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1 **A low-cost toolbox for high-resolution vulnerability and hazard-**
2 **perception mapping in view of tsunami risk mitigation: application**
3 **to New Caledonia**

4
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20

21 **Abstract**

22 The drive towards improving tsunami risk mitigation has intensified along many populated coastlines.
23 Like many islands in the Pacific Ocean, the coastal population of New Caledonia is exposed to
24 tsunamis triggered by powerful earthquakes. Intersecting exhaustive population data with high-
25 resolution building location data within a user-defined coastal fringe is an accurate means of
26 geolocating vulnerable residents, and an important step towards disaster risk reduction. This paper
27 presents a mixed methodology built on GIS-based dasymetric techniques for assessing, classifying,
28 and mapping population distribution in New Caledonia, with the aim of quantifying and ranking the
29 areas most vulnerable to tsunami-related hazards. Results reveal that 33% of the population,
30 inclusive of previously unmapped precarious housing, lives between sea level and the 10 m elevation
31 contour in well-defined clusters. A pilot field survey of 412 respondents was additionally conducted
32 in the capital Nouméa (66% of the nation's population) to assess tsunami awareness, risk perception,
33 and risk-related behavioral patterns among the ethnically and demographically diverse population.
34 By further mapping the spatial association between coastal population concentrations, the perceived
35 natural shielding capacities of coral reefs and mangroves, and the benefits of alarm siren networks,
36 the study delivers a comprehensive assessment of the country's disaster preparedness, with policy
37 recommendations for the future. The methodology is transferable to other types of hazards and
38 other insular settings where civil security and risk-management organizations acquire and curate
39 reliable primary data but may also need guidelines for transforming them into serviceable disaster
40 risk reduction methods and policies.

41 **Keywords**

42 Tsunami hazard; dasymetric population mapping; perception survey; community-based disaster-risk
43 reduction; ecosystems shields; New Caledonia

44 **1. Introduction**

45 Modern human societies tend to underprepare for disasters. Reasons typically include environmental
46 myopia [1], historical amnesia [2], administrative inertia [3], technological optimism [4,5], herding
47 bias (a tendency to base choices only on the observed actions of others [6]), and simplification bias (a
48 tendency to selectively attend to only a subset of the relevant factors requiring to be considered [3]).

49 Disaster risk reduction (DRR) addresses a wide spectrum of potential strategies for risk abatement
50 and disaster management [7]. Risk abatement includes taking steps towards prevention and
51 preparedness, often with emphasis on a reduction of vulnerability (vulnerability refers to the
52 physical, social, economic, and environmental factors or processes that increase the susceptibility of
53 a human population to the impacts of a given hazard). Disaster management addresses warning,
54 alert, emergency response strategies, and sometimes aspects of recovery. Hazard assessment
55 (recognition, rating and quantifying the hazardousness of a place through mapping, scenario testing,
56 and/or instrumental monitoring of hazard-related threats) is thus not fully part of DRR but its results
57 gain from being used as a guide – however preliminary or perfectible – to risk analysis (key question:
58 what can happen?) and risk assessment (key question: what is acceptable?), both required prior to
59 planning of prevention and preparedness measures [7]. DRR thus addresses the whole risk cycle of
60 prevention, intervention, and recovery in a context where exposure to hazards is at least already
61 documented, short of necessarily being scientifically understood in reductionist terms or under full
62 probabilistic constraints.

63 Disasters and risks are no longer purely humanitarian issues in the context of reactive disaster
64 management: DRR is now a matter of proactive risk reduction and thus an integrative part of
65 sustainable development and adaptation to global change [8]. An International Strategy for Disaster
66 Reduction has been drawn up by the United Nations [9], defining ‘Ten Essentials’ in order to
67 empower local governments and other agencies in the implementation of the Hyogo Framework for
68 Action (HFA). Priorities for action therein were (i) to ensure that DRR is a national and local priority

69 with a strong institutional basis for implementation; (ii) to identify, assess and monitor disaster risks
70 and enhance early warning; (iii) to use knowledge, innovation, and education to build a culture of
71 safety and resilience at all levels; (iv) to reduce the underlying risk factors; and (v) to strengthen
72 disaster preparedness for effective response at all levels. Obviously, all nations do not have the same
73 needs in terms of DRR, or indeed the same management capacities [10]. Quantitative risk analysis
74 and assessment methods currently attain high levels of sophistication in industrialized countries such
75 as, for example, the USA (with its Federal Emergency Management Agency [11]). However, different
76 economies, cultures, and environmental settings may call for different risk control options, which
77 typically range from structural measures ('hard' structures belonging to the repertoire of civil
78 engineering) to nonstructural measures (land-use planning, ecological restoration, hazard risk zoning,
79 education, awareness campaigns, early warning systems, affordable disaster insurance, and other
80 regulatory policy measures). Those approaches, whether structural or nonstructural, tend to be top-
81 down and technocratic, but community-based holistic and integrative approaches are also emerging,
82 where civil society, scientists, the state and/or third-sector organizations (and thus the private
83 marketplace) endeavor to co-construct the safety of their own futures (on community-based disaster
84 risk reduction, or CBDRR, see [12]).

85 New Caledonia is a 18,575 km² archipelago located in the South West Pacific Ocean, about 200 km
86 west of the seismically highly active Vanuatu subduction zone (Fig. 1). This region is frequently
87 subject to earthquakes of magnitude M_w up to 7.0 and more. The earthquakes pose a threat to the
88 island's population, particularly when a tsunami, as on December 5, 2018 (Maré, M_w 7.5) [13] and
89 February 10, 2021 (Matthew Island, M_w 7.7), is triggered. Distant earthquakes can also affect the
90 archipelago through transoceanic tsunamis, with potential impacts on coastal communities on the
91 other side of the ocean. New Caledonia is fully concerned by this, and destructive tsunamis have
92 been reported during the 19th and 20th centuries. New Caledonia's vulnerability to tsunami, its
93 ethnographically and culturally diverse population, its appeal as a destination for seaside tourism,
94 and its imperfect emergency planning and management policy, make this group of islands an ideal

95 laboratory for (i) probing why the region is underprepared for natural disasters, (ii) formulating policy
96 recommendations towards setting up an effectual disaster management system, and (iii) showcasing
97 its relevance to other similar tropical insular regions concerned by tsunami risk assessment. The
98 coasts of New Caledonia are also vulnerable to other inundation produced by events such as wind
99 waves, strong swells [14], and storm surges [15]. Given that these processes also expose New
100 Caledonia to coastal erosion [16,17,18] and thus enhance baseline threats to human life and
101 infrastructure, the risks related to these hazards call for being assessed while also bearing in mind
102 the threats of sea-level rise associated with global climate change (for its impact on tsunamis, see
103 [19]; impact on waves, see [20]; impact on surges, see [21,22]).

104 Ideally, full tsunami hazard assessment includes predicting the likely maximum heights reached by
105 tsunami waves while taking account of the location and magnitude of the source; of geometry of
106 shorelines, straits and bays that may be affected; of seafloor morphology; of the occurrence of
107 natural features such as reefs and mangroves; and of the distribution of low-lying land. The finer
108 detail of some of these aspects, however, is still work in progress for New Caledonia [23]. A recent
109 update of the tsunami catalog of New Caledonia documents 37 tsunamis triggered by local, regional,
110 and distant earthquakes between 1875 and 2018 [24]. The two largest local earthquakes generated
111 at the southern Vanuatu subduction zone on March 28, 1875 and September 20, 1920, with
112 respective magnitudes M_w 8.1–8.2 and M_w 8.0, triggered two destructive tsunamis in New Caledonia
113 and Vanuatu. Wave heights reached 5 m at specific locations, and the first event killed 25 people in
114 the south of Lifou Island (Loyalty Islands), while also causing various levels of damage and human
115 injury [25]. These earthquakes are directly linked to high tectonic compression rates along the
116 Vanuatu Trench ranging between 5 and 12 cm/yr horizontally in the central and southern part
117 (maximum at the latitudes of the Loyalty Islands [26]). A seismic gap between the Loyalty Islands and
118 the southern Islands of the Vanuatu arc (Erromango, Tanna, Aneityum) suggests the forthcoming
119 possibility of a major rupture [27], potentially triggering catastrophic tsunamis in the coming years or
120 decades. Finally, 20% of recorded/reported wave heights were more than 1 m, two of them ranged

121 between 2 and 5 m [24], justifying the relevance of an island-wide, DRR-focused investigation of New
122 Caledonia.

123 Tsunamis have the potential to generate human loss and material destruction, but the nature,
124 magnitude, and duration of tsunami impacts are also a function of where and how people choose to
125 live, and how they adapt to and recover from the consequences of the destruction [28]. Major
126 concerns for resilience are thus population preparedness and infrastructure resilience, both of which
127 require finding ways of reducing coastal vulnerability to marine inundation [29,30,31]. Human
128 presence in New Caledonia goes back ~3,000 years, with the settlement of Melanesian communities
129 today known as Kanaks [32]. The first European settlers arrived in 1774 [33,34]. The population
130 census [35] recorded 268,767 inhabitants in August 2014, and today the island is entirely settled [36].
131 Overall, the population of New Caledonia today is composed of Kanaks (nearly 40%), Europeans
132 already present for several generations or recently arrived (nearly 30%), Oceanians (Polynesians,
133 Wallisians, Futunians, Ni-Vanuatu, etc.), and Asians (mainly Vietnamese, Japanese and Indonesian).
134 The main city, Nouméa, and its suburbs host > 66% of the entire population (Fig. 1).

135 Figure 1

136 These general features lay the foundations for a marine inundation hazard assessment that includes
137 defining protection priorities along the coastline—typically housing and critical infrastructure such as
138 hospitals, fire stations, polluting industries, etc. In most countries, however, the exact number of
139 residents close to the shoreline is commonly unknown. Such is the case in New Caledonia, where,
140 furthermore, 25% of the population was not born on the island and 16% are expatriates from
141 mainland France [36]. Such situations vary but are not uncommon among island nations. As a result,
142 cultures and traditions vary within the population, depending on geographic origin, social
143 background, and education level [37]. The same is true for risk culture (way a community handles
144 questions of safety and security), which varies on an international scale and within a population as a
145 function of past and current exposure to hazards [38]. In New Zealand, for example, the Māori have

146 developed their own knowledge about local hazards. It is typically based on environmental indicators
147 and geographic place names remembered as high-risk and is passed on through oral tradition [39]. It
148 is, therefore, relevant to know how much of the population is aware of impending tsunami hazards,
149 and what knowledge people have about these hazards and about existing safety measures to guard
150 against them [40,41,42,43]. This emphasizes the need to conduct a vulnerability analysis of the
151 island's coastal fringe, which has a potential for exposure to tsunami-related hazards along its entire
152 length.

153 In several tropical settings, the potential for natural ecosystems to protect populations from marine
154 inundation is an important component among possible risk-mitigation options [44,45,46]. New
155 Caledonia benefits from three such ecological assets (Figure 2):

156 (i) Grande Terre is surrounded by a 1,600 km coral reef barrier. The lagoon between the barrier
157 and the coast is about 20 km wide at Nouméa, and much narrower on the east coast (3 km at
158 Touho, and 8 km at Yaté; Fig. 2). Although not all tsunamis or storm surges have their
159 amplitudes attenuated after crossing a reef, most wind waves and long-period swells are
160 attenuated by reefs [47,48].

161 (ii) Numerous carbonate constructions, such as fringing reefs, also occur inside the lagoon and
162 around the smaller islands [49].

163 (iii) Mangroves cover 359 km² of New Caledonia's coastline [50]. These forests function as an
164 important buffer between the world's largest natural coralline lagoon [51] and the high
165 sediment and heavy-metal loads of rivers conveying opencast mine tailings to the coast.
166 Some mangrove forests are even advancing seaward because of sediment accretion in
167 estuaries [52]. Whether in the case of tsunamis [53,54,55,56] or storms [45,56,57],
168 mangroves have repeatedly demonstrated their protective effect on coastlines [58], with a
169 proven reduction in human casualties when forming barriers seaward of human settlements.

170 The aerial roots of mangroves provide additional resistance to wave energy and reduce
171 impacts by increasing friction [59].

172 Figure 2

173 This paper focuses on a low-cost toolbox for vulnerability and hazard-perception mapping crafted in
174 the context of studying tsunami-related hazards in New Caledonia. It relies on a mixed methods
175 approach [60,61] involving an opensource geographical information system, dasymetric population
176 mapping, rapid field interviews (combination of structured and semi-structured), and hazard
177 perception analysis. The HFA recognizes that governments have the primary responsibility to guide
178 and implement measures for achieving DRR (priority 1); accordingly, this comprehensive study is
179 framed under a national focus and presents the methodology and its associated toolbox primarily as
180 a basis for creating a national DRR platform. However, New Caledonia is also held here as
181 representative of other coastal environments and communities in the Tropics, where the toolbox
182 could be also adopted and adapted for framing proactive risk reduction policies in those settings. We
183 begin by presenting a methodology for systematic mapping of the archipelago's coastal population in
184 order to quantify the magnitude of its vulnerability to tsunami-related hazards. Given that the
185 analysis covers a vast territory based on a standard set of criteria and low-cost tools, a tradeoff also
186 occurs between geographic range — the larger the better for preliminary strategic planning — and
187 site-specific analytical precision, which for some variables (e.g., building height, or digital elevation in
188 the absence of LiDAR coverage) is limited or unavailable compared to what may exist in wealthier
189 countries. We subsequently report the results of a rapid assessment survey of tsunami hazard
190 perception by residents of the capital Nouméa and by visitors from other parts of the islands. Using a
191 quota sampling approach, the rapid survey was crafted as a means of assessing behavioral patterns
192 among a cross-section of the population in the event of a tsunami, and of identifying future policy
193 priorities for optimizing DRR on that basis. The potential for existing coastal ecosystems to efficiently
194 protect exposed residents is discussed, and the effectiveness of an alarm siren network, currently

195 being deployed throughout the islands by the regional emergency management agency (*Direction de*
196 *la Sécurité Civile et de la Gestion des Risques*), is assessed. Conclusions advocate the advantages of
197 jointly developing a map-based and social science approach to disaster risk management in coastal
198 areas exposed to tsunamis, with potential for transferability of the methodology to other island
199 settings where standards of preparedness are still limited.

200

201 **2. Methods: a toolbox for vulnerability and hazard-perception mapping**

202 **2.1. Step 1: defining the coastal fringe based on topographic data**

203 A coastal fringe is a fuzzy, purpose-dependent concept. Usually considered in hazard risk zoning as a
204 strip of land containing human settlements and shaped by certain forms of land use that give it
205 unique ecological and/or economic value (e.g., urbanization in [62]), its width between the coastline
206 and the hinterland will depend on the topic of interest and (given the fractal nature of coastlines) will
207 also be a function of scale (more information in Supplementary Material; [63,64]). The French Naval
208 Hydrographic and Oceanographic Service (SHOM), which establishes nautical charts for New
209 Caledonia, defines the coastline as the line of intersection between the topographic surface and the
210 level of the highest astronomic tide (HAT). In the context of understanding the impact of tsunamis on
211 terrestrial environments, important criteria for defining the coastal fringe are wave height at the
212 coast, current speed, flood depth, and run-up height and/or distance [65]. Run-up height is the
213 maximum elevation reached by the tsunami during inundation. A definition of the coastal fringe on
214 that basis also includes the banks of estuaries that are lower than that critical elevation. From an
215 inundation depth perspective, given the narrowness of New Caledonia (< 60 km) and the strong
216 currents observed in certain river estuaries during previous tsunamis [24], areas situated at low
217 elevation but inland from the coast should be ruled in as they could also be vulnerable to tsunami-
218 related hazards.

