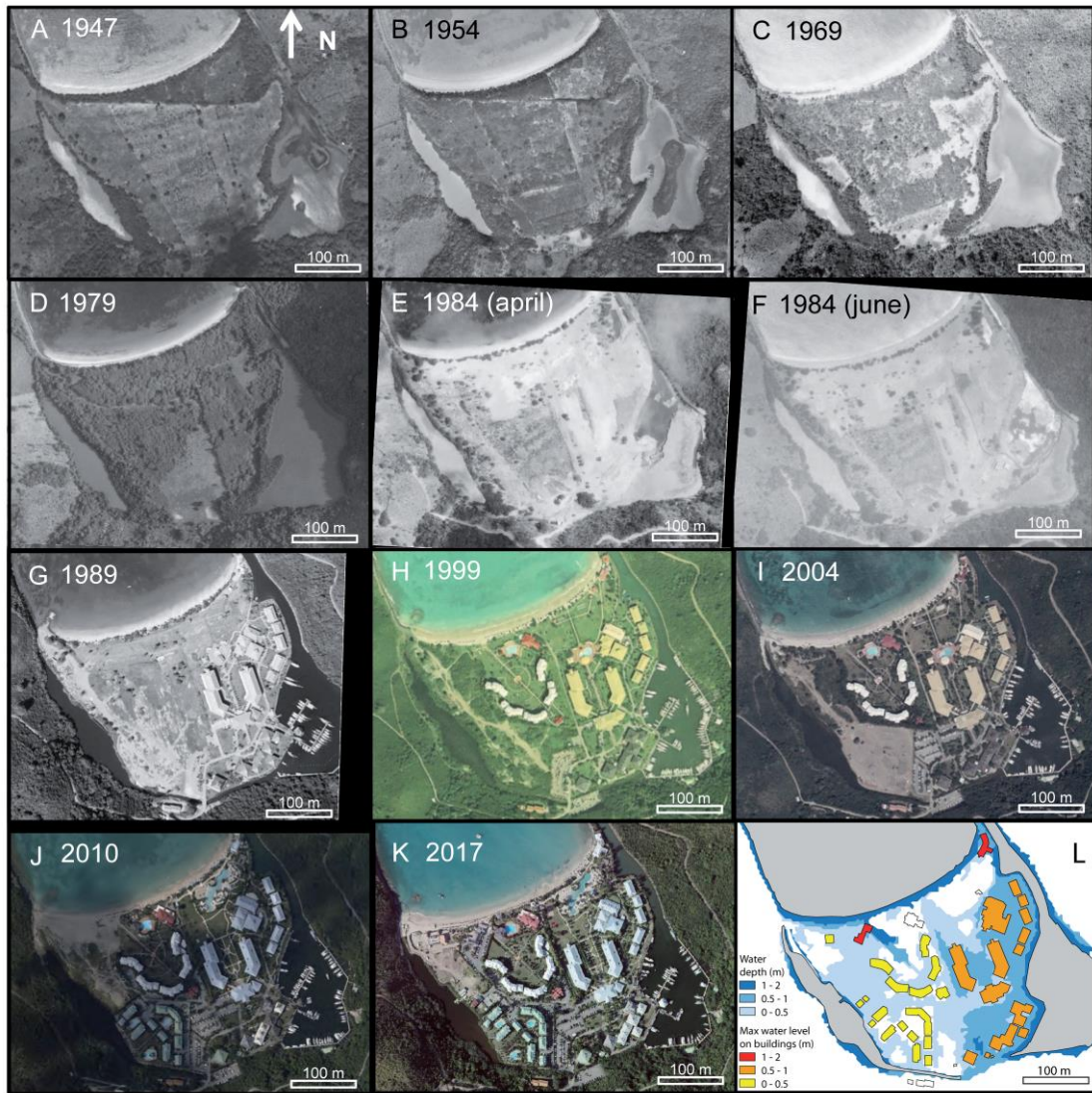
#### 175 **3.1 Building maps**

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

184 occurrence of Hurricane Irma. To compare data from Saint-Martin and Saint-Barthélemy, we  
185 presented only the results where photographic campaigns or satellite images were  
186 contemporaneous in both territories: 1954, 1969, 1989, 1999, 2010, and 2017.

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

190



191  
 192 *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  
 198 buildings on the island of Saint-Martin and Saint-Barthélemy between 1954 and 2017 (before

199 Hurricane Irma). Comparison between the two islands is possible because datasets are similar  
200 (resolution, year). In total about 19,185 buildings were surveyed in 6 aerial campaigns for both  
201 islands and more than 150,000 descriptions have been made. Notably, only buildings having a  
202 surface area greater than 20 m<sup>2</sup> were counted, to avoid any bias in relation with variations in the  
203 image accuracy/resolution of old data. This choice permit to reduce error in the counting and to  
204 obtain a more homogeneous estimation at the various times. Furthermore, in the islands considered,  
205 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.

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

223 describe the relation between: (1) the number of buildings and the number of buildings in marine  
224 inundation 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

246 of the number of houses between different categories allowed us to discuss risk apprehension and  
247 space availability.