219 In this study, the topographic data used were derived from a digital elevation model (DEM)
220 generated by the *Direction des Infrastructures de la Topographie et des Transports Terriens* (DITTT) of
221 the government of New Caledonia (<https://dittt.gouv.nc>). Average ground elevation (excluding
222 vegetation and buildings) is provided at a horizontal resolution of 10 m. Although altimetric accuracy
223 does not exceed ~2 m in areas with steep slopes and dense vegetation (e.g., in the mountain
224 rainforests), it increases to 1 m or more in the flatter coastal areas of interest. Reference sea level
225 was the coastal outline proposed by the GEOREP GIS portal of New Caledonia (<https://georep.nc>).
226 Meanwhile, setting the desired critical inland elevation, z (necessarily situated above the HAT line),
227 presented several options. Based on the maximum run-up elevation observed in Indonesia in 2004,
228 for example, z could be set to 50 m [66], but such large run-up amplitudes seem highly unlikely in
229 New Caledonia given that the tsunami catalog reports a 5 m maximum amplitude in Ouvéa (Loyalty
230 Islands) for September 21, 1920 [24]. Thus, opting for $z = 10$ m appeared to be a safe limit for
231 defining terrestrial areas most at risk in New Caledonia. ‘No regrets’ elevations of 20 m and 50 m
232 nonetheless provide a broader perspective and are useful guides for planning evacuation routes and
233 refuge areas. Such variables are clearly operator-defined and depend on context. Thus, the coastal
234 fringe considered in this study is defined between the astronomical highest tide limit to the elevation
235 of 10 m.

236

237 **2.2. Step 2: inventorying buildings and population distribution**

238 **2.2.1. Buildings: location and function**

239 New Caledonia has a mean population density of 14 inhab./km², with buildings spread all over the
240 land (many often isolated and usually low-rise). For this study, the DITTT provided a vector-format
241 database which includes all infrastructure data located with a precision of ~1 m. It currently serves as
242 the database for New Caledonia (BDTOPO NC) and is used in all environmental and urban planning

243 studies on the islands. Easy to work with using GIS tools, it consists of 8 vector families: buildings,
244 drainage network, elevation, place names, roads, other networks, administrative boundaries, and
245 vegetation cover. It additionally provides a special layer of 'remarkable buildings', including public,
246 industrial and commercial buildings. Figure 3 illustrates these different types of buildings in
247 Hienghène, Northern Province. This additional layer was used to locate all potential buildings of this
248 nature within the coastal fringe exposed to tsunami-related hazards. The layer was first simplified by
249 regrouping some entities, such as all the buildings belonging to a same school. **It was also updated**
250 **for this study by adding dialysis centers (diabetes is widespread in Pacific island communities [67,68])**
251 **and facilities which may present health and environmental hazards in case of damage by inundation.**
252 Lastly, a new attribute was created to code the utility of each building and determine its function in
253 connection with healthcare, transportation, energy supply, administration, education, or leisure
254 activities.

255 Figure 3
256

257 **2.2.2. Population distribution**

258 The census carried out in 2014 provides data on nationality, gender, age, employment, but also type
259 of residence, commuting patterns, etc. [35,36]. The Grand Nouméa metropolitan area includes the
260 municipalities of Nouméa, Mont-Dore, Dumbéa and Païta. Importantly, 'squat' dwellers ('squats' are
261 makeshift urban slums) are also included in the census; they represent 5,300–8,100 people in Grand
262 Nouméa [69,70].

263 This census also provides mean population distribution by municipality. With 33 municipalities in the
264 country (average size: 562 km²), this makes the proportion of population living within the coastal
265 fringe difficult to locate. The statistics also do not provide information about residential addresses for
266 confidentiality reason, and thus altitude and distance to the coastline of individual households is

267 unknown. However, the census does break down its accounting into 2,392 smaller census wards,
268 each municipality consisting of several such units [35]. In low-density areas, these units can,
269 however, be quite extensive. The largest, Pourina Kouakoué (west of Yaté), covers 982 km² but has
270 only 3 reported inhabitants (Fig. 4).

271 To refine population distribution maps, the DITTT created in 2014 a GIS layer of the ‘population
272 clusters’ of New Caledonia. Within a given census unit, a ‘population cluster’ represents a geographic
273 area that effectively concentrates all the inhabitants of that unit. The purpose is thus to exclude non-
274 residential spaces such as green and other uninhabited open spaces. Filtering out these spaces was
275 achieved by placing a buffer around buildings standing less than 100 m apart. The minimum count for
276 each area thus defined is 10 buildings, except for large structures such as hospitals, schools, or
277 industrial plants. Inspection of the supplied GIS layer, however, revealed several omissions and
278 blunders. For this study, the DITTT GIS layer was thus updated by a population of more recently
279 constructed buildings based on a detailed Google Earth search used as a proxy form of ground truth
280 inspection. A total of 518 population clusters were defined.

281 Figure 4

282

283 **2.3. Step 3: dasymetric mapping of the coastal population**

284 **2.3.1. Available methods**

285 Spatial resolution and population density distribution are key components for correctly assessing
286 population numbers impacted by coastal hazards [71,72]. A variety of methods exists for quantifying
287 the population distribution of a user-defined geographic area that differs from census unit
288 boundaries, the latter being dictated by the convenience of data collection and suited to generating
289 choropleth maps, but ill-suited to geolocating households precisely and for inferring spatially

290 accurate population densities. They depend mainly on datasets initially available and on time
291 available for the study.

292 Low-resolution, broad-scale reconnaissance studies of population distribution for the purpose of
293 estimating exposure to coastal hazards worldwide have worked with 30-arc-second elevation data,
294 i.e., a spatial resolution of ~1 km [63]. In another study [73], the population distribution used was the
295 Gridded Population of the World (GPW) from NASA's Socioeconomic Data and Applications Center
296 (SEDAC). The spatial resolution was ~5 km, but with significant variation depending on the country.
297 At the other end of the spectrum, very high-resolution approaches can rely on the accuracy of
298 national topographic and postal address databases for locating buildings as vector data, and thus for
299 estimating resident population numbers [72,74,75,76]. A study conducted among 22 Pacific islands
300 [77] worked with GPS-located homes, except in New Caledonia where a uniform population
301 distribution among the different census units was postulated by the authors instead. The use of
302 mobile phone distribution data as global positioning systems through time is ideal but controversial
303 [78,79]. This last aspect has potential for tourist areas that are vulnerable to tsunamis, but the
304 approach still needs to assure anonymity for users given that it is potentially intrusive. Like the
305 emergency mobile alert currently in place in New Zealand [80], it could nonetheless be a huge
306 improvement in the general response to disasters.

307 In fine-scale studies of areas such as New Caledonia, where GPS address registers are unavailable,
308 where furthermore mobile phones are not universally available, and where widespread poverty at
309 least potentially implies that people exposed to natural hazards live in slums and/or do not have
310 registered addresses, coarse-resolution population data can be disaggregated with some accuracy by
311 using dasymetric mapping techniques [81,82,83,84,85,86]. In a dasymetric approach, population data
312 are redistributed from choropleth map zones to dasymetric map zones based on a combination of
313 areal weighting and the estimated population density of each ancillary class. The output is thus
314 spatially far more accurate than in the case of a choropleth map. Dasymetric mapping is achieved by

315 (i) establishing a spatial association between building data and census units to define target zones,
316 (ii) deciding the weight of each target zone by defining the importance of each building according to
317 its footprint, height, or function; and finally (iii) distributing the population of the target zone within
318 each building according to its known or estimated weight. Using the data collected as part of Step 2
319 (Section 2.2), this procedure was implemented in an opensource GIS package (QGIS) and is
320 summarized in Figure 5.

321 Figure 5

322

323 2.3.2. Defining the boundaries of built-up areas

324 A first component of dasymetric target-zone mapping involved dealing with building data. Settlement
325 patterns in New Caledonia are weakly nucleated, with frequently dispersed building even in the
326 capital city. Elements of the built-up area GIS layer were thus initially generated as combinations of
327 urban buildings and non-agricultural open spaces. The road network was not included. The method
328 consisted in outlining a buffer area within a radius of 50 m around each individual building, two or
329 more buildings ≤ 100 m apart getting aggregated into one polygon. This choice of 50 m (see [87]), is
330 consistent with the low-density urbanization pattern prevalent in New Caledonia. All the polygons
331 thus generated individually were subsequently merged into one or several larger clusters using GIS
332 'dissolve' and 'merge' tools. Lastly, a 30 m band was shaved off the outer boundary. This automated
333 trimming process generates a tighter fit around the buildings and, therefore, a more accurate map of
334 strictly urban land use. Buildings less than 100 m apart remained connected (an operator-defined
335 value chosen following numerous tests and based on context), thereby satisfying the 100 m rule
336 formulated in Section 2.2.2.

337 In summary, the built-up land cover category in this study includes every building and artificial non-
338 agricultural green space, surrounded by a user-defined, and freely adjustable based on context 20 m
339 buffer zone. The buffer zones make sense because the Caledonian lifestyle involves much time spent

340 outdoors near (often small, potentially overcrowded) places of residence rather than inside them
341 [88,89].

342

343 **2.3.3. Defining the boundaries of populated areas**

344 A further component of dasymetric target-zone mapping involved the creation of a separate GIS
345 layer of 'populated areas'. Apart from two units among the 518 'population clusters' previously
346 defined in Section 2.2.2, the remaining 516 all intersect at least one of the built-up area polygons.
347 The 'populated areas' were thus obtained by intersecting the 'population clusters' (generated in
348 Section 2.2.2) with the 'built-up areas' (generated in Section 2.3.2), as follows:

349 (i) A 200 m GIS aggregation tool was applied over the built-up areas layer to combine small and
350 disconnected map units into larger ones (because of building dispersal outside Grand
351 Nouméa).

352 (ii) Any built-up areas located less than 200 m from one of the 518 'population clusters' were
353 eligible to enter the 'populated areas' GIS layer. This procedure helped to detect potentially
354 new built-up areas that had appeared since 2014 and had not been referenced among the
355 DITTT-derived 'population clusters'.

356 (iii) Built-up areas exceeding 0.1 km² — a size which, on average, hosts with 100% certainty at
357 least 1 resident whose life may need saving in the context of a disaster — were also
358 aggregated to the GIS layer of 'populated areas'.

359 (iv) The 'populated areas' layer was subjected to the previously described 20 m buffering
360 procedure ('50 m merge' and '30 m erosion' routine) to assure a better geographic fit around
361 each element.

362

Figure 6

363

364 **2.3.4. Defining population densities**

365 The dasymetric approach subsequently calls for feeding into the map matrix precise information
366 about population numbers residing within the 'populated areas' defined above. The 'populated
367 areas' vector layer was geographically carved up along the lines of the census units (see Section
368 2.2.2), and corresponding census population values were allocated accordingly (Fig. 7; data available
369 in Supplementary Material).

370 In this study, spatial weighting was thus overall defined by a simple binary distinction between built-
371 up and unbuilt areas as given by the BDTOPO NC and DITTT databases. Finer distinctions of
372 population density distribution based on building height are unavailable for New Caledonia, but the
373 toolbox can be enriched by this kind of additional data without changing the basic dasymetric
374 approach. Building height assists in generating isopleth maps of population density, thus affording a
375 valuable increment of accuracy to the dasymetric basemap. In the context of New Caledonia and
376 many other regions and cultures, high-rise seaside construction is not, however, widespread. A
377 dasymetric approach in low-rise environments is thus less inaccurate than it would be in other
378 settings [90].

379 Figure 7

380

381 2.3.5. Focus on the coastal populated areas

382 The final stage of the mapping procedure involved restricting the full dasymetric approach to the
383 tsunami-exposed coastal fringe. Given that the population density inside any 'populated area' was
384 considered uniform by default because the census does not provide geolocated household-level
385 information, population numbers were allocated in proportion to polygon area. Thus when 70% of a
386 population polygon straddles the coastal hazard fringe, with the remaining 30% in the hinterland,
387 then only 70% of the population in that map unit qualifies as belonging to the 'coastal populated
388 area' category, as shown in Figure 7.

389 Because of the successive buffers, the ‘populated areas’ tend to overestimate the size of areas of
390 where people live. However, this somewhat compensates for the accounting lacunae in the building
391 data provided by the BDTOPO NC vector layer. An example of these lacunae concerns the ‘squats’,
392 which are not referenced or represented by map symbology in the BDTOPO NC but nonetheless
393 represent a demographic vulnerable to tsunami hazards given that such settlements often occur
394 along waterfronts. The ‘squats’ were identified based on prior knowledge of their approximate
395 whereabouts in Grand Nouméa [69,91], augmented by recent photographs [92] and by observations
396 in Google Maps as of June 1st, 2020. Figure 8 is the result of this procedure, thus capturing within the
397 ‘populated areas’ any potentially vulnerable slums initially unreported by the source data.

398 Figure 8

399

400 2.4. Step 4: pilot survey of tsunami hazard perception

401 Rescue services are continuously trying to find out how the public will react to catastrophic events to
402 know how to manage a crisis effectively [93,94], but the public also “relies on risk perceptions to
403 evaluate hazard situations” [95]. Both the emergency management authorities and the public thus
404 gain from learning about how they each perceive the hazard, thereupon improving on skills and
405 behaviors suited to hazardous events. Existing gaps between the reality of a hazard and the social
406 perception of it [96] can be amplified or attenuated depending on education to hazards, personal
407 and subjective experiences, and one’s own beliefs or ideology [97,98]. Collective memory of risk [99]
408 is also a component of hazard awareness. Trying to precisely date or locate a past disaster, however,
409 is often difficult [100]. Risk memory tends to be short and distorted, particularly after a long hazard-
410 free period [101,102]. In New Caledonia, a partial collective memory loss of tsunami events has been
411 reported even within oral tradition: spaces previously impacted by marine inundations are now
412 reoccupied [103]. **These various, interrelated issues explain why communities can be underprepared**
413 **for disasters [3]. An important component of the vulnerability assessment toolbox presented herein**

414 thus focuses on collecting and analyzing data about how the population of New Caledonia perceives
415 tsunami-related hazards.

416

417 **2.4.1. Survey methodology**

418 Analyzing risk perception involves psychometric studies that quantify the factors and consequences
419 of risk through survey tools [97,104,105]. Selecting the sample of interviewees is an essential basis
420 for producing meaningful risk perception studies. For a large population, questionnaire methods
421 ideally allow a statistical treatment of spatial information (place of residence, distance from the
422 danger zone) as well as providing demographic, social, environmental, and cultural data about the
423 respondents. It then becomes possible to match response profiles with population profiles, and
424 consequently to characterize collective categories of discourse and practice [106]. Questionnaires in
425 the form of a list of closed or open questions that target certain themes or issues are commonly used
426 [107,108,109] and show the complexity and diversity in perception and preparedness among
427 interviewees [110,111]. Letting people put across their point of view, elaborate on their answers, and
428 measure the learning trajectory from a situation of low awareness / knowledge of the hazard to their
429 behavior during an effective crisis is also important [104,112].

430 Here, ethnographic 'thick description' and other time-consuming methods were ruled out for
431 practical reasons, opting instead for the efficiency of a rapid assessment survey. The survey was
432 based on quota sampling and was aimed at capturing the spontaneous feelings of people [113] in
433 order to gain an overview of their reactions in the event of a tsunami alert, arrival or inundation. The
434 survey was underpinned by a set of seven questions (Table 1) allowing respondents to answer as
435 freely as possible about tsunamis as potential threats to their daily lives. The survey was conducted
436 verbally, and IT tools were ruled out (the use of a smartphone, suited to obtaining complete answers
437 and to automated data classification was tested at first, but was found to disturb the respondents
438 [108]). The vocabulary used was chosen and adapted to all potential types of interviewees to avoid

439 discomfort or misunderstanding, and therefore to avoid biased replies [106]. It was decided not to
440 interview children under the age of 10 because of potential comprehension issues. This lowered the
441 national target population from ~269,000 to ~227,000. The written data were subsequently entered
442 into a spreadsheet to facilitate data classification and statistical analysis.

443 Several items of information were recorded from each respondent before asking the questions
444 relating to tsunamis:

445 (i) country of birth. If the answer was New Caledonia: then in which town; otherwise: how long had
446 they lived on the island.

447 (ii) place of residence in New Caledonia. If the answer was Nouméa: in which neighborhood.

448 (iii) age groups: 10–19 years old; 20–39; 40–59; 60 and over.

449 The influence of place of birth and age were considered key factors of interest for a study on tsunami
450 risk perception because most of the resident population of the Northern Province is Kanak, and the
451 east coast furthermore faces the Vanuatu trench. Age group provides information on education to
452 tsunami risk. Place of birth is helpful for studying the impact of historical knowledge and memory on
453 tsunami-related risk. This knowledge is transmitted down the generations through the observation of
454 natural phenomena such as the sea receding before the surge [114] and through an oral tradition of
455 stories and lullabies on islands of the Pacific [115] such as Hawai'i [116], Mentawai islands [117], New
456 Zealand [39,118,119], and New Caledonia [24,120]. Also, several tribes (who live in Kanak villages)
457 have experienced tsunamis in the past, as at the village of Mu on Lifou, Loyalty Islands [103]. The
458 communities have transmitted an awareness of that risk to their children through memory-based
459 narratives.