248

### 249 **3.4 Correlation with social, economic, political, and environmental events**

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

260

## 261 **4. Results**

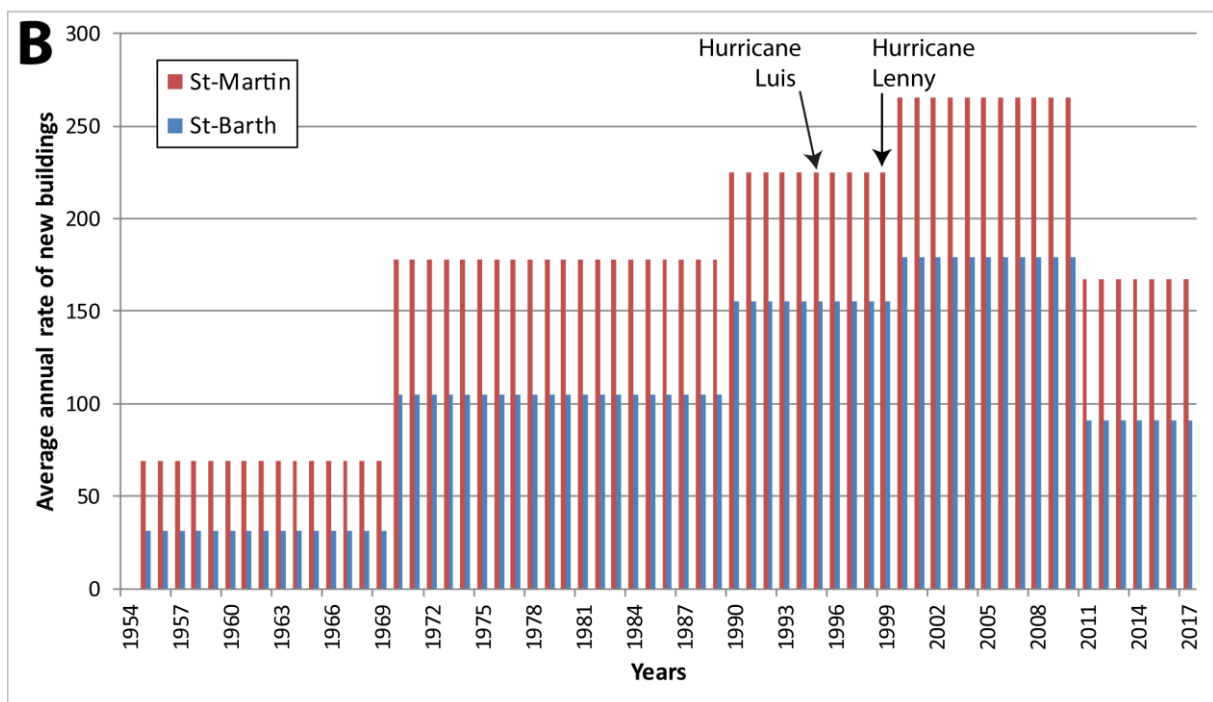
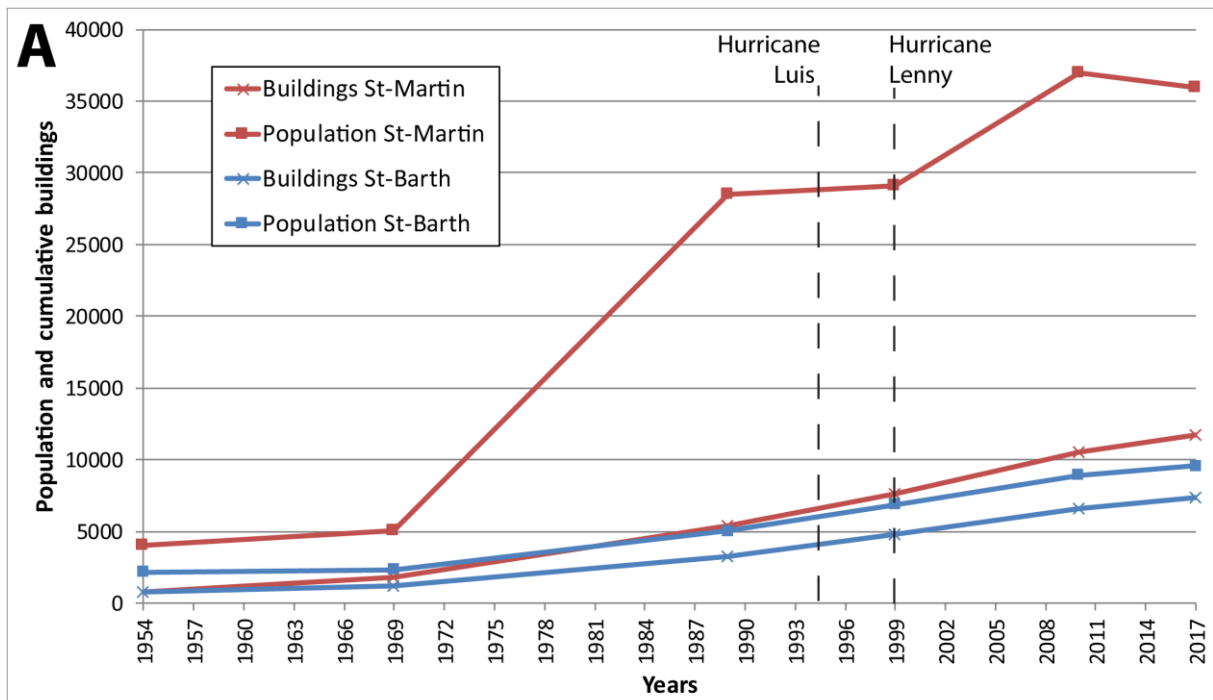
262

### 263 **4.1. Urbanization from 1954 to 2017**

264

265





266

267 *Figure 3. Graphs for the French part of Saint-Martin and the island of Saint-Barthélemy from 1954 to*

268 *2017 (before Hurricane Irma): A) Graph of evolution of population (INSEE)[44] and number of total*

269 *buildings, and B) Graph of growth in buildings per year (on average)*

270



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.

275 From 1954 to 1969, 1040 buildings were constructed on the island. This is equivalent to 69 buildings  
276 constructed per year during 1954–1969 (Fig. 3B). Urbanization and embankments increased at  
277 Marigot and Sandy Ground. The Sandy Ground channel was dug to connect a lagoon to the sea. In  
278 1969, a total of 1840 buildings were present on Saint-Martin (Fig. 3A).

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

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286

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293

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

Year	Population		Annual rate of building construction		Average number of people per building	
	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

296

297

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

303 Between 1999 and 2010, 2910 buildings were constructed on the island. Thus, during this period  
 304 around, ~265 buildings were built by year (Table 1). Urbanization was increasing throughout the  
 305 island. An industrial zone developed near the airport of Grand Case as well as of the industrial harbor  
 306 near Marigot, and in 2010, approximately 10,560 buildings were present.

307

308 Finally, between 2010 and 2017 (before Hurricane Irma), 1170 new buildings were constructed,  
309 equivalently to 165 buildings per year. The densification process continued throughout the island,  
310 mainly on the coast, reaching approximately 11,730 buildings (with an area of more than 20 m<sup>2</sup>) in  
311 2017 (Fig. 3).

312

#### 313 *4.1.2 Saint-Barthélemy Island*

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

318 Between 1954 and 1969, Saint-Jean Airport was in construction. The Shell Beach near Gustavia  
319 harbor was enlarged and embankments were developed. The number of construction increased: 472  
320 new buildings were constructed. This is equivalent to ~31 buildings built per year. No environmental  
321 modifications were observed in the lagoon areas. In 1969, 1242 buildings were present on the island.  
322 From 1969 to 1988, 1993 news buildings were constructed on the island, with an average of 105  
323 buildings constructed per year. One of the lagoon area was almost covered with buildings built on  
324 the embankments. The eastern part of Saint-Jean lagoon was also covered with buildings, and the  
325 airport was constructed. In 1988, a total of 3234 buildings were observed on the island (Fig. 3).

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

329 Between 1999 and 2010, 1969 new buildings were constructed on the island, which is equivalent to  
330 179 buildings constructed per year (Fig. 3B). In 2010, 6655 buildings were present on Saint-

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

333

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

335 The number of buildings constructed on both the islands increased between 1954 and 2017. The  
336 evolution was similar even if Saint-Barthélemy showed a lower number of buildings than Saint-  
337 Martin (Fig. 3). The rate of increase in building construction is higher from 1954 to 2010, than from  
338 2010 to 2017. The highest construction rate was between 1999 and 2010 for the two islands (Fig.  
339 3B), but the highest growth of new constructions was between 1969 and 1989 for both islands.