460 The seven questions were written, tested, and discussed among research team members before
461 asking them in French or in English depending on the respondent's language. The effectiveness and
462 quality of the rapid survey also hinged on sequencing the questions following a pattern that allowed

463 smooth transitions (see 'Methodological notes' column in Table 1) so that respondents could remain
464 engaged throughout the rapid survey [121].

465 Table 1

466

467 **2.4.2. Organization in the field**

468 Carrying out a survey experiment across all New Caledonia was difficult to achieve timewise.
469 However, 66% of New Caledonia's population lives in Nouméa, and the capital city is also home to
470 most non-native residents [36]. The survey was thus carried out over several days not only in several
471 districts of Nouméa (Fig. 8), which, as the human hub of the archipelago, offers a natural mix of local
472 and provincial residents on its streets and in public spaces, but also in Lifou (Loyalty Islands) and on
473 the Isle of Pines, where tsunamis are documented. Target survey areas were thus located:

- 474 (i) in the south of the city along the bays and in Motor Pool district, where most non-natives live
475 and where native islanders visit during weekends and school holidays.
- 476 (ii) in the city center, which is the commercial hub and starting point for public transport and taxis.
- 477 (iii) on Nouville peninsula, frequented daily by fishers and walkers as well as a major slum area.
- 478 (iv) in Magenta district, near the aerodrome, where islanders flock daily to the morning market.

479 The survey was carried out over several days and at different times: in the early morning during
480 market time in Magenta and the city center, early afternoon on the beaches when most crowded,
481 and evening along the bays. This diversity of time and location avoid overrepresenting certain types
482 of interviewee [106]. Before each survey, the place was chosen but the precise canvassing route was
483 not predefined (the investigator was free to target the town square, public garden, beach, etc.).

484

485 **3. Results**

486 **3.1. Mapping results**

487 The results presented here focus on Nouméa because it concentrates the largest population, and on
488 Lifou, where urbanization is sparse. However, an atlas for each of the 33 municipalities of New
489 Caledonia is provided in the Supplementary Material. Maps are shown for both areas in Figures 9 and
490 10. They highlight the following evidence:

491 (i) Figures 9a and 10a represent all the ‘populated areas’ for one municipality. Note the strong
492 contrast between Lifou, with 38 polygons totaling 1,207 km² but only 3.4% of them (41 km²)
493 counting as ‘populated areas’; and Nouméa, with nearly 100% of urbanized land cover.

494 (ii) Figures 9b and 10b highlight buildings for front-line services such as rescue and health centers,
495 transport services, educational establishments, and energy production plants. Half of these
496 essential buildings in New Caledonia are located less than 10 m above sea level and more than a
497 quarter of them within the 0–5 m coastal fringe. Half of the rescue centers and fire stations
498 likewise lie below the 10 m contour, i.e., within the estimated inundation hazard zone.

499 (iii) Figures 9c and 10c show graphs of the proportion of residents in three user-defined coastal
500 fringes (below 50 m, below 20 m and below 10 m).

501 (iv) Figures 9d and 10d outline the ‘coastal populated areas’ within the 50 m potential hazard fringe.
502 Almost 100% of the population of Lifou, and 94% in Nouméa (i.e., n = 94,384), lives below the 50
503 m contour.

504 (v) Figures 9e and 10e outline the ‘coastal populated areas’ within the 10 m potential hazard fringe.
505 Less than 21% (n = 1,950) live within the 10 m coastal fringe in Lifou, and 41% in Nouméa (n =
506 40,803).

507 Figure 9

508 Figure 10

509 Overall, it is estimated that 87% of New Caledonia’s population lives within 0 and 50 m. Likewise,
510 55% and 33% of the population live below 20 m and 10 m respectively. Table 2 shows the percentage
511 of residents by municipality and by user-defined coastal fringe: this is a tool for understanding where
512 the greatest disaster-management challenges are located. While 97% of inhabitants in Ouvéa live in
513 the 10 m coastal fringe, this number falls below 1% for municipalities such as Sarraméa or Farino,
514 which are located higher up. The data in Table 2 are illustrated in the graphs for each atlas map in
515 the Supplementary Material. It clearly shows large differences in population numbers between two
516 coastal fringes, as in the example of Lifou where the coastal topography displays a staircase of wave-
517 cut terraces (Figure 9).

518 Table 2

519

520 3.2. Perception survey results

521 Given the time and resources available, 413 individuals were approached in total, with only 11
522 refusals and covering a very broad spectrum of the population: native islanders and non-natives
523 living in Nouméa, native islanders living elsewhere among the islands, and non-natives not living in
524 Nouméa but present in the capital for work or holidays. Figure 11 maps the municipalities of
525 residence of the respondents. A large majority of the surveyed population (80.4%) lived in Greater
526 Nouméa (Nouméa, Dumbéa, Païta, and Mont-Dore), and more than 12% were from the Loyalty
527 Islands.

528 Figure 11

529 The extremely high response rate compared to rates commonly reported for questionnaires and long
530 interviews can be explained by the fact that (i) most people were surveyed at a moment of the day
531 when they had some time to spare, and (ii) the questions were short and limited to 7. **The survey**
532 **took an aggregate of 20 hours to be completed by four interviewers, and adequate time was granted**

533 to obtain detailed answers to the open questions. The questions generally interested the
534 respondents and motivated them to develop their answers or even debate on the subject. Most
535 people were concerned about the tsunami hazard, but some of them clearly felt insufficiently
536 informed about the associated risks in New Caledonia. The main trends in the answers given to each
537 question are presented below. Binary responses to closed questions are simple to classify, whereas
538 answers to open questions require a recategorization process prior to analysis. Some proportions are
539 given to show significant similarities or differences between native and non-native groups, or
540 between age groups below and above 40.

541

542 3.2.1. Answers to the two open questions

543 The first open question yielded 18 different answer categories. Certain categories were combined to
544 reduce the total to 9 separate classes. Choosing how to combine answers was based on the main
545 image that emerged from the answer. For example, the class “find a safe place (shelter)” includes
546 responses such as “I go home” and “I find a refuge.” The classes also consider the different answers
547 provided by a same respondent, even when they were contradictory. For example, some people
548 explained that, following a tsunami alert, they would move to higher ground, but they would also try
549 to go home to find safety even though their house was close to sea level. The results in Figure 12
550 thus present the raw data.

551 Figure 12

552 Figure 13 illustrates answers concerning elevation. In the event of a tsunami alert, ~88% of the
553 respondents said they would want to move from their location to a place that was safer for them.
554 More than 73% specified the need to access higher ground; half (36.2%) noted that reaching higher
555 ground would be strategic.

556 Figure 13

557 Respondents provided a range of 13 different answer categories to question 2 on protective
558 landscape elements against tsunamis (Fig. 14). Three main categories stand out: height relative to
559 the coast, natural ecosystems as effective barriers, and the built environment. Precise proportions
560 are given in the table embedded in Figure 14.

561 Figure 14

562

563 3.2.2. Answers to the closed questions

564 Tables 3 and 4 summarize the results, which are commented here via the letter superscripts (a) to (f)
565 indicated in those two tables.

566 Table 3

567 Table 4

568

569 3.2.3. A preliminary hazard perception map

570 Question 4 was addressed to the ~80% of respondents who considered that the tsunami hazard was
571 real. It promotes a geographical and mental visualization of the hazard (Fig. 15). Each color on the
572 map indicates a zone perceived by the respondents as presenting a certain level of tsunami threat,
573 ranked into 4 perceived risk intensity classes. Both the Loyalty Islands and the east coast of Grande
574 Terre (because “it is right behind the Loyalty Islands”) are mentioned far more than other locations,
575 especially among respondents above age 40. Almost 5% of the surveyed population made the
576 (scientifically correct) link between tsunami-related hazards and geographic location of the nearby
577 Vanuatu fault zone. Some also explained that the threat would be greatest at gaps in the coral reef
578 since gaps can amplify the phenomenon.

579 Figure 15

580

581 **4. Discussion: policy recommendations and toolbox adaptations**

582 This study focused on two methodological components of an approach aimed at improving disaster
583 response management among decision makers: (i) how to locate and quantify vulnerable residents as
584 precisely as possible without overstepping certain ethical boundaries (privacy, etc.) and with limited
585 data; and (ii) how to capture the general perception of tsunami hazards by the local population. Here
586 we discuss the strengths and weaknesses of current achievements in the warning, protection, and
587 preparation of the population to tsunami hazards in New Caledonia, with potential implications for
588 other island environments.

589

590 **4.1. Toolbox application no. 1: warning the population with a siren system**

591 Although the earthquakes with epicenters located in the Vanuatu subduction zone are regularly felt
592 in New Caledonia, the ones located elsewhere along the Pacific Fire Belt, and able to trigger
593 transoceanic tsunamis, are never perceived in the New Caledonia archipelago [23]. A first step to
594 answer this immediate threat is to develop warning systems, including earthquake and tsunami
595 monitoring, siren deployment, text-messaging systems, radio information, social networks, and risk
596 alert apps. All these components play an essential role in alerting the population about imminent
597 tsunami-related danger and must be fully understood to be useful and efficient on the day [110].

598 In New Caledonia, a siren network managed by the DSCGR was set up in 2014. As of June 2020, there
599 are 79 active sirens located mainly on the east side of Grande Terre and on the Loyalty Islands. The
600 range of each siren is 2 km. The DSCGR has already planned to install 92 additional sirens facing the
601 Vanuatu subduction zone, and in densely populated strategic areas like Grand Nouméa (Fig. 16).

602 The tsunami warning system can be confused with other emergency signals for fires, industrial
603 accidents, etc. [122], as reported in Nouméa during the tsunami alert of December 5, 2018. Similar
604 situations have been described in New Zealand where, depending on their whereabouts, people
605 could either hear both signals from two neighboring towns or not hear them at all [110].

606 A spatial intersection between the coverage of sirens in service, the planned siren coverage, and the
607 'populated areas' helps to quantify the number of inhabitants likely to hear the alert in the
608 foreseeable future. This GIS-based method can be applied to other geographic contexts and for other
609 hazards. Table 5 identifies the proportion of people living in the range either of sirens already in
610 service or of the entire future warning system for several geographic areas and under two scenarios.
611 The data show that current coverage concerns 15% of the 'populated areas', meaning that 20,687
612 New Caledonians (8% of the total population) can hear the alert: a relatively small figure that
613 highlights the current absence of sirens in Grand Nouméa. Among the 63% of survey respondents
614 aware of the existence of sirens, nearly 34% of native respondents reported having already heard the
615 signal. Moreover, alerts are sounded outside Grand Nouméa, mostly in the Loyalty Islands or on the
616 east coast, where native communities are dominant (94%, for 95,000 native inhabitants [36]). This
617 highlights that 100% of native islanders not living in Grand Nouméa have already heard the alert.
618 Ratios are quite good in those regions below the 10 m elevation contour and should improve
619 palpably (all above 80%) with the 92 forthcoming new sirens. With 28 sirens planned in Grand
620 Nouméa, 12 others will be located in major towns along the west coast, and the remaining 52 placed
621 at strategic locations within the 'populated areas' defined by this study. Some gaps still exist in the
622 south of Grande Terre and in Ouvéa (in Figure 16, some of the 'populated areas' in red are covered
623 neither by current or by planned sirens). A new strategic plan for a few more sirens in coastal
624 population hotspots below the 10 m contour would rank the New Caledonia siren network as
625 exceptionally good. Almost all residential areas would be fully covered, and through public training
626 sessions and educational programs, awareness of the siren warning system could improve rapidly.

Figure 16

627
628

629 **4.2. Toolbox application no. 2: protecting the population with healthy ecosystems shields**

630 During the December 5, 2018 tsunami, the sea rose by about 2 m in some places, such as on the east
631 coast of the Isle of Pines where it circled around a big resort and struck the only bridge connecting it
632 to the main island. The surge uprooted trees and could have swept people away if they had not been
633 evacuated quickly. The video discussed in Roger et al. [13] demonstrates how not just the advancing
634 wave, but also the strength of currents caused by tsunamis remains an important danger and is often
635 overlooked [123,124]. Another strategy for mitigating tsunami-related hazards in the long term is
636 thus to promote healthy ecosystems as population shields (Fig. 2). The survey questions raised the
637 issue: although most answers emphasized the urgency of reaching high ground, almost 60% of
638 respondents revealed that either reefs (14%), or mangroves (20%), or both (26%), could be part of
639 the hazard mitigation equation.

640

641 **4.2.1. The coral reef**

642 The survey showed how almost half of the respondents felt protected from marine inundations by
643 the reef barrier, some of them having learned at school about the attenuating effect of reefs. Studies
644 on this topic are scarce, and experimental results or field observations often divergent. Thus,
645 although most of these studies estimate that friction by the coral reef would in some cases reduce
646 the energy of the tsunami (i.e., a healthy coral reef displaying structural complexity and a high coral
647 cover area will enhance the wave friction factor and substantially improve coastal protection
648 [125,126]), reef distance from the coast and openings in the reef could also influence wave
649 amplification in the lagoon before striking the shoreline (for tsunamis, see [127,128]; for storms, see
650 [129]). Thus, a continuous coral reef can prove to be an effective barrier to the propagation of low-

651 amplitude tsunamis if there is no disturbing gap [127,128,130]. In support of this independent
652 evidence, Andréfouët et al. [131] mention the case of several discontinuous fringing reefs facing
653 localities already affected by tsunamis (case of the 1875 tsunami, considerably impacting the village
654 of Mu on Lifou). **The overall conclusion is that many parameters enter the equation and further
655 scientific investigations must be conducted.** This is echoed by 11% of respondents, who explained
656 (based on either intuition or memory) that the reef is only partly protective, or that it depends on
657 other reef-related conditions. Four interviewees also specified that the largest tsunami risk occurred
658 at locations facing the gaps in the reef, a response empirically consistent with the laws of wave
659 refraction.

660 In terms of policy recommendations, managing tsunami risk in New Caledonia and in other similar
661 islands context should give priority to refining reef mapping and bathymetry, **assess accurately the
662 role of the New Caledonia reef in terms of tsunami protection**, surveying coral health conditions in
663 areas directly facing the 'coastal populated areas' defined in this study, and subsequently promote
664 an educational program to show the potential value of the coral reef as a first line of defense and
665 provider of multiple ecosystem services [132].

666

667 **4.2.2. Mangroves**

668 More than half of the survey's respondents felt protected against marine inundations by the
669 mangrove, thus even more than by the barrier reef. This tendency is particularly clear among native
670 islanders and in the above-40 age group (Table 4), highlighting a strong culture of risk awareness still
671 present among Kanak natives and the older demographic. In support of this, several discussions in
672 the field showed how native islanders respect and understand the usefulness of mangroves much
673 more than other inhabitants: for example, several mangrove restoration programs are taking place
674 around Grande Terre like in Touho, Northern Province.

675 Mangroves, however, cover only 0.12% of the world's total land area [133] and have been receding
676 worldwide by up to 35% [134] as a consequence of deforestation [135], sea-level rise [136,137,138],
677 beach-sand mining, and the various environmental impacts this inflicts on the trees
678 [139,140,141,142]. Although a loss of 14.5% of mangrove land cover in New Caledonia has been
679 anticipated between now and the year 2100 [143], apart from Nouméa (where several areas of
680 mangrove were destroyed in the last 150 years) New Caledonia is an island where mangroves remain
681 comparatively well preserved.

682 Mapping and investigating the health of mangrove forests facing the 'coastal populated areas'
683 defined in this study would help to identify the level of protection this ecosystem provides to the
684 coastline and to its residents. The percentage of mangrove-lined coast in New Caledonia was
685 estimated as follows: a 20 m GIS buffer was generated around mangrove areas, and parts of the
686 coastline disconnected from the lagoon by a dense mangrove zone were also included. Results show
687 that 48% (2,843 km) of the New Caledonia coastline is lined by mangroves, particularly on the west
688 coast. The east coast and other islands host fewer mangroves. A similar process was used to
689 determine how much of the 'coastal populated areas' (i.e., 1,464 map units below the 10 m contour,
690 hosting 90,009 residents according to the 2014 census) are mangrove-lined. Depending on the
691 buffering criteria used, the inventory indicates that between 382 and 721 of those 'populated areas'
692 are potentially shielded by mangrove areas.