340 Since 1967, Saint-Martin and Saint-Barthélemy portrayed different population evolution. The  
341 population of Saint-Martin increased from 4001 inhabitants in 1954 to 35,941 in 2017 (Fig. 5A). This  
342 represents an increase of 900 %. On Saint-Barthélemy, the population increased from 2176  
343 inhabitants in 1954 to 9,567 inhabitants in 2017 (Fig. 5A). This corresponds to a growth of around  
344 450 %. The evolution of population in Saint-Martin and Saint-Barthélemy was thus,  
345 contemporaneous.

346 The main difference between the two islands was relative to the number of inhabitants in 1989. In  
347 1989, the ratio between the population and the number of buildings was of 5.3 for Saint-Martin and  
348 of 1.5 for Saint-Barthélemy, indicating the different urban and social trajectories of the two islands.

349

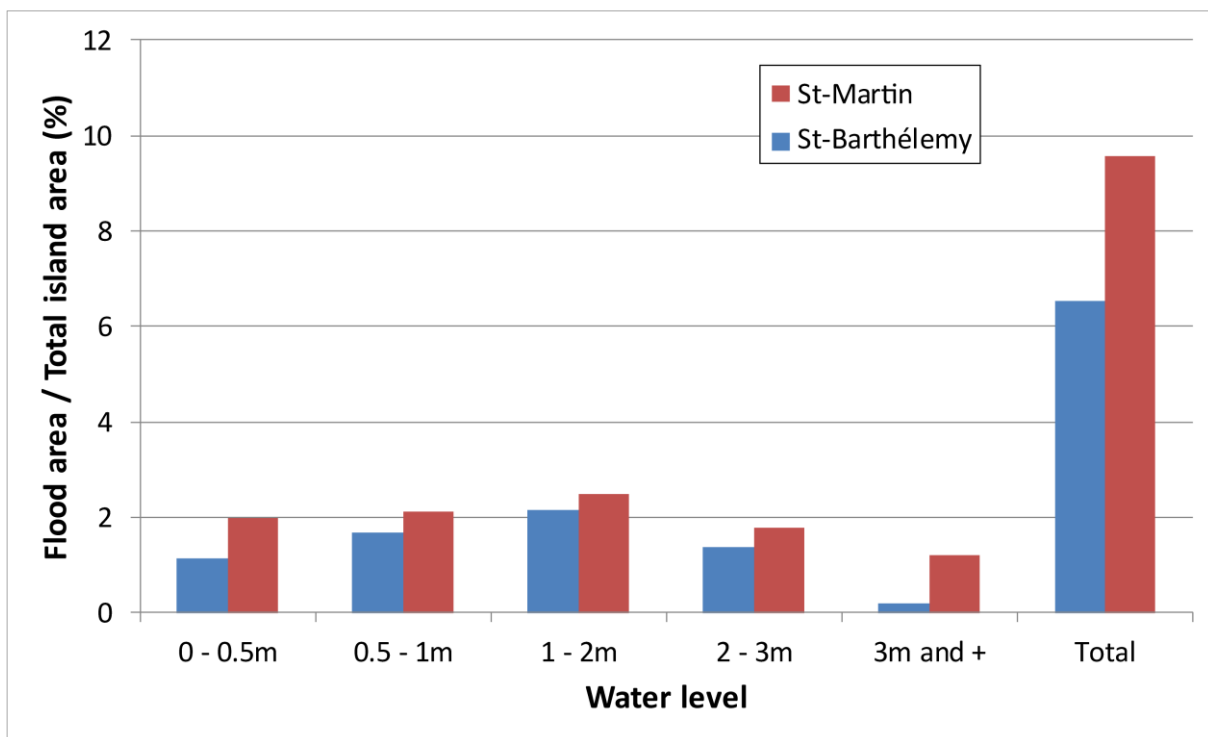
#### 350 **4.2 Construction in marine inundation areas from 1954 to 2017**

351 The surface of marine inundation risk areas was more than three time higher in Saint-Martin than  
352 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  
353 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.  
354 1.5 km<sup>2</sup> of 24 km<sup>2</sup>) (Fig. 4).

355 The surface potentially affected by marine inundation was higher in Saint-Martin than Saint-  
356 Barthélemy, whatever the water level categories. However, the difference between the amounts of  
357 inundated surfaces of Saint-Martin and Saint-Barthélemy was small (3 % of the total island surface).  
358 The water level category from 1 m to 2 m covered the largest area and is dangerous for children and  
359 adults, and could damage buildings.