693 This preliminary estimate shows that between 22 and 49% of the population living below the 10 m
694 elevation contour is located behind a mangrove-lined coastal defense and is *a priori* more protected
695 than the population directly exposed. The SOCPacific project (<https://socpacific.net/>) workshops in
696 November 2019 gave a voice to children in Touaourou, and a 10-year-old explained that "we plant
697 mangroves so that we are cleaner and so that the waves break on them". Given that mangroves also
698 provide ecosystem services as fish hatcheries and marine wildlife nurseries [144], the urgent
699 restoration of mangroves in the unprotected 'populated areas' is a low-cost, sustainable, and

700 effective way to protect communities from marine inundation effects while enhancing their
701 livelihood potential.

702

703 **4.3. Toolbox application no. 3: preparing the population through risk awareness**

704 In the collective imagination, tsunamis remain associated with terrible waves destroying everything
705 in their path, similar to what the media displayed for the 2004 Indian Ocean and 2011 Tōhoku
706 tsunamis. Moreover, risk memory tends to be distorted or erased when no hazard strikes for a long
707 time [3,101,102]. **New Caledonia is no exception.**

708

709 **4.3.1. The tsunami perception survey as a wake-up call**

710 The preliminary survey presented in this study highlights how nearly 80% of the respondents were
711 aware of the existence of a tsunami hazard in New Caledonia. According to 70% of the respondents,
712 the largest tsunami hazards arise (i) in the Loyalty Islands, (ii) on the east coast, and (iii) on the Isle of
713 Pines, where historical tsunamis have scarred memories and landscapes [23,24,103]. The results
714 show a certain global awareness of the tsunami hazard in the archipelago. Response patterns by
715 place of birth show that 76% of native islanders against 53% of non-natives identify those three
716 locations as vulnerable. Likewise, 23% of non-natives, but only 9% of native islanders, stated that
717 tsunami hazards did not exist in New Caledonia, some of them specifying that they had never heard
718 about or seen large waves along the coast. About 30% of non-natives over age 40 replied that no
719 tsunami hazard existed in New Caledonia, compared with 8% among the native generation in the
720 same age group. The gap narrows for the generation under 40: 17% against 9%, respectively, but the
721 pattern overall can be explained by historical ignorance about tsunamis and an absence of
722 transmission among non-natives before the publication of recent studies [23,24,103]. It also

723 highlights the contribution of intergenerational memory among native islanders, especially after the
724 large tsunamis of the past hitting the Loyalty Islands.

725 Since economic activities in New Caledonia mainly focus on fishing, maritime export (minerals, etc.),
726 and tourism, the coast is heavily populated and has been increasingly so over the years. The GIS
727 maps generated with this study show that 33% of the population lives below an elevation of 10 m.
728 Furthermore, apart from Grand Nouméa and a few other towns, most of the land in New Caledonia is
729 private. Culturally, occupation of the coastline is also a matter of belonging to the land by claiming it
730 [145], and this can lead to oversights of empirical knowledge concerning coastal hazards. Thus, the
731 generation that experienced previous tsunamis and had marked out the land areas affected by
732 marine inundation is disappearing and, with it, part of the collective memory that was ordinarily
733 passed on.

734 Reviving this risk culture and risk memory involves periodic communication to keep people updated
735 on individual and common safety measures. The rapid risk perception survey carried out for this
736 study was part of this communication effort: it sparks the interest of the respondents and provides
737 insights into the disparities in culture and education within the population. It was based on a total
738 sample of 402 respondents. Online sample-size calculators, which are based on standard equations
739 used in statistical power analysis and survey sampling techniques [146,147], recommend surveys of
740 representative minimum sample sizes that vary as a function of target population size. At the 95%
741 confidence level, the sample obtained for each age or birth (native or non-native) class in this pilot
742 study provided results with an error margin of 6 to 12%. To reduce error margins to the
743 conventionally acceptable 5% confidence level and attain the quantitative robustness required for
744 political decision-making, it would be necessary to increase sample sizes in each of the above
745 statistical classes to between 100 and 300 depending on total class population, i.e., in total
746 somewhat more than 402. Clearly, such street surveys are time consuming and labor-intensive, but
747 the survey shows that a representative study for a total population of ~230,000 (young children

748 excluded) can be a rewarding ‘first shot’ without going through major operations and could be
749 implemented on many other islands of a similar or smaller population size in the Pacific, Indian,
750 Caribbean and Mediterranean. To go further on communication strategies, it would be also relevant
751 to conduct longer semi-structured interviews with a shortlist of key informants.

752

753 **4.3.2. Improving population mapping accuracy to expand hazard awareness to all**

754 Given its tropical landscapes, reputation for coral biodiversity in the lagoon, mild weather, and
755 traditional way of life, New Caledonia is an attractive region for seaside tourism (water sports,
756 boating, whale and underwater fauna watching [88]). As part of the pilot survey, 15 tourists from
757 France, Australia, New Zealand, Japan, the United Kingdom and Poland were questioned: eight of
758 them were unaware of tsunami hazards in New Caledonia, even among populations who know this
759 risk quite well (e.g., Japan). Thus, any large-scale study at the next scheduled census should also
760 expand to non-residents and tourists. The annual synthesis of tourist frequentation carried out in
761 2018 estimates at 120,340 the number of tourists arriving at Tontouta international airport, and at
762 456,000 the number of cruise passengers, i.e., more than double the resident population. **Most flock**
763 **to the coast. Similar figures can be found on other Pacific islands [148,149], highlighting the urgent**
764 **need to (i) map local and tourist populations and their interactions in order to refine population**
765 **distribution, and (ii) deploy a communication strategy about tsunamis or other natural hazards for**
766 **visitors on arrival [150].**

767 In light of these observations, our methodology for mapping the coastal population generates a static
768 representation of vulnerable areas. No distinction is made, for example, between daytime and
769 nighttime: large industrial or commercial areas are included in the ‘populated areas’ but are only
770 occupied during the day. Fishing is a common activity in New Caledonia [89], but details on activity
771 patterns are scarce. Similarly, figures about tourist frequentation of small islands vulnerable to
772 tsunami hazards off the mainland (where $z < 5$ m) are currently unavailable. More precise statistics

773 could also be gained from including roads in the built-up areas GIS layer, combined with day- and
774 nighttime analysis of population presence and interaction. One solution, used in several countries
775 during the 2020 international Covid-19 crisis, proposes to track people using data provided by their
776 mobile phones, a way to gather data at different times of the day [78]. Should data relating to
777 population dynamics ever become available, the work on 'populated areas' could be refined by
778 monitoring those dynamic parameters.

779 The population mapping work produced here is the first of its kind in New Caledonia and benefits not
780 only tsunami hazard assessment but also all other natural and industrial hazards and any other
781 applications where a dasymetric approach to population distribution is needed. Even though these
782 maps are accessible to all, many interviewees (as also reported elsewhere around the Indian Ocean:
783 [105]) urged for more public information on tsunami-related hazards. Awareness campaigns could
784 thus be necessary to reactivate fading knowledge and jog the collective memory of tsunamis, while
785 also drilling the population to understand the warning systems and accept security training after a
786 crisis and/or housing relocation above the hazard area [151]. A first communication tool is the wide
787 circulation of brochures (Fig. 17). Producing attractive GIS-based maps of the tsunami hazard and
788 displaying them around cities and tsunami risk areas would be another important educational tool
789 [152,153]. Live risk simulations in schools or at work meetings is also a dynamic tool for enhancing
790 awareness and learning. The ultimate aim is to engage the population in tsunami prevention and
791 communication [43]. In the spirit of CBDRR (see Section 1), Ouvéa Island has elaborated maps co-
792 designed by scientists, local managers, and residents to assess their vision of the risk and their
793 possible concerns and questions [154]. This participatory and collaborative mapping in that context
794 fully becomes 'citizen mapping' [155], enhancing collective risk memory, risk culture, and potentially
795 improving population resilience [156,157].

796

Figure 17

797

798 **5. Conclusion**

799 New Caledonia is a large insular region previously never studied from a disaster risk reduction
800 perspective. Using these tropical islands as a testing ground, this paper showcases what can be
801 achieved with a relatively simple toolbox based on two classes of low-cost instrument: (i) GIS
802 mapping using opensource software to produce maps and atlases, which in themselves can serve as
803 important, and potentially dynamic tools for communication and education with the public as well as
804 with emergency management authorities; and (ii) the conduct of rapid risk perception surveys, for
805 which sample size can be adjusted as a function of target population size and time and resources
806 available, always in full knowledge of the associated error margin for a given confidence level (and
807 thus of the statistical robustness of the results). This two-pronged approach can potentially be
808 implemented over a reasonably short time in many contexts and can yield useful results suited to the
809 lift-off of more detailed and ambitious DRR projects, leading thereafter to more refined decision-
810 making tools as data collection expands.

811 Precision mapping of the built environment and of population distribution based on dasymetric
812 techniques is a tool for establishing where people live over potentially vast areas. Its accuracy
813 depends on the databases initially available, and the approach can be tailored to specific needs and
814 hazard types and distributions — for example, a user-defined coastal fringe based on elevation
815 criteria in the context of tsunami-related and other coastal hazards.

816 This study has established that 33% of New Caledonia's population on Grande Terre lives in the 10 m
817 coastal fringe; the proportion rises to 97% on Ouvéa (Loyalty Islands). New Caledonia was also used
818 as a testbed for a tsunami risk perception survey based on carefully crafted and sequenced short
819 questions aimed at capturing knowledge levels about the hazard (almost 80% think that a tsunami
820 hazard exists in New Caledonia), behavioral patterns (73% would aim for higher ground), and disaster
821 preparedness. Population awareness is a strong component of contingency plans in response to
822 tsunami-related risk, and the rapid risk perception survey was a tool entirely new to the island.

823 Perhaps because of this, it received a response rate close to 100%, suggesting that similar
824 assessments could be deployed on other Pacific islands where populations are comparable or
825 smaller, and tourism industries proportionally larger.

826 Thematic mapping of the coastal fringe also captures patterns of spatial association between
827 population clusters and potentially protective occurrences of buffering ecosystems either on-
828 (mangroves) or offshore (reefs). Preserving or restoring such natural ecosystems is a cost-effective,
829 long-term step towards achieving an efficient disaster response system to marine inundation hazards
830 (51% and 45% of survey respondents were convinced of it in the case of mangroves and reefs,
831 respectively), even though the efficiency of those ecosystems can vary and requires case by case
832 investigation. The historical destruction of those protective ecosystems by urbanization and mass
833 tourism have multiplied and magnified factors of human vulnerability to natural hazards, also
834 entailing a loss of risk culture and knowledge. Figure 18 summarizes the results obtained from the
835 different approaches implemented in this pilot study of New Caledonia.

836  Figure 18

837 The data, tools, and mixed methodologies combined in this paper can be transferred to other
838 disaster risk reduction contexts. Topographic and bathymetric data in New Caledonia itself could, for
839 example, be updated to very high-resolution mapping and DEM with the use of LiDAR technologies.
840 Closed questions such as those included in this rapid survey would gain from being added to the
841 forthcoming national census questionnaires, next scheduled for 2023. The population mapping
842 methodology provides a broad basis for future research work on population vulnerability or in
843 cognate fields where there is an urgent need to know more precisely where people live and what
844 their movements are. The study also revealed a gap in the BD TOPO NC concerning slum areas
845 ('squats'), a useful lesson for other similar studies in other parts of the world, where precarious
846 housing settlements may be absent from spatial databases. This must be compensated by using

847 satellite imagery calibrated against field surveys to visualize all housing types and make sure that the
848 administration of safe spaces through risk management science is systematic and socially just.

849

850 **Author contributions**

851 **BT:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing - Original
852 draft preparation; **JR:** Conceptualization, Methodology, Resources, Writing - Original draft
853 preparation, Visualization, Supervision; **YG:** Methodology, Resources, Writing - Review & Editing,
854 Visualization, Supervision; **CS:** Methodology, Resources, Writing - Review & Editing; **JA:** Funding
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856

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867

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1319

1320 **Figures**

1321 Figure 1. Population by municipality in New Caledonia. Black lines: municipality boundaries; each
1322 Loyalty Island, Bélep Islands and the Isle of Pines correspond to distinct municipalities. Red squares:
1323 main towns. Purple dashed line: boundary between the Northern and the Southern Provinces. Data
1324 from [35].

1325 Figure 2. Mangroves (data from
1326 <https://geo.data.gouv.fr/fr/datasets/6dbcfb633c48a8b9c3a121ab1e464de9383a2f27>) and coral-reef
1327 ecosystems [48] in New Caledonia. Black frame in (a) locates La Foa in (b).

1328 Figure 3. Buildings dataset laid over shaded topography around the town of Hienghène. Public
1329 buildings (in red) are listed from 1 to 13. Blue: mostly private residential housing. Contour interval:
1330 20 m. Data from <https://georep.nc/>.

1331 Figure 4. Population density of New Caledonia by census unit. Black frame in (a) locates panel (b).
1332 Data from [35].

1333 Figure 5. Methodology used for dasymetric mapping of the coastal population of New Caledonia
1334 potentially vulnerable to tsunami-related hazards. Text in blue: vector data provided by public
1335 agencies. Text in black: vector data generated by this study. Text in green: major steps in the
1336 dasymetric method. See Figure 4 for census unit boundaries, and Section 2.3 for definitions of
1337 population cluster, populated area, coastal populated area, and coastal fringe.

1338 Figure 6. Superposition of a population cluster (red) with several built-up land-cover polygons
1339 (yellow) and with buildings (gray). Example provided: municipality of La Tontouta.

1340 Figure 7. Schematic dasymetric evaluation of residents in 'populated areas' and 'coastal populated
1341 areas'.

1342 Figure 8. Areas (red circles) canvassed for the tsunami perception survey in Nouméa. Green stars:
1343 slums. Gray lines: street grid.

1344 Figure 9. Population distribution on Lifou island.

1345 Figure 10. Population distribution in Nouméa.

1346 Figure 11. Places of residence of survey respondents (n = 412). Red discs: proportions of surveyed
1347 people by municipality (exact values).

1348 Figure 12. Pattern of answers to Question 1: "What is your first reaction in the event of a tsunami
1349 alert?".

1350 Figure 13. Answers mentioning "elevation" ratings in Question 1: "What is your first reaction in the
1351 event of a tsunami alert?". Note: 10x10 squares = 100%.