360

361



362

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

365

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

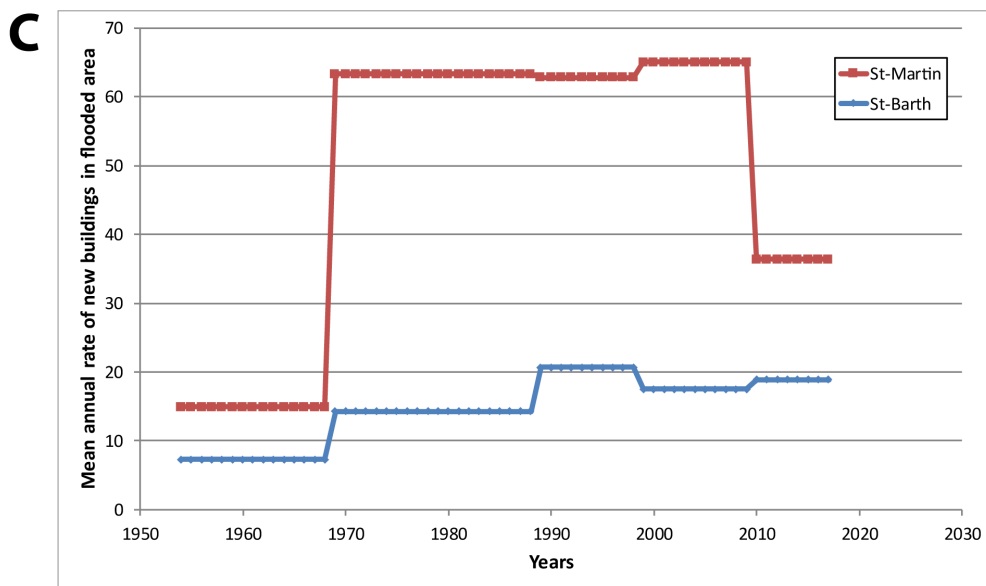
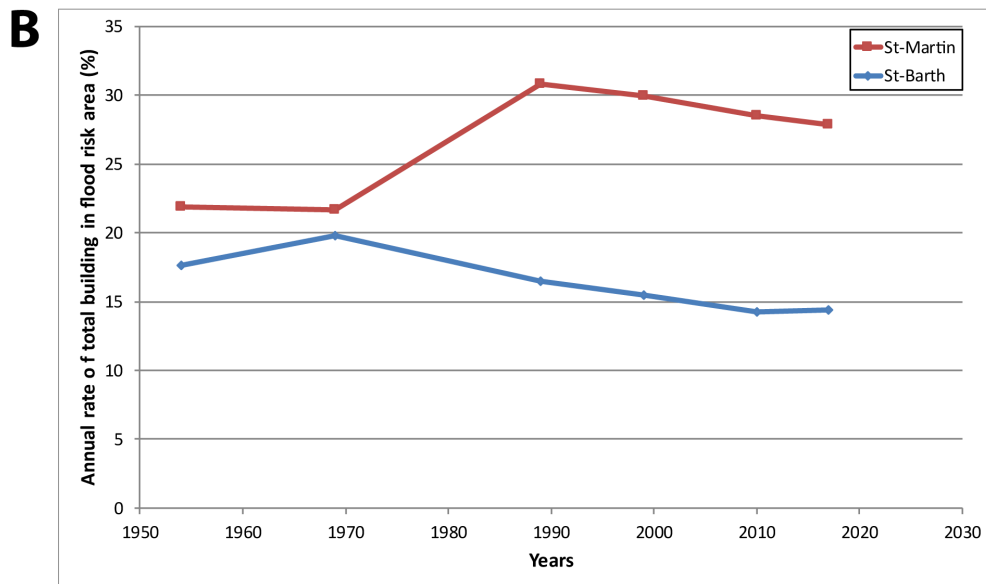
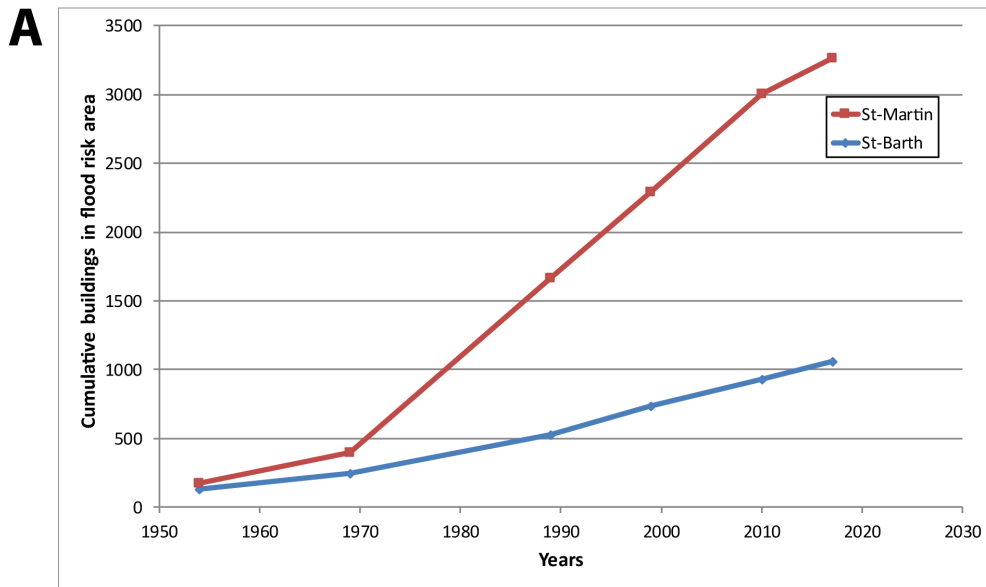
369 coastal inundated area, there were 652 buildings/km<sup>2</sup> in Saint-Martin and 709 buildings/km<sup>2</sup> in Saint-  
370 Barthelemy, in 2017 when Hurricane Irma hit.

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.

380 Concerning the mean number of buildings constructed per year from 1954 to 2017 in coastal flooding  
381 areas, several trends were observed in our study. At Saint-Martin, the number of constructions  
382 exposed to marine inundation increased from 1969 to 1989. Between 1969 and 2010, the average  
383 number remained approximately constant; in Saint-Martin, this number decreased after 2010 (Fig.  
384 5C). The peak number of new buildings was achieved between 1999 and 2010 in Saint-Martin. At  
385 Saint-Barthélemy, the trend was less clear; the construction rate increased from 1954 to 1999, after  
386 which, it was almost constant.

387

388



390 *Figure 5. Urban evolution in marine inundation risk areas in Saint-Martin and Saint-Barthélemy from*  
391 *1954 to 2017 (before Hurricane Irma): A) Number of buildings constructed in areas of marine*  
392 *inundation, B) Percent of buildings present in marine submersible area relative to the total number of*  
393 *buildings on the whole island, and C) Average number of buildings constructed in the submersible*  
394 *area per year*