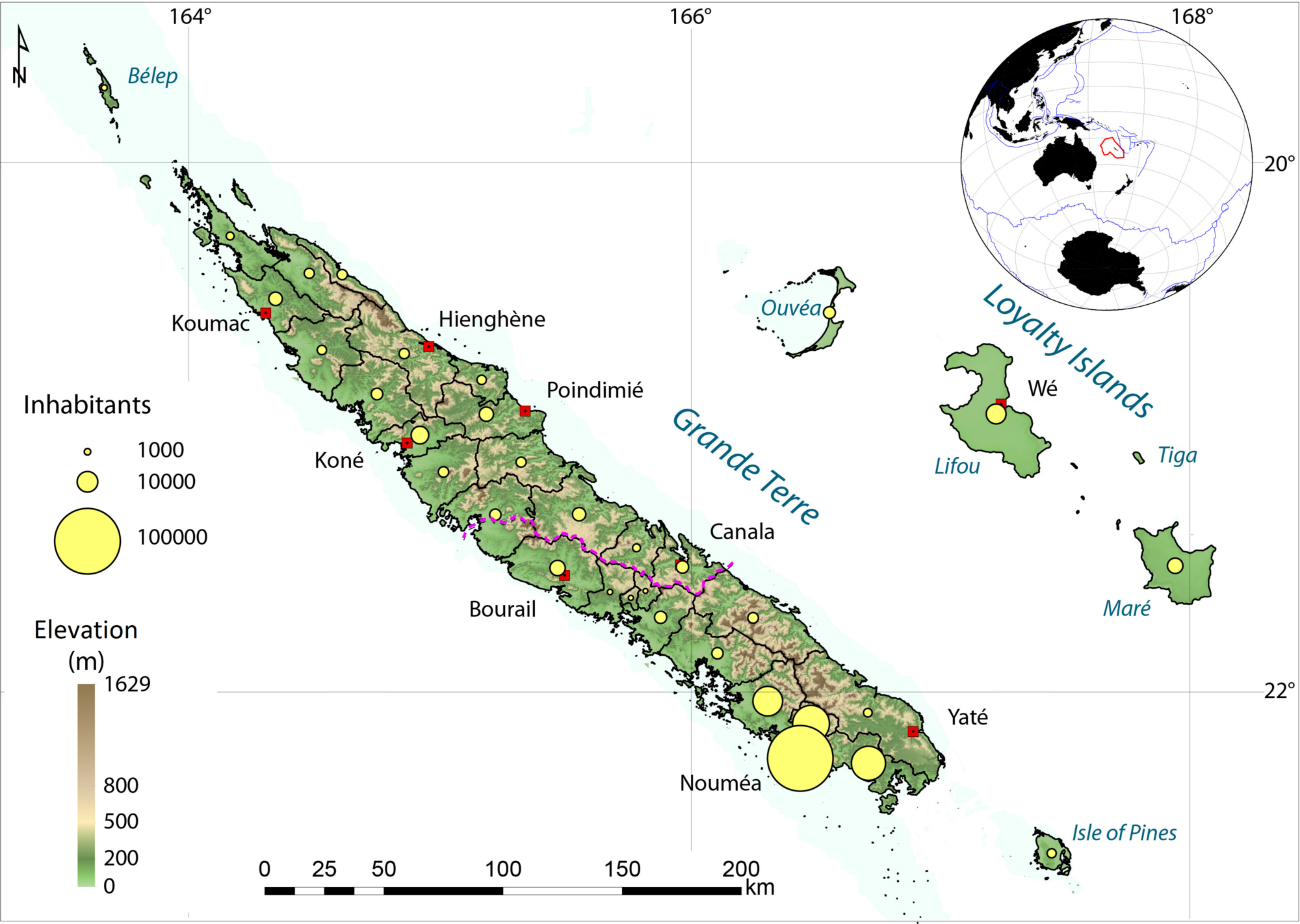
1352 Figure 14. Pattern of answers to Question 2: "Have you identified any features in your immediate or
1353 more distant environment that might protect you from tsunamis?".

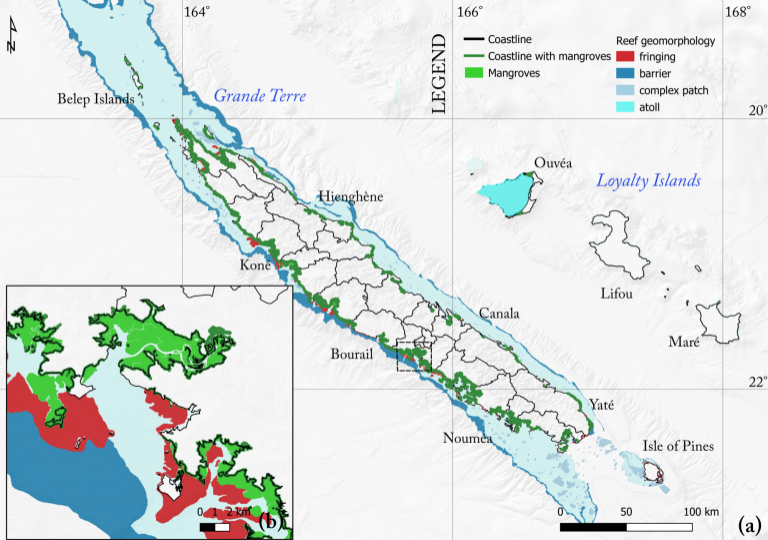
1354 Figure 15. Pattern of answers to Question 4: "If you think a tsunami hazard exists in New Caledonia,
1355 where is it most threatening?". The map is a geographic representation of the five perceived areas of
1356 largest tsunami threat given by respondents.

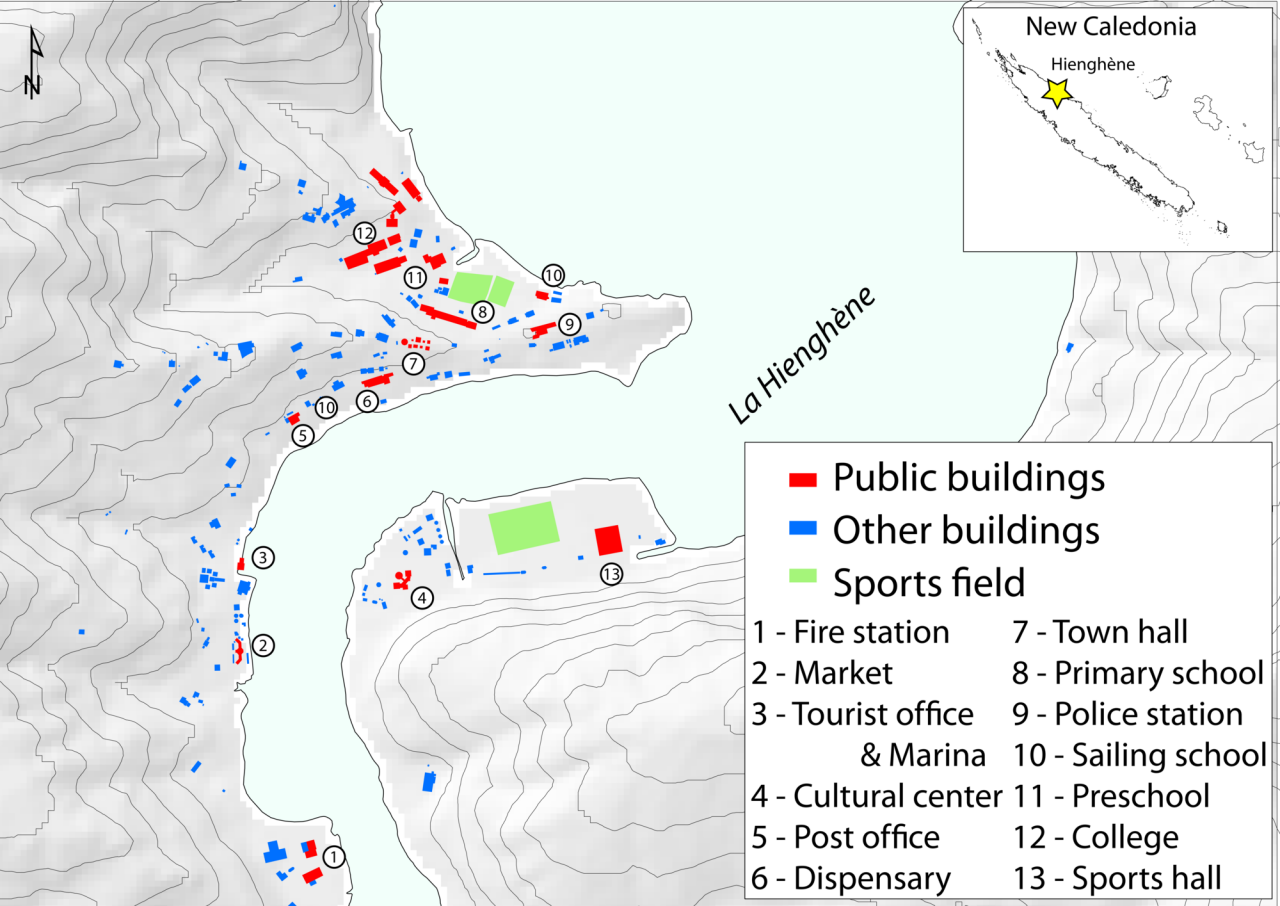
1357 Figure 16. Coverage of in-service and planned sirens in New Caledonia. Black frame in (a) locates
1358 Ouvéa in (b), with information on 'populated areas' below 10 m elevation.

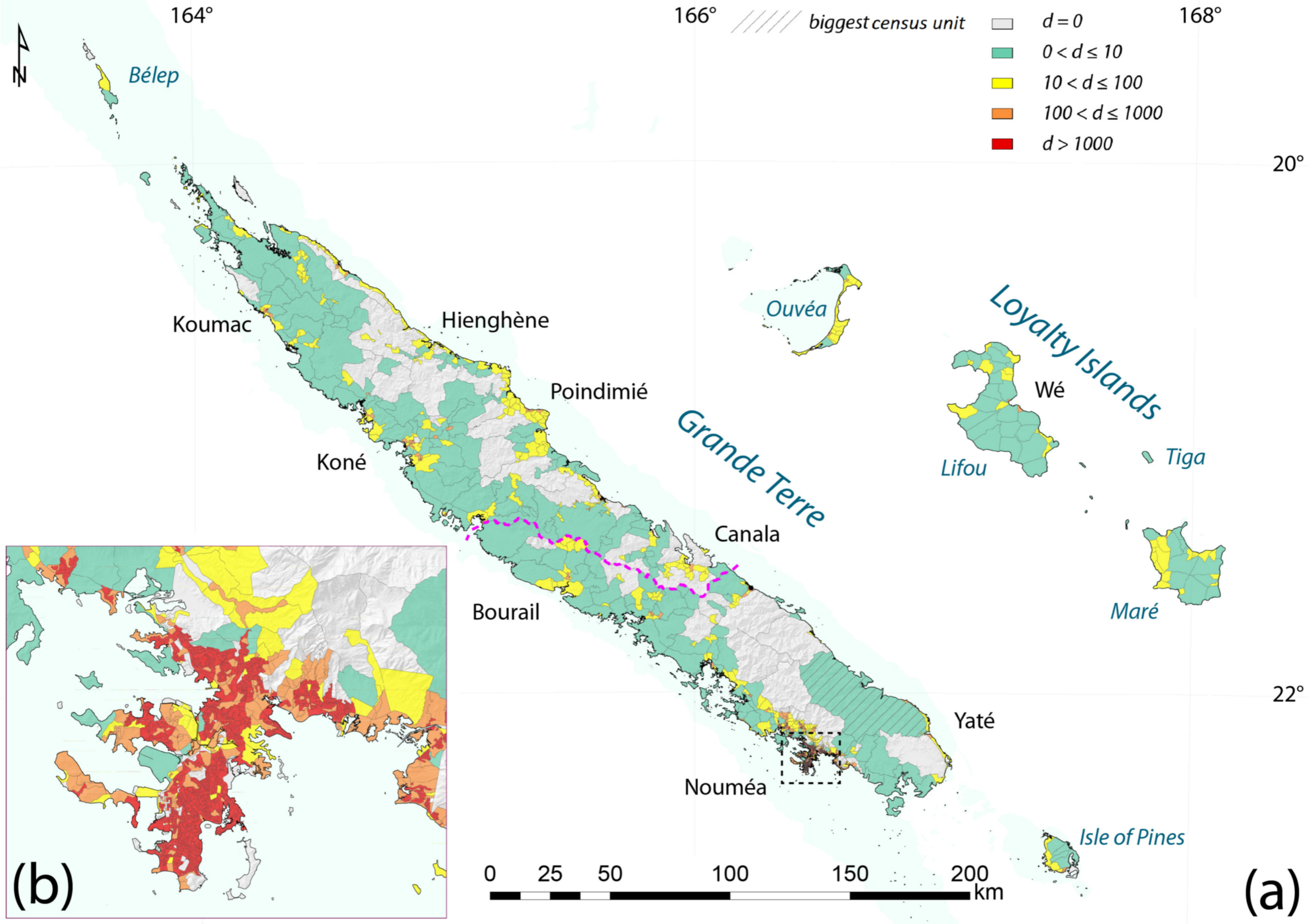
1359 Figure 17. Free self-service flyer about the tsunami siren warning system at a store counter, Yaté
1360 village.

1361 Figure 18. Graphic abstract of tsunami hazard vulnerability results for New Caledonia. Synoptic
1362 diagrams of this kind can be used in comparative studies between many islands or regions for
1363 summarizing their respective similarities or differences, and for charting disaster risk reduction policy
1364 objectives.

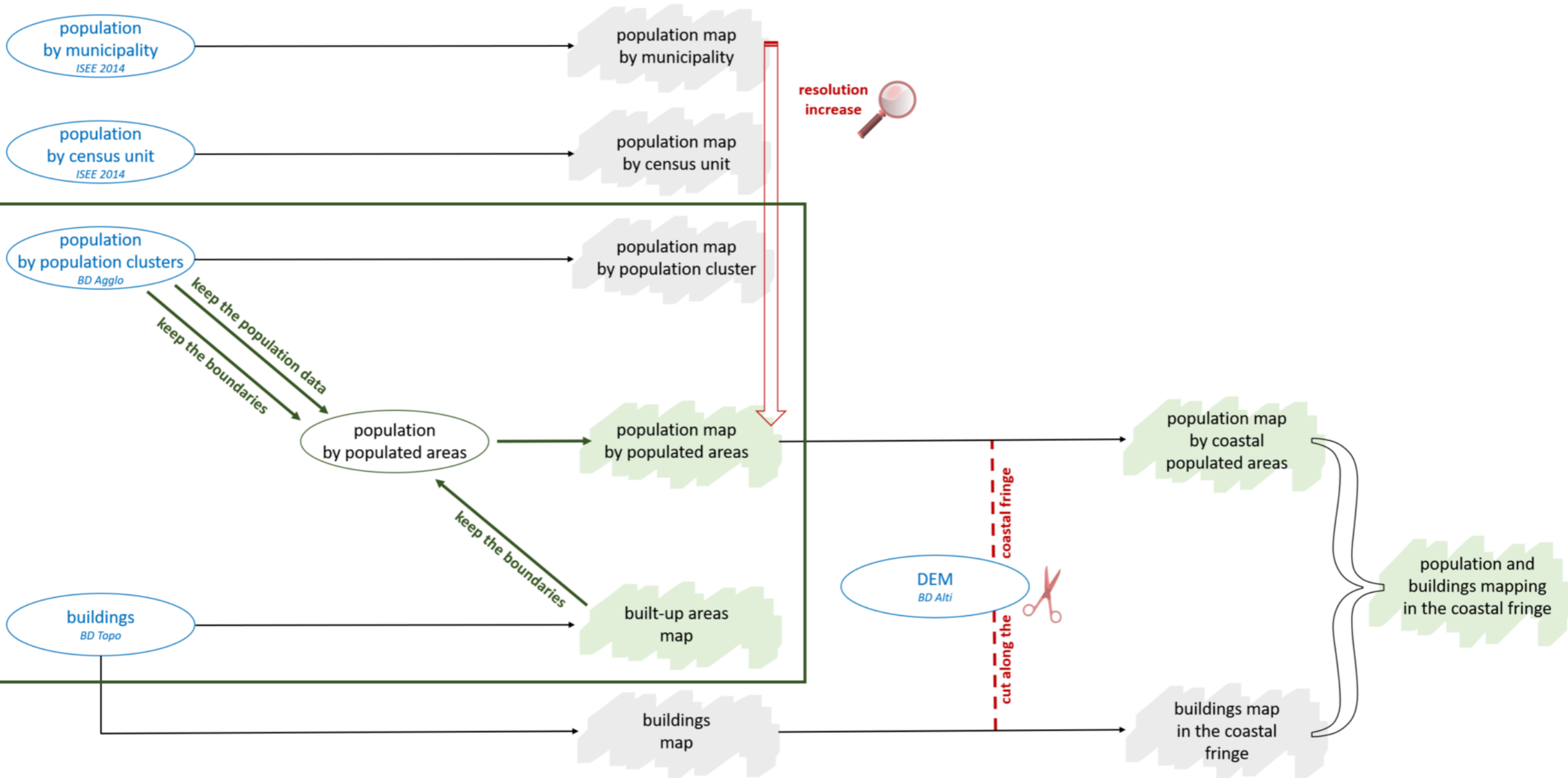


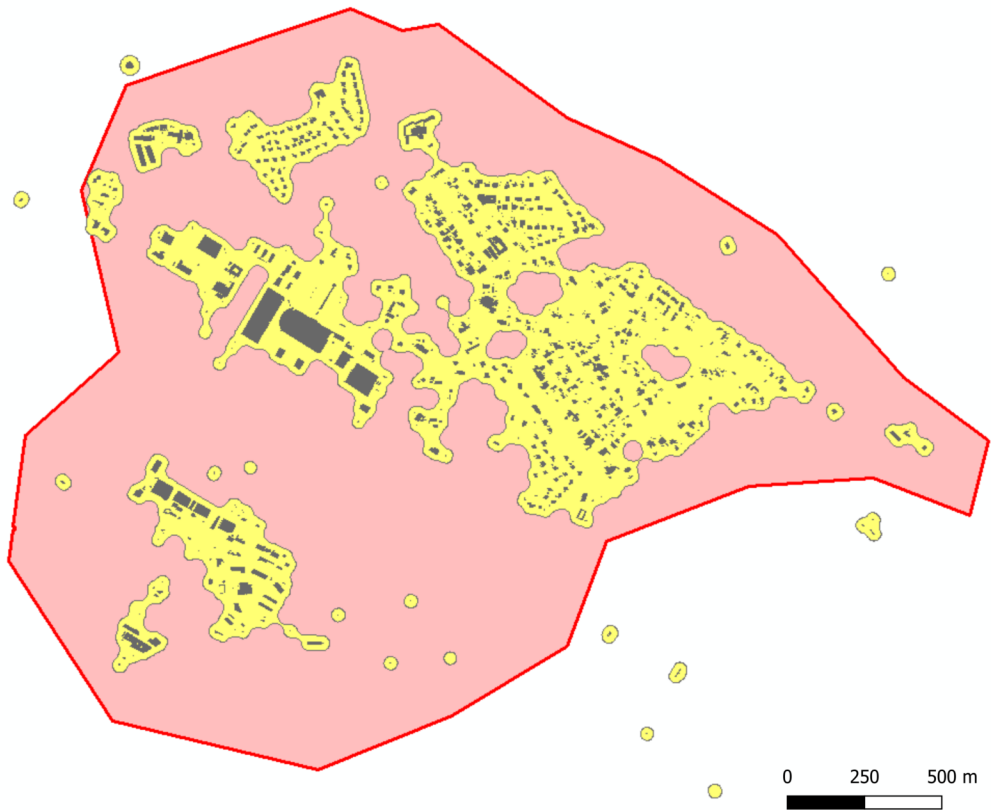


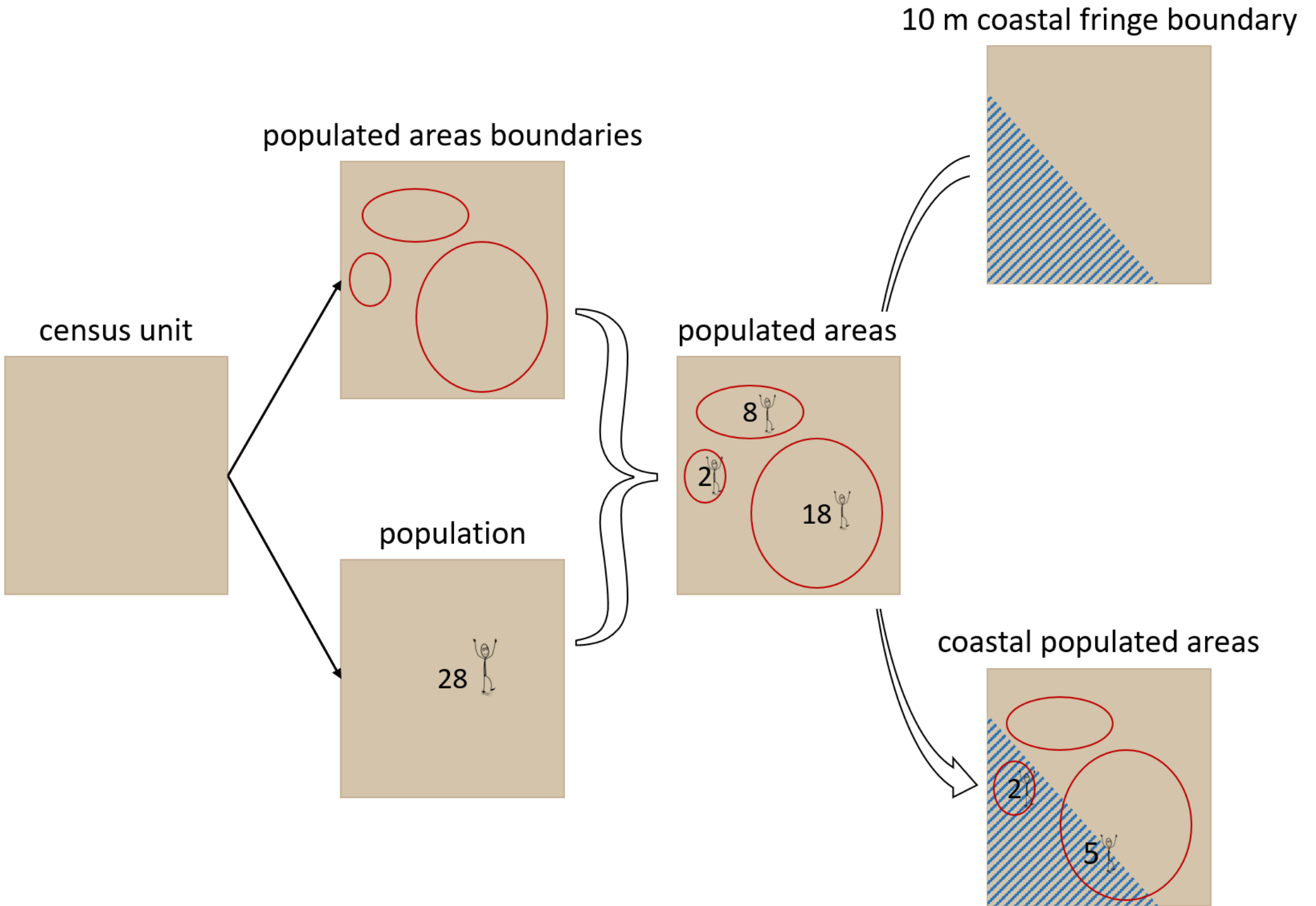


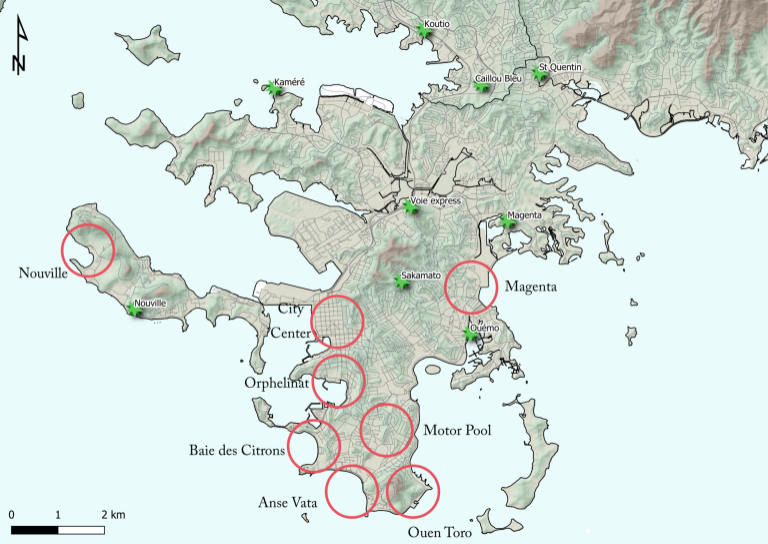


Dasymeric Mapping











(a)



(b)

LEGEND

Lifou



10 m coastal fringe

50 m coastal fringe

Populated areas

0 to 20 people

20 to 100 people

100 to 800 people

• Education Centers

• Health / Rescue Centers

+ Airports

• Energy Centers

• Harbors

0 5 10 km

% of population in coastal fringe



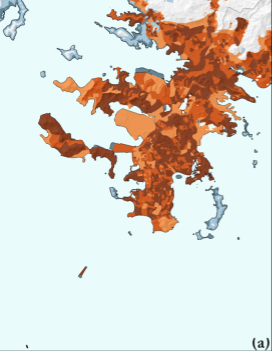
(c)



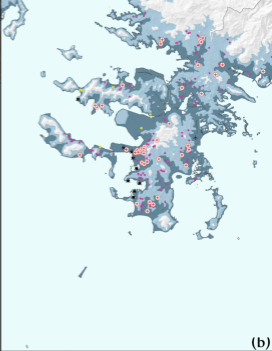
(d)



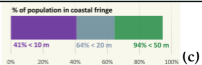
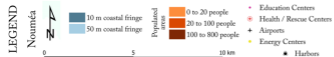
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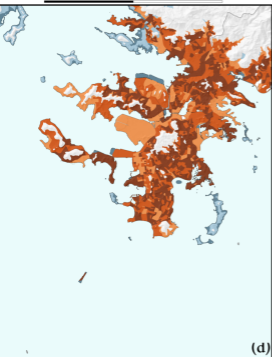
(a)



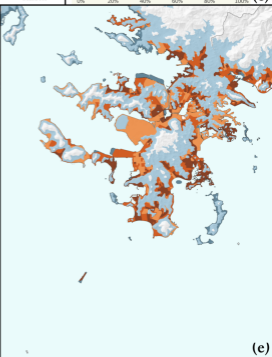
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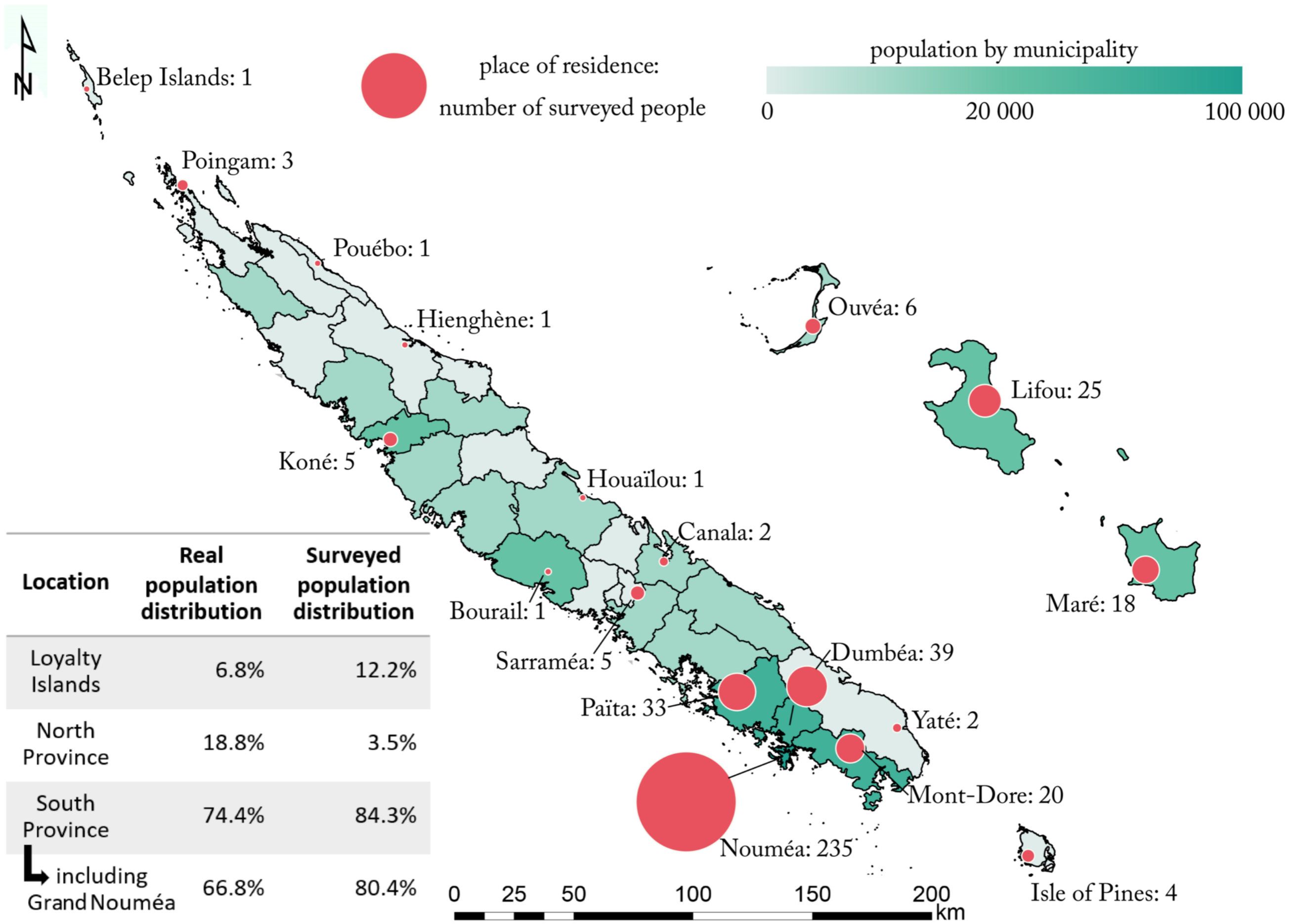
(c)