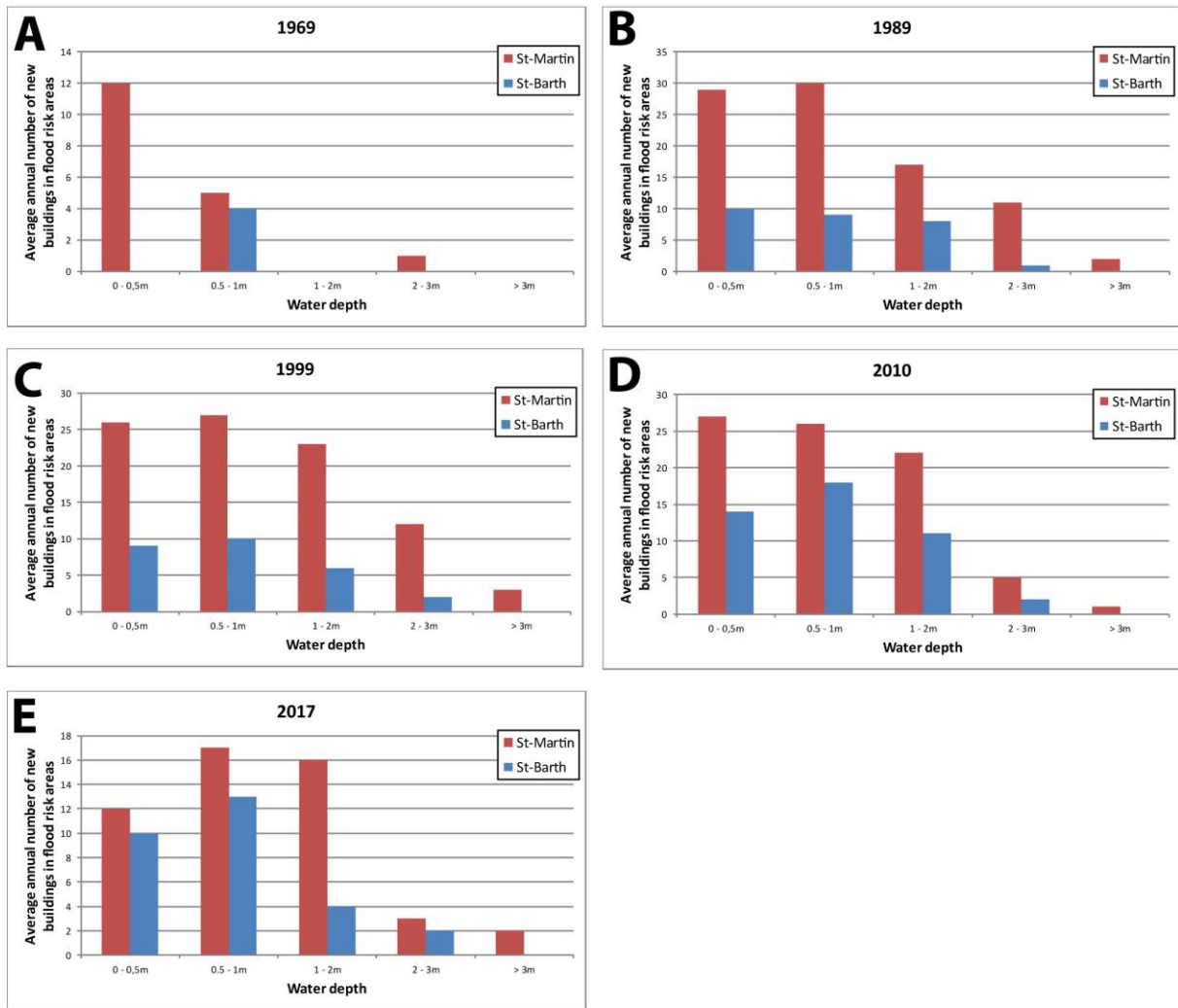
395

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

406





407

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

411

## 412 5. Interpretation and discussion

413

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

417 significantly higher in Saint-Martin than Saint-Barthélemy [44,47], even if it was almost similar in  
418 1960; (iii) the protection of populations against natural hazards benefited from a Natural Hazard  
419 Prevention Plan (called Plan de Prévention des Risques Naturels, PPRN in French [62]) implemented  
420 in 2011 in Saint-Martin but not in Saint-Barthélemy; and (iv) the economic strategies of both islands  
421 were different (quality/quantity and luxurious/mass for Saint-Barthelemy vs. Saint-Martin) [55,63],  
422 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  
428 where there was a maximum of 1m of water in case of inundation (50 cm in Saint-Martin).  
429 Population growth began in 1986, after the French government decided to develop  
430 economical activities in French overseas territories [2,64,53] and the increase in the number  
431 of buildings was almost contemporaneous. A detailed evolution of the number of  
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  
434 to 3 m.

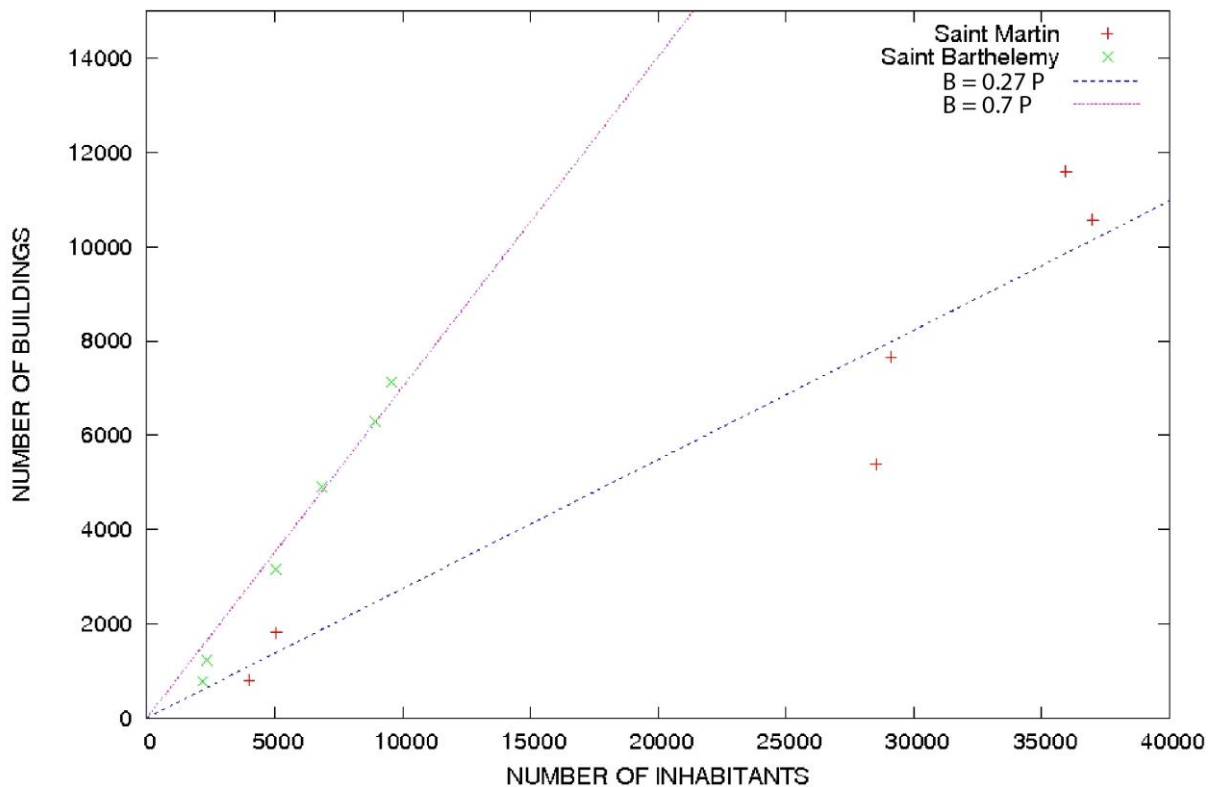
435

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

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  
442 French territories for a period of 5 years for companies and 10 years for individuals. This law  
443 led to the construction of numerous second homes, tourist accommodations, and hotels, but  
444 also indirectly led to the development of housing for construction and tourist workers and  
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  
448 infrastructures and residences or work as tourism employees [55]. Notably, a peak in new  
449 constructions was achieved between 1999 and 2010 (Table 1). For the higher risk areas  
450 (depth >2m), the number of new construction slightly decreased after 1999 (i.e. after  
451 Hurricane Luis and Lenny; Figure 6).

452

453



454

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

458

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

464 The mean number of construction per year decreased after 2010 in Saint-Martin and Saint-  
 465 Barthélemy (Figure 3 and Table 1), even when there were local differences in Anse Marcel in Saint-  
 466 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, from 1947 to 2017*

Year	Cumulated number of building	Number of new buildings	New buildings per 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

479

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  
494 marine inundation risk area (Table 3). Until 1986, many coastal areas were not inhabited or  
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 specific laws.