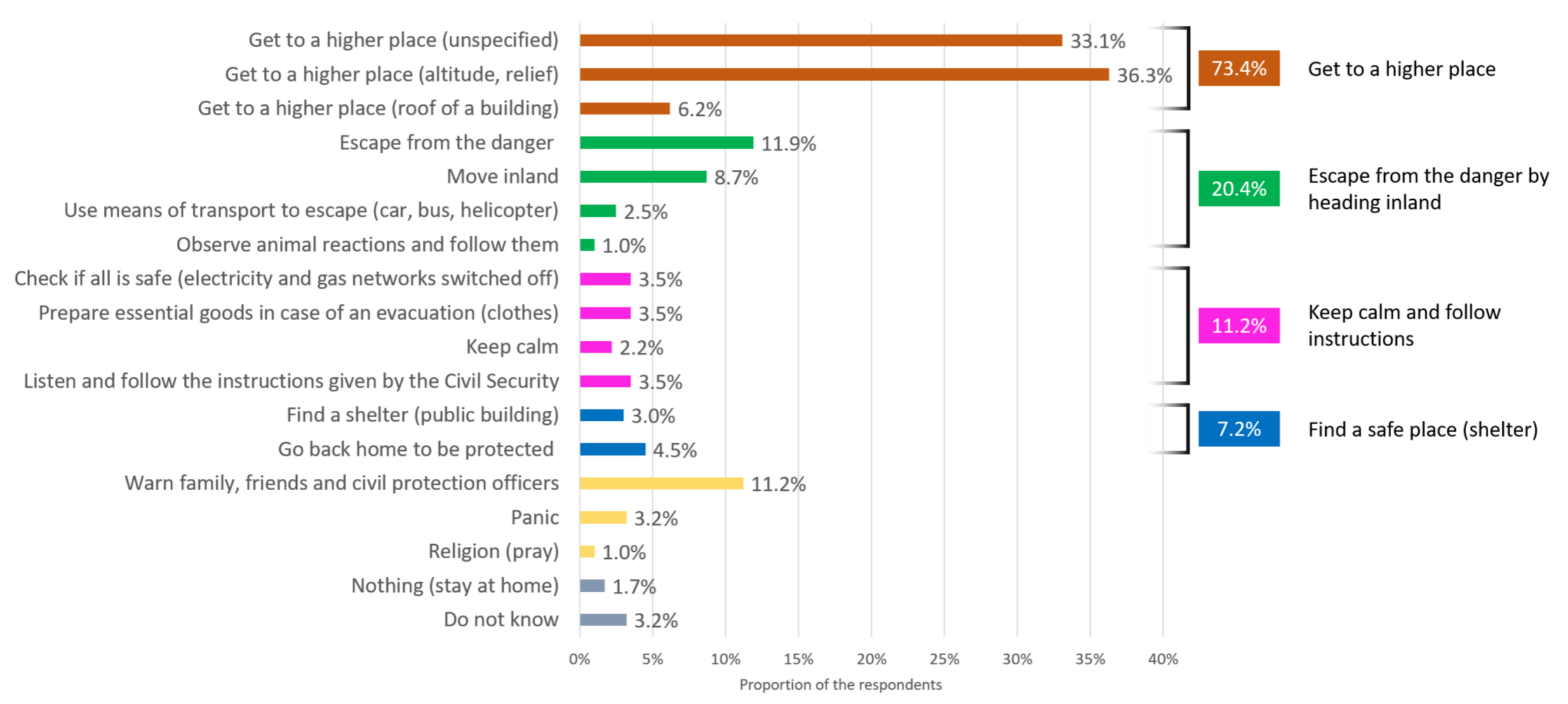


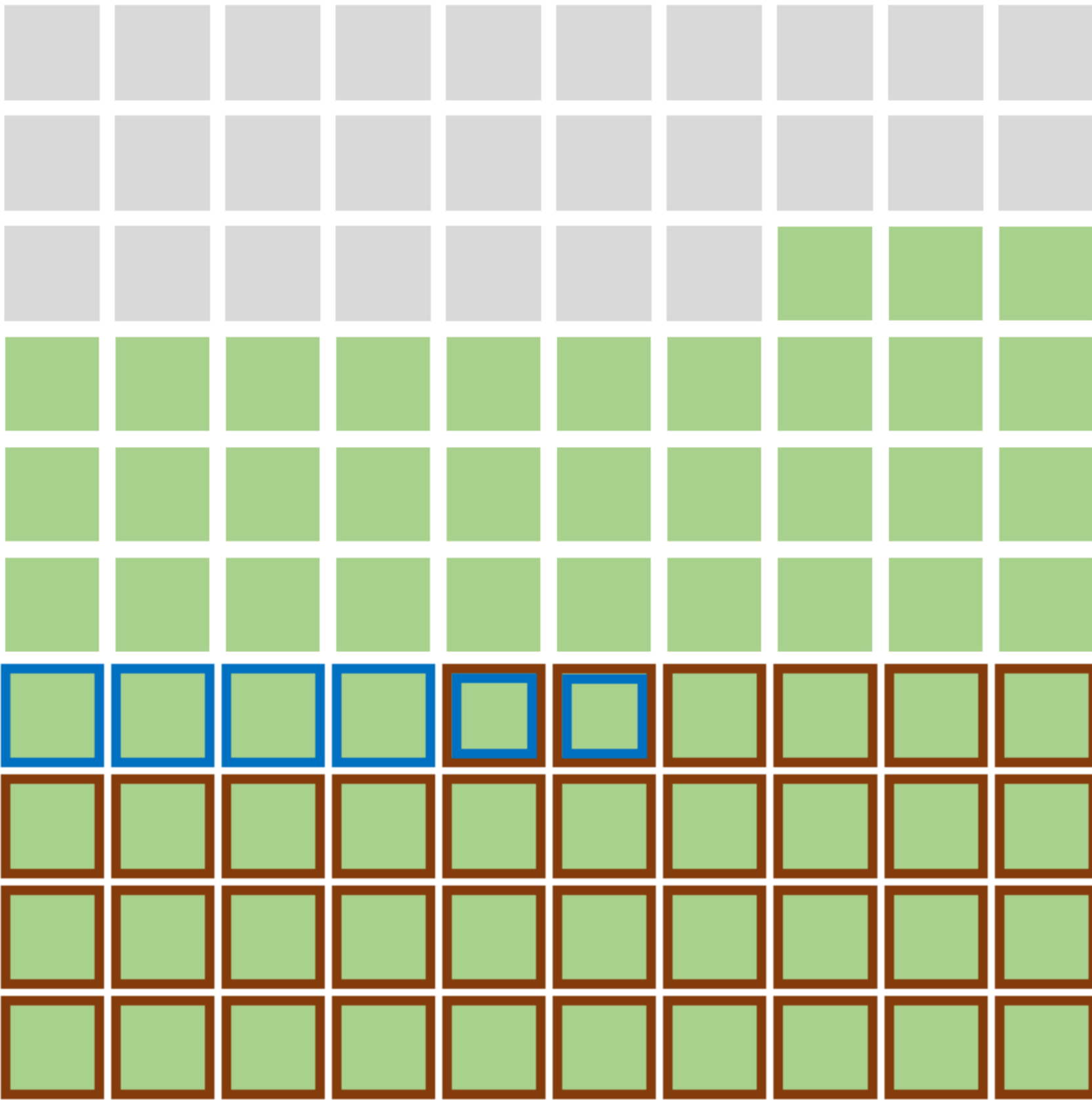
(d)



(e)







No mention of elevation



Mention elevation



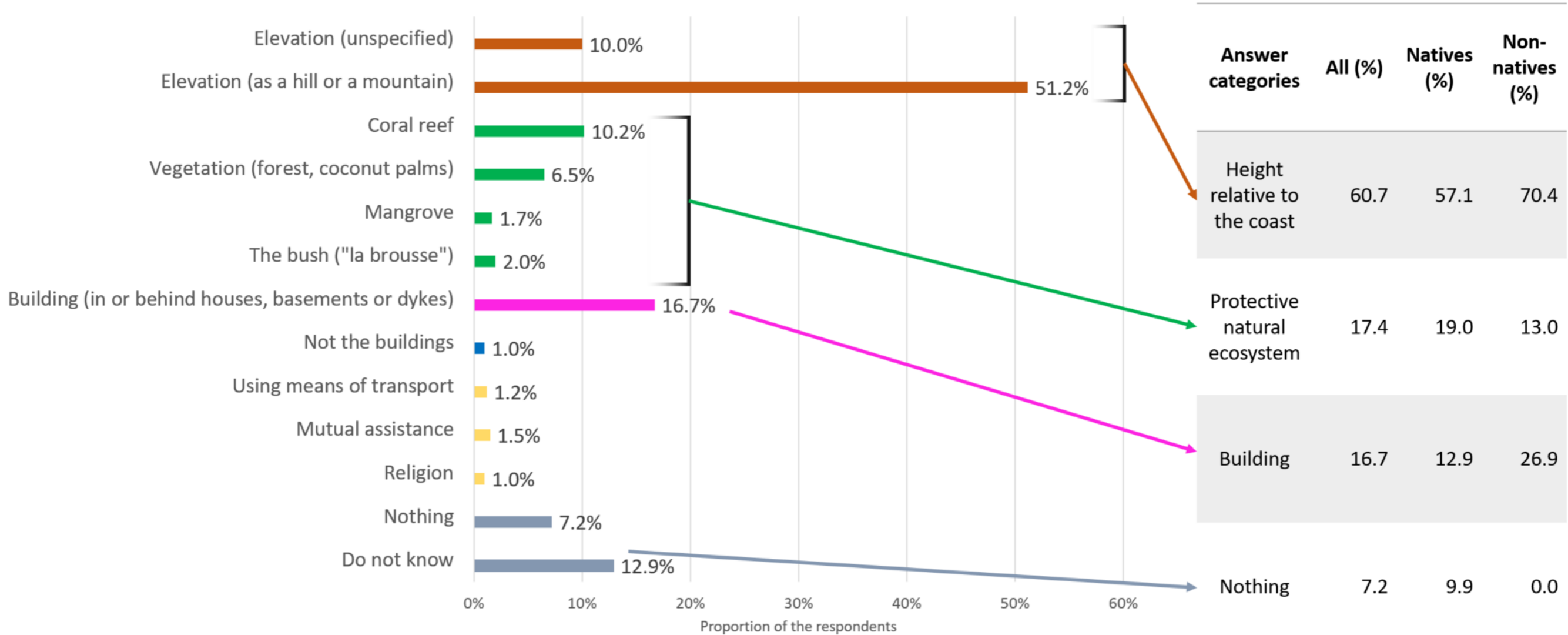
Access higher ground
on a topography



Access higher ground
on a building



Access higher ground
(no precision
if topography or building)



Elevation (unspecified)

10.0%

Elevation (as a hill or a mountain)

51.2%

Coral reef

10.2%

Vegetation (forest, coconut palms)

6.5%

Mangrove

1.7%

The bush ("la brousse")

2.0%

Building (in or behind houses, basements or dykes)

16.7%

Not the buildings

1.0%

Using means of transport

1.2%

Mutual assistance

1.5%

Religion

1.0%

Nothing

7.2%

Do not know

12.9%

Answer categories

All (%)

Natives (%)

Non-natives (%)

Height relative to the coast

60.7

57.1

70.4

Protective natural ecosystem

17.4

19.0

13.0

Building

16.7

12.9

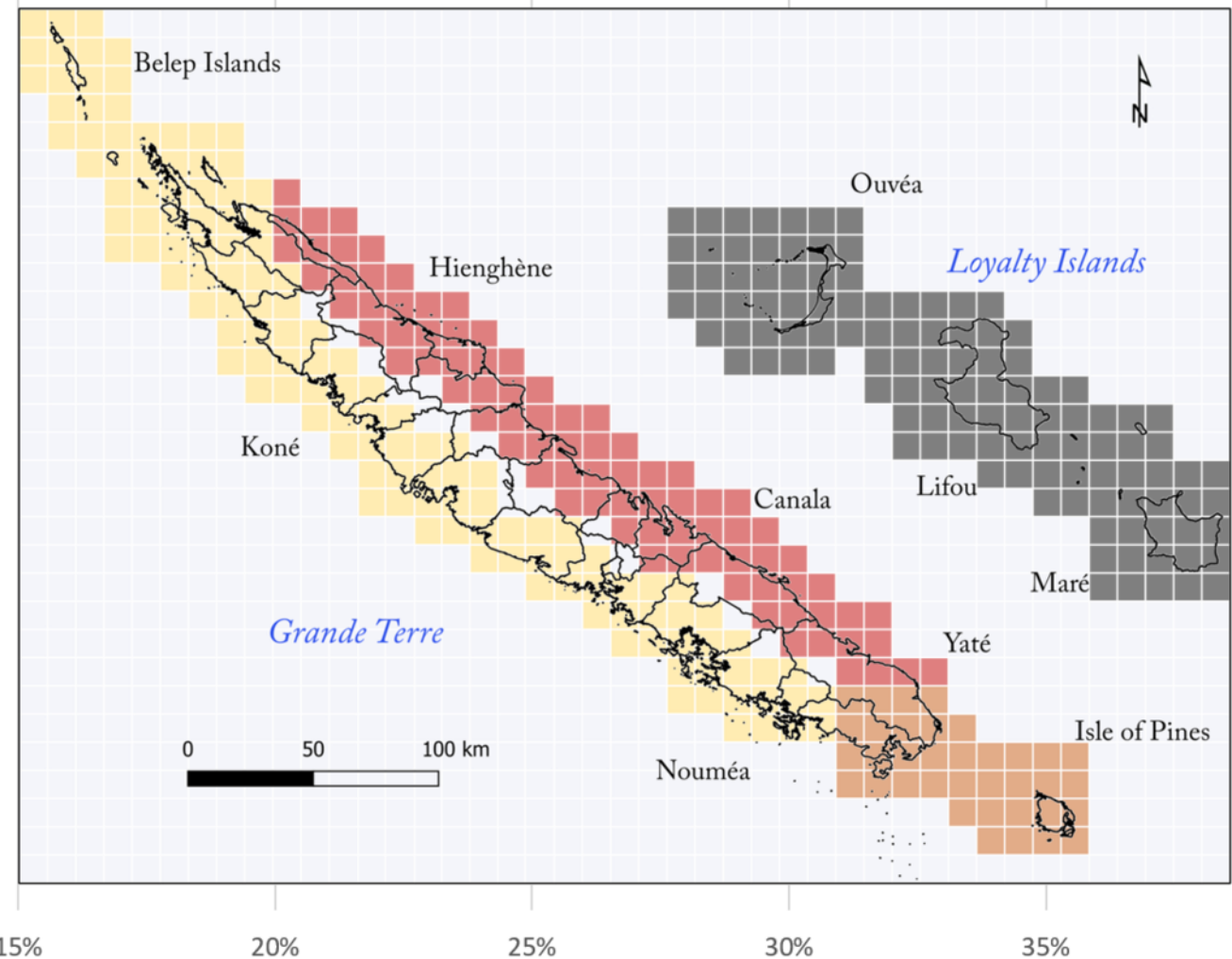
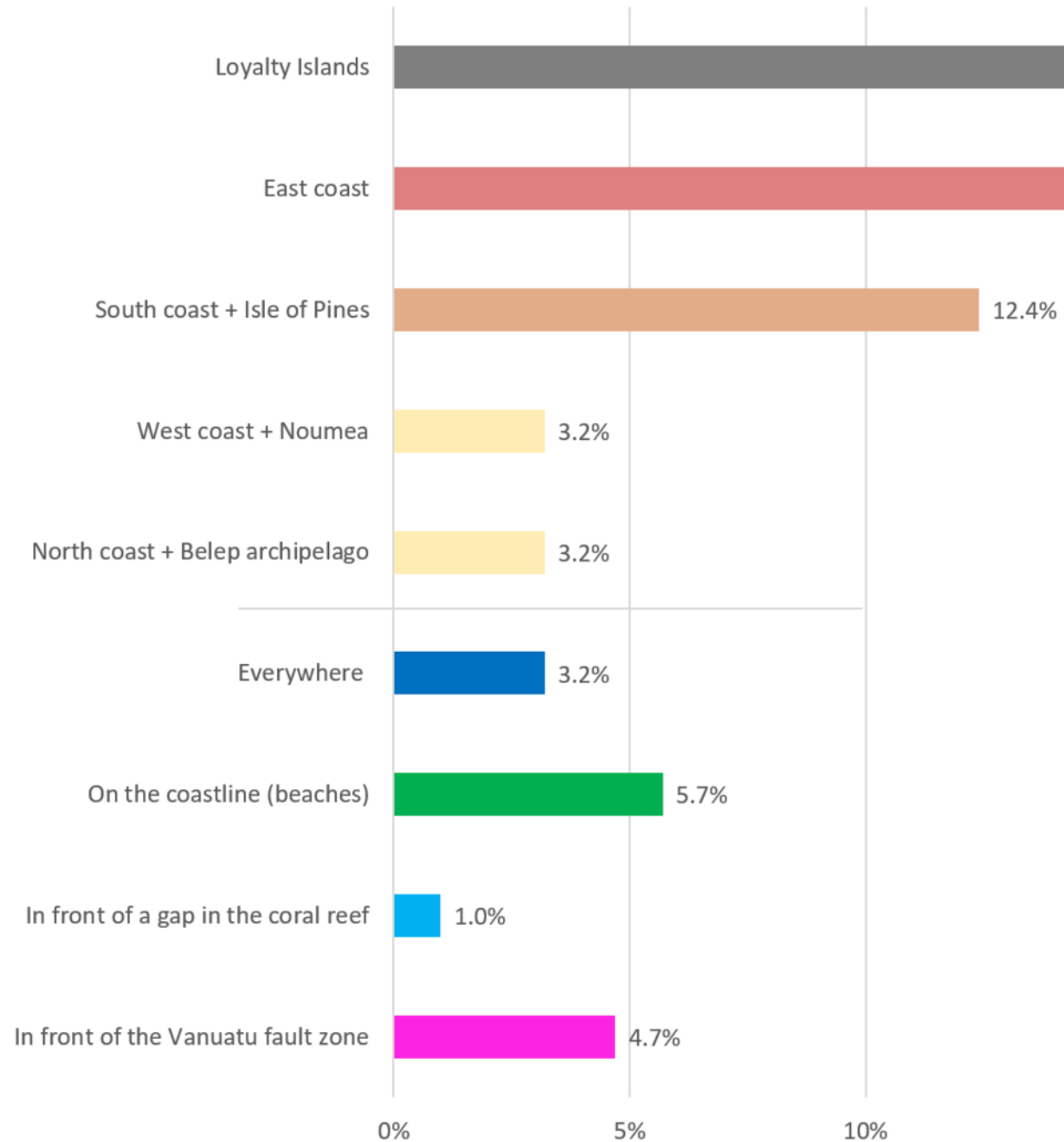
26.9

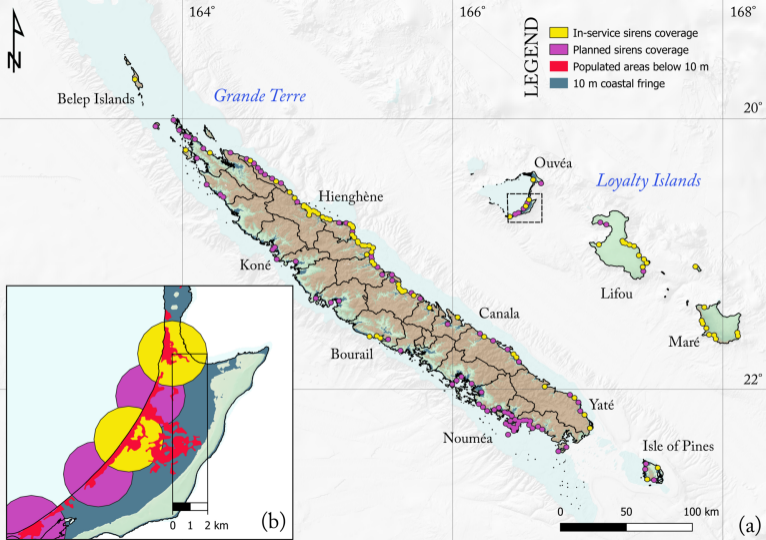
Nothing

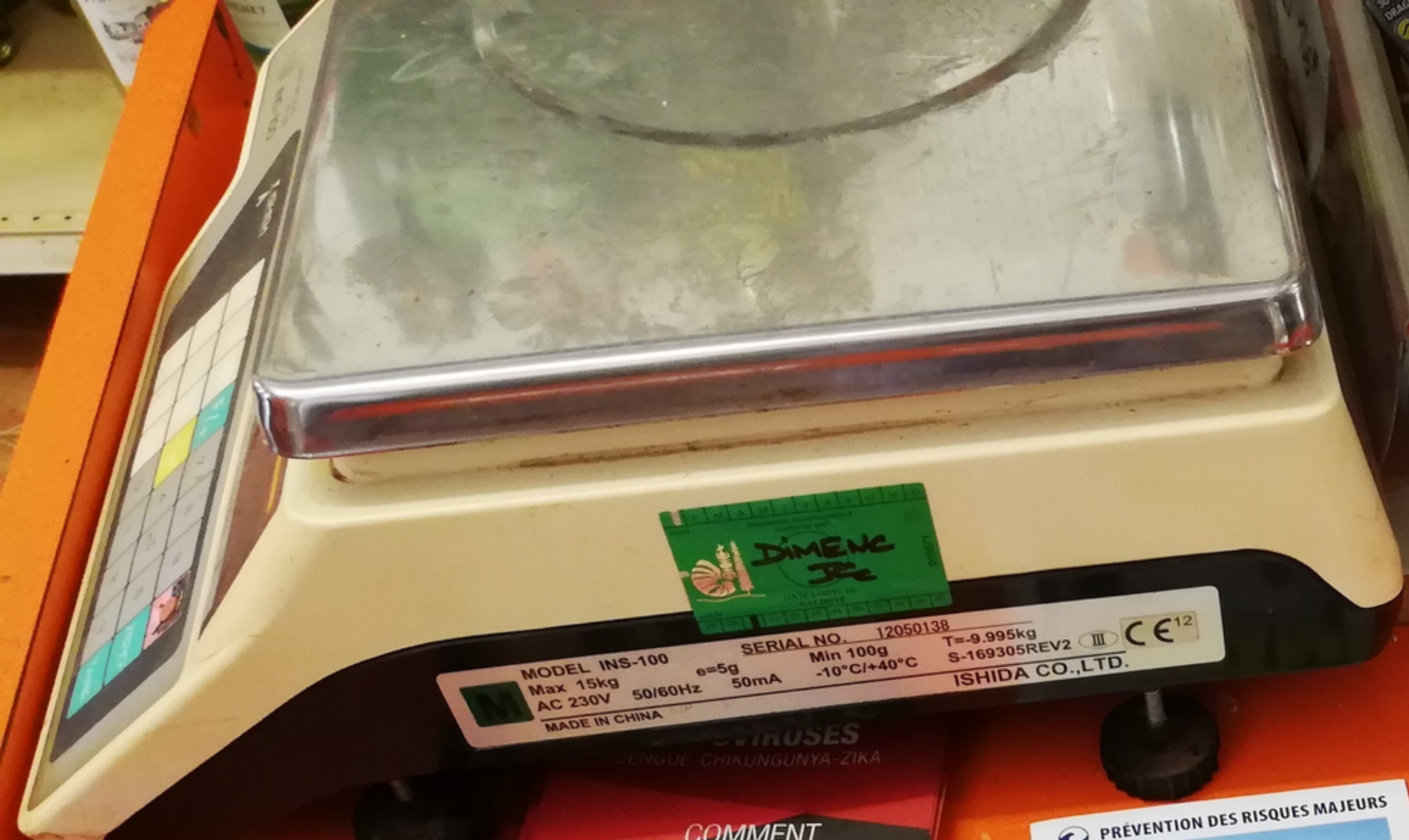
7.2

9.9

0.0







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 Max 15kg Min 100g S-169305REV2
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PRÉVENTION DES RISQUES MAJEURS

ESSAI DU SIGNAL D'ALERTE

TSUNAMI

ZONE A RISQUE DE TSUNAMI

Tous les 1^{er} MERCREDIS du mois à midi
 les sirènes de Nlle Calédonie retentiront durant 30 secondes

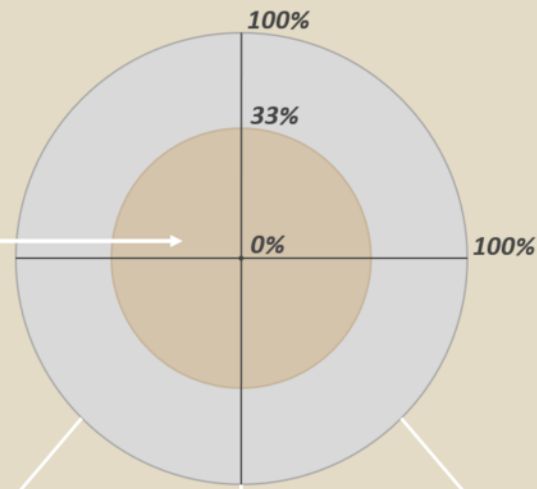
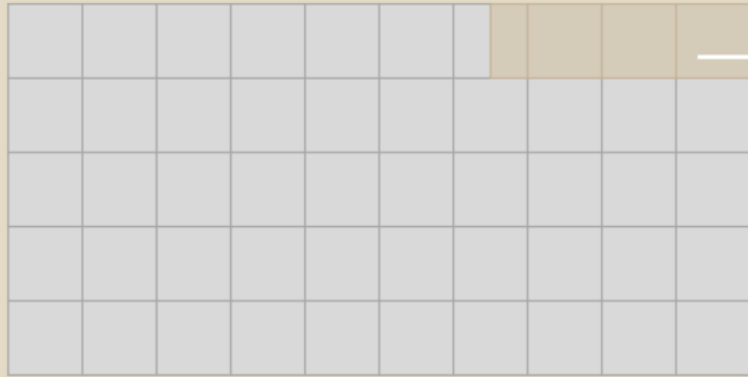
GOUVERNEMENT DE LA NOUVELLE-CALÉDONIE

DOSSIER SUR LES RISQUES MAJEURS DE LA NOUVELLE-CALÉDONIE

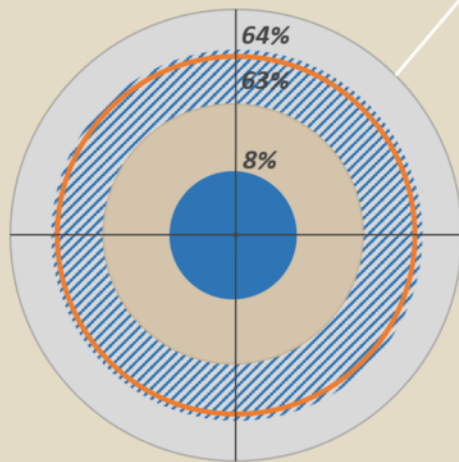
www.gouv.nc



Surface of New Caledonia · 7% < 10 m

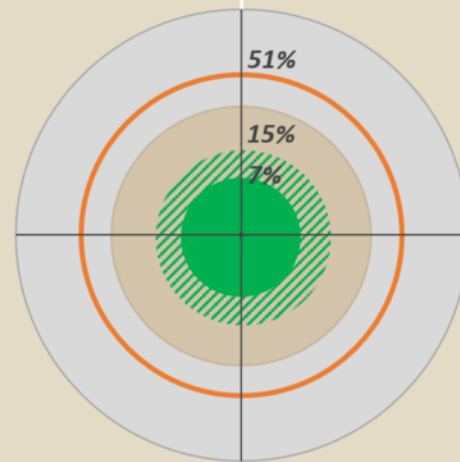


Key	
	All population in New Caledonia (100%)
	Population living below 10 m elevation (33%)
	Survey's results ("Yes I know the sirens alert network" or "Yes I feel protected by the mangroves / coral reef")
	Population inside the current siren coverage zone (estimation for the planned sirens in shaded)
	Estimation of the range of population living behind mangroves
	Estimation of population living behind the reef barrier



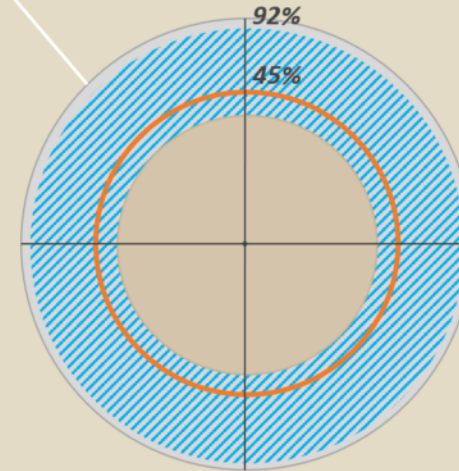
Sirens

79 actives sirens
mostly in Loyalty Islands & East coast
92 planned sirens



Mangroves

359 km² coverage
mostly West of Grande Terre
48% of the coastline with mangroves
but 15% loss of mangroves estimated for 2100



Reef

1,600 km of barrier reef
around Grande Terre
but several gaps in the reef

Table 1. Question sequence for the risk perception survey

N°	Questions	Methodological notes
1	<p>French version: <i>En cas d'alerte tsunami, quel est votre premier réflexe ?</i> English version: What is your first reaction in the event of a tsunami alert?</p>	Open question to spark interest
2	<p>French version: <i>Quels sont les éléments dans votre environnement proche ou lointain qui vous semblent protecteurs face aux tsunamis ?</i> English version: Have you identified any features in your immediate or more distant environment that might protect you from tsunamis?</p>	Open question to elaborate on ideas such as naturally protective ecosystems
3	<p>French version: <i>Pensez-vous que le risque tsunami existe en Nouvelle-Calédonie ?</i> English version: Do you think a tsunami hazard exists in New Caledonia?</p>	Closed question asked in third position so as not to influence answers to the previous questions; also prepares for Question 4
4	<p>French version: <i>Si vous pensez que le risque tsunami existe en Nouvelle-Calédonie, où est-il le plus fort ?</i> English version: If you think a tsunami hazard exists in New Caledonia, where is it most threatening?</p>	Open question to elaborate on geographic and mental perceptions of the hazard
5	<p>French version: <i>Pensez-vous que la barrière de corail peut vous protéger d'un tsunami ?</i> English version: Do you think the coral reef can protect you from tsunamis?</p>	
6	<p>French version: <i>Pensez-vous que la mangrove peut vous protéger d'un tsunami ?</i> English version: Do you think mangroves can protect you from tsunamis?</p>	Closed questions to assess spontaneous perceptions of the tsunami issue
7	<p>French version: <i>Connaissez-vous l'existence des sirènes d'alerte spécifiques aux tsunamis (7a)? Est-ce que vous les avez déjà entendues (7b)?</i> English version: Do you know about the existence of specific tsunami warning sirens (7a)? Have you already heard them (7b)?</p>	

Table 2. Proportion of inhabitants by municipality and by coastal fringe bandwidth

Municipality	Population distribution			
	Population totals	Within 50 m coastal fringe (%)	Within 20 m coastal fringe (%)	Within 10 m coastal fringe (%)
New Caledonia	268767	87	55	33
Northern Province	50717	80	58	36
Belep Island	843	78	50	35
Canala	3687	79	57	37
Hienghène	2483	69	49	36
Houailou	4240	89	63	44
Kaala Gomen	2033	73	46	14
Koné	7340	75	54	29
Kouaoua	1452	65	38	26
Koumac	4252	87	61	36
Ouégoa	2360	81	57	35
Poindimié	4868	89	63	43
Ponérihouen	2370	92	61	34
Pouébo	2452	95	67	47
Pouembout	2591	81	62	27
Poum	1463	98	95	76
Poya	3036	34	19	11
Touho	2087	87	59	43
Voh	3160	90	79	56
Loyalty Islands	18297	90	43	36
Lifou	9275	100	27	20
Maré	5648	68	36	27
Ouvéa	3374	100	99	97
Southern Province	199753	88	56	33
Boulouparis	3005	71	51	25
Bourail	5444	80	48	22
Farino	612	34	9	1
Isle of Pines	1958	98	84	51
La Foa	3542	84	53	28
Moindou	709	66	43	31
Sarraméa	584	15	1	0
Thio	2643	85	60	51
Yaté	1747	97	86	67
Grand Nouméa	179509	89	56	27
Dumbéa	31812	83	39	15
Mont Dore	27155	89	58	35
Nouméa	99926	94	64	41
Païta	20616	72	36	15

Table 3. Pattern of answers to the closed questions

- (a) A large proportion of the respondents were convinced that tsunami hazards in New Caledonia are a reality (82.7% native, 72.2% non-native; and 79.6% below age 40, 80.1% above). Others insisted on explaining that there have never been any tsunamis in the archipelago, or that their occurrence is impossible (8.5% native, 23.1% non-native; and 11.1% below age 40, 14.0% above).
- (b) Respondents predominantly considered that the coral reef could protect the land from tsunamis. Another 5% explained that reef protection was conditional on coral reef depth under water or on the absence of gaps in the reef, and the severity of the tsunami hazard would be modulated by those factors.
- (c) Respondents also considered in a majority that the mangroves could protect from tsunamis, especially among the age group above 40 (59.1%), against 43.1% for the age group below 40.
- (d) Respondents were mostly aware of the existence of tsunami alert sirens, and 28.9% had already heard them (33.7% native, 15.7% non-native). Some, however, may have confused this specific alert with fire alerts. Indeed, during the alert of the last tsunami on December 5, 2018, several residents stated that they had heard the tsunami sirens although no specific tsunami sirens are installed in the capital. Firefighters had, in fact, sounded their own alert to evacuate the beaches, so there was a confusion between the purpose-designed tsunami sirens and the ad hoc siren alert of 2018. In terms of perception by the respondents, however, the purpose of those alerts was identical and thus correctly remembered.

	Types of response			
	Yes (%)	No (%)	Don't know (%)	It depends (%)
Q 3 – Do you think a tsunami hazard exists in New Caledonia?	79.9 ^(a)	12.4 ^(a)	7.7	–
Q 5 – Do you think the coral reef can protect you from tsunamis?	44.8 ^(b)	39.6	10.7	5.0 ^(b)
Q 6 – Do you think mangroves can protect you from tsunamis?	50.5 ^(c)	35.3	11.7	2.5
Q 7 – Do you know about the existence of specific tsunami warning sirens?	62.9 ^(d)	37.1	–	–

Table 4. Pattern of answers concerning the protective effect of natural ecosystems

- (e) The first response concerns coral reef protection, and the second mangrove protection: for example, “Yes – No” in column 3 means “yes, the coral reef protects, and no, the mangroves do not protect”.
- (f) Comparing the answers to the two questions about naturally protective ecosystems (reefs and mangroves), the highest scores favored the mangrove, especially among native islanders.

	Types of response to questions 5 and 6 (protection by coral reef – protection by mangroves) ^(e)			
	Yes – Yes (%) ^(e)	No – No (%) ^(e)	Yes – No (%) ^(e)	No – Yes (%) ^(e)
Respondents	25.9	17.2	13.7	19.9
Surveyed (native islanders)	26.9 ^(f)	16.7	12.6	20.1 ^(f)
Surveyed (non-native)	23.1	18.5	16.7	19.4

Table 5. Proportion of people living within the range of in-service sirens or of the entire future warning system

Location	Scenarios					
	In all the archipelago			In the 10 m coastal fringe		
	With sirens in service (%)	With the future warning system (%)		With sirens in service (%)	With the future warning system (%)	
New Caledonia	8	64	(+734)	14	81	(+483)
Grand Nouméa	0	75	–	0	90	–
Loyalty Islands	41	51	(+25)	70	85	(+21)
Yaté	49	83	(+71)	49	81	(+67)
Isle of Pines	16	75	(+356)	31	82	(+165)
Hienghène	52	56	(+6)	83	86	(+4)