503

504

505 *Table 3. Number of building (B) and number of buildings in marine inundation risk areas (B<sub>MIRA</sub>) in*  
506 *Saint-Martin and Saint-Barthélemy*

507

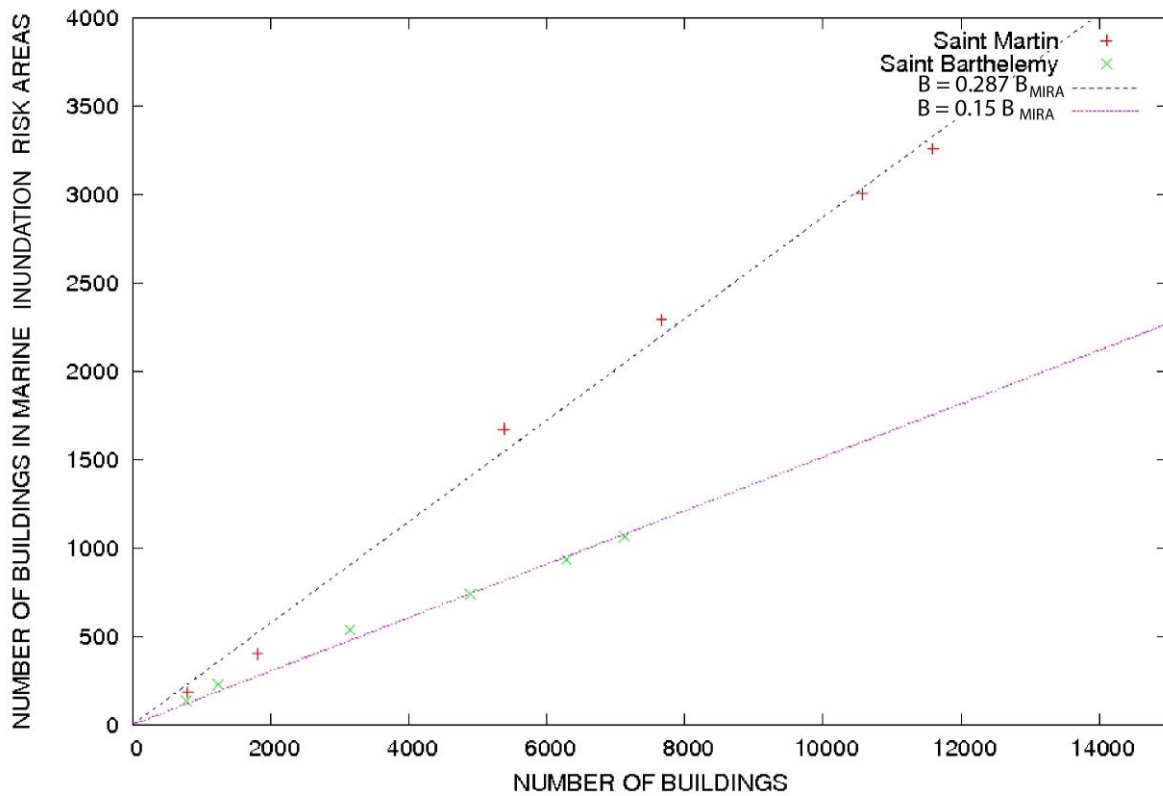
Year	Number of buildings (B)		Number of building in marine inundation risk areas (B <sub>MIRA</sub> )	
	Saint-Martin	Saint-Barthélemy	Saint-Martin	Saint-Barthélemy
1954	800	777	182	136
1969	1807	1237	400	226
1989	5381	3149	1672	532
1999	7661	4896	2292	739
2010	10565	6284	3007	932
2017	11593	7120	3262	1064

509

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

516

517



518

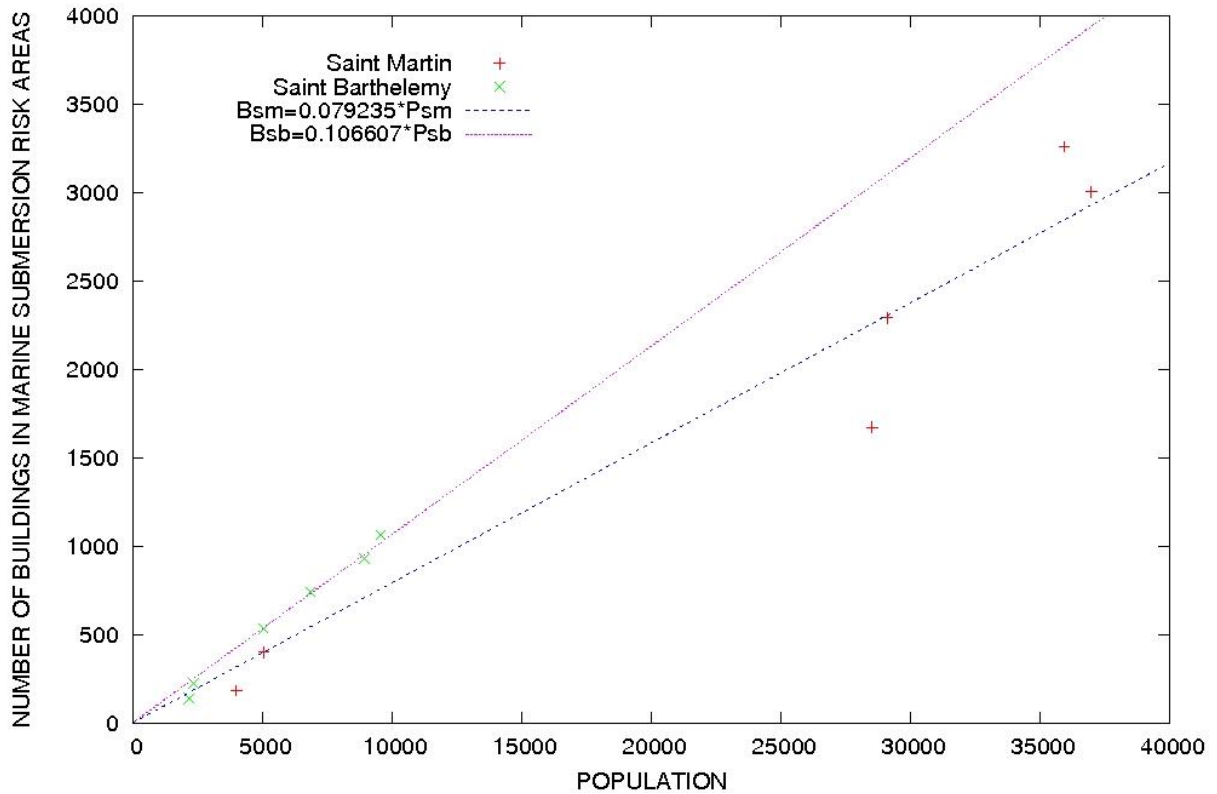
519 *Figure 8. Number of buildings in marine inundation risk areas  $B_{MIRA}$  in relation with the total number*  
 520 *of buildings  $B$  in Saint-Martin and Saint-Barthélemy. The coefficient of proportionality is  $\beta \approx 0.287$  in*  
 521 *Saint-Martin and  $\beta \approx 0.15$  in Saint-Barthelemy, with a standard error of 1.82% ( $\pm 0.00523$ ) and*  
 522 *1.943%, ( $\pm 0.002943$ ), respectively.*

523

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



531  
532



533  
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536  
537  
538

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 ( $\beta$ ) is equal to  $\approx 0.08$  in Saint-Martin and to  $0.10$  in Saint-Barthélemy, with a standard error of  $6.29\%$  ( $\pm 0.004982$ ) and  $2.9\%$ , ( $\pm 0.003111$ ), respectively.

### 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

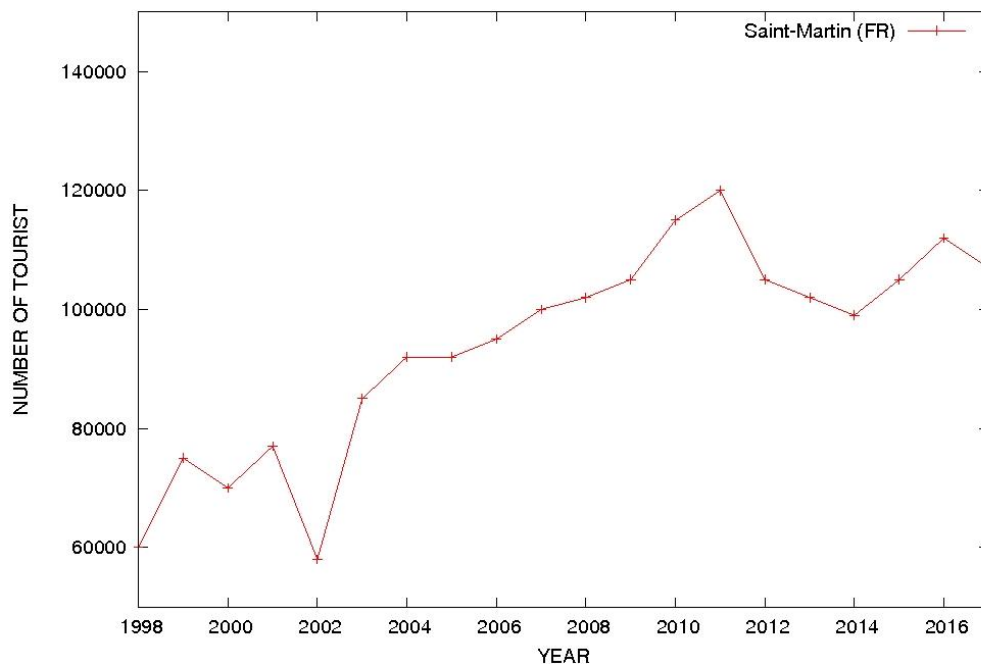
543 increases only after tourist infrastructures, such as hotel and residence, but also airport and harbor,  
544 are built [14,55,63].

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

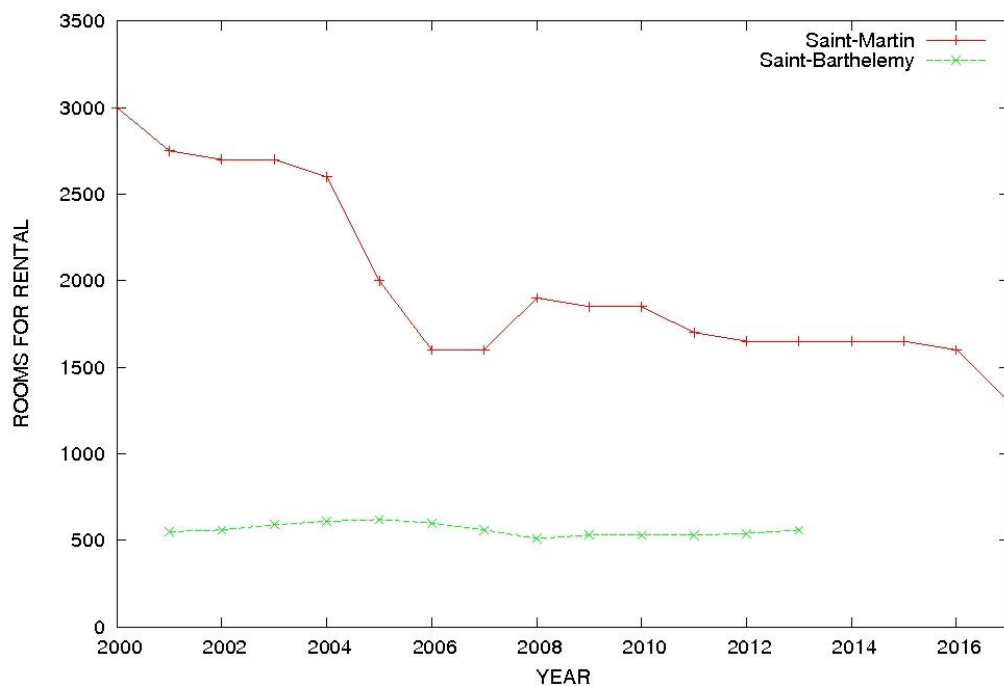
554 The decrease in the number of construction per year after 2010 in Saint-Martin could not be related  
555 to the decrease in the tourism flux to the island (Fig. 10) [45]. The mean number of passengers that  
556 arrived in Saint-Martin per year in the harbor and airport was higher during 2010–2018 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].  
565 The apparent reduction in the official number of rooms available (Fig. 11) and the simultaneous  
566 increases in the touristic flux (Fig. 10) could appear contradictory. In 2011, Airbnb activity began in

567 Saint-Martin, and more than 2700 apartment and home rentals per month were proposed in 2017  
568 [5]. These new housing opportunities not always appeared in official statistics and could explain the  
569 apparent decrease of room availability in Saint-Martin. A reduction in the mean duration of vacations  
570 could also explain this drop. In Saint-Barthelemy, more than 300 lodging are available in 2022 via the  
571 same platform.



572

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



574

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

577

578 **5.4 “Free space” availability and environmental protection**

579 Available spaces are limited on small islands, and there is a potential of saturation of coastal areas by  
 580 buildings. It could be suggested that the progressive reduction of free areas for construction could  
 581 have reduced the number of constructions per year. Nevertheless, in the case of Saint-Martin, we  
 582 observed “free spaces” (i.e. without construction) in coastal areas, as well as in the internal part of  
 583 the island. For example, the western part of Nettle Bay in Saint-Martin had no new constructions in  
 584 2020. During our study, several areas at the north of the Orient Bay, along with Happy Bay and Friar’s  
 585 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.

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

601 Notably, the reduction in new construction in Saint-Martin and Saint-Barthélemy during the last  
602 decade could result from a strategy of mitigating urbanization of the islands, after decades of  
603 neglecting environmental protection in this region. Environmental protection is also a way to protect  
604 the way of life [20] and health interest. Recent studies highlight that waste management as well as  
605 electricity and water production are specific problems in an insular context that increase vulnerability  
606 [18,58,73].

607

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

609 Hurricanes Luis (1995) and Lenny (1999) have damaged Saint-Martin and Saint-Barthélemy [16,53].

610 However, after they occurred, from 1999 to 2010, the number of buildings constructed in the marine  
611 inundation risk areas still increased on both the islands. It must be taken into account that (1) during

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

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

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



633

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

636

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

641

## 642 **5.6 Influence of prevention plan on construction in marine inundation areas**

643 The possibility that hurricanes can destroy private and public infrastructures along the coast and  
644 deeply disorganize socio-economic structures was not sufficiently anticipated in previous studies in  
645 French overseas territories before Hurricane Irma [74]. Several decades of rules (Land Use Plan  
646 regulation – Plan d’Occupation des Sols in French, 2002; “Littoral protection” law [71,75]) were not

647 able to limit or decrease the vulnerability of these islands. During this period, part of the construction  
648 on the coast were built without authorization and property documents [16,70].

649 From 1970 to 2010, the number of buildings constructed was 2–4 times higher in Saint-Martin than  
650 Saint-Barthélemy, with the population being ~3.5 times higher. After 2010, the annual number of  
651 construction in the marine inundation risk areas was only 1.8 times higher in Saint-Martin than Saint-  
652 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).

664 The mean number of buildings constructed in marine inundation risk areas each year was 65 during  
665 the 2000–2010 in Saint-Martin; this decreased to 36 after 2011, representing a reduction of around  
666 45 %. Contemporaneously, the number of new buildings constructed at Saint-Barthélemy was stable  
667 at around 20 each year. In Saint-Barthélemy, no prevention plan was established, which allowed us  
668 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

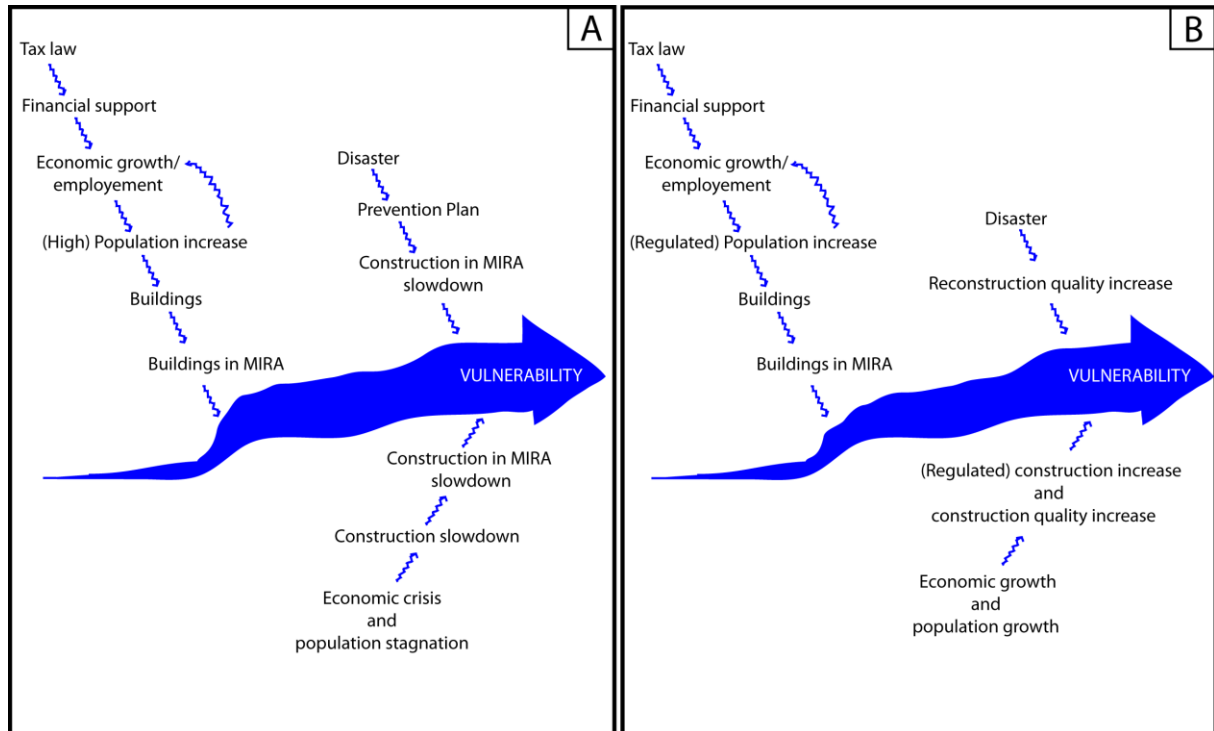
691 Figure 9 indicates that the  $B_{MIRA}$  values for Saint-Martin and Saint-Barthélemy could be determined  
692 by the number of inhabitants (P). This trend is similar in Saint-Martin and Saint-Barthélemy, and thus,

693 an increase in the population of Saint-Barthélemy should increase the number of buildings in the  
694 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  
716 buildings/km<sup>2</sup>/inhabitants vs 0.018 buildings/km<sup>2</sup>/inhabitants, respectively). Notably, decision to

717 reduce vulnerability to marine inundation could take a long time, e.g., the high level of vulnerability  
 718 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)*

723

724 **5.8. Systemic vulnerability and risks**

725 The relative nature of the notion of vulnerability invites reflection on the temporal scales of these  
 726 concepts, because goods, people, or society cannot be defined as vulnerable *per se*. For example,  
 727 concrete roof are more resistant than metal roof during category 5 hurricanes. Nevertheless,  
 728 reconstruction of concrete roofs in a seismic zone instead of metal or wooden roofs in Saint-Martin  
 729 after hurricane Irma, without compliance with specific seismic regulations (Eurocode 8) do not  
 730 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  
749 Saint-Barthélemy have been estimated to be of  $82.3 \times 10^3$  euros/inhabitants (i.e., 823 million euros  
750 for 10,000 inhabitants) whereas it was of  $33.4 \times 10^3$  euros/inhabitants (i.e., 1170 million euros for  
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.

758 Insured damages are only part of total damages in Saint-Martin and Saint-Barthélemy, where 60 % of  
759 people have no insurance [9]. Furthermore, during hurricanes, people lose assets that have no  
760 financial value. Thus, insured damages are not efficient to evaluate the vulnerability of a territory to  
761 a specific event. Data necessary to build specific indicators and evaluate vulnerability of the region  
762 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.

773 After Hurricane Irma, a new prevention plan was decided by the French government to accelerate  
774 the reduction of vulnerability to marine inundation in Saint-Martin. For the French government, the  
775 aims of the new risk plan were to: (1) reduce potential damage and injuries in case of marine  
776 inundation, (2) inform residents and potential investors about risks involved, and finally, (3) support  
777 a faster recovery after the occurrence of a natural hazard. The revision of the Natural Hazards  
778 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  
789 claim that working class and touristic activities will experience disadvantages, especially in Sandy  
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 casualties 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.

803

804 The relocation of people accommodation with their agreement outside risky areas, no new  
805 constructions in inundation risk areas, preservation of natural areas (mangrove, lagoon, sand  
806 dune and beach), promoting risk prevention by various approaches, a financial support to  
807 promote renovation for more robust housing, improved critical networks infrastructures  
808 [83], diversified economic activities (not overspecialization in tourism activities), efficient  
809 Public Service (emergency staff, emergency shelter, prevention staff, etc.), could reduce  
810 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.

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

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

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

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

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

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

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



849 socio-economic problems is often a slow process, and abrupt transformations could cause future  
850 crises.

851

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860

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