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

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Abstract :

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

Highlights

► The population of New Caledonia (Western Pacific) is vulnerable to tsunami hazards ► A GIS-based mapping methodology and atlas of exposure to tsunami risk are presented ► A perception survey was conducted to assess risk awareness based on age and ethnicity ► Some mitigation options (reefs, mangroves, education, warning systems) are discussed ► The methodological package is transferable to other disaster risk reduction contexts

Keywords : Tsunami hazard, dasymetric population mapping, perception survey, community-based disaster-risk reduction, ecosystems shields, New Caledonia

1. Introduction

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

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

Disasters and risks are no longer purely humanitarian issues in the context of reactive disaster management: DRR is now a matter of proactive risk reduction and thus an integrative part of sustainable development and adaptation to global change [8]. An International Strategy for Disaster Reduction has been drawn up by the United Nations [9], defining 'Ten Essentials' in order to empower local governments and other agencies in the implementation of the Hyogo Framework for Action (HFA). Priorities for action therein were (i) to ensure that DRR is a national and local priority with a strong institutional basis for implementation; (ii) to identify, assess and monitor disaster risks and enhance early warning; (iii) to use knowledge, innovation, and education to build a culture of safety and resilience at all levels; (iv) to reduce the underlying risk factors; and (v) to strengthen disaster preparedness for effective response at all levels. Obviously, all nations do not have the same needs in terms of DRR, or indeed the same management capacities [10]. Quantitative risk analysis and assessment methods currently attain high levels of sophistication in industrialized countries such as, for example, the USA (with its Federal Emergency Management Agency [11]). However, different economies, cultures, and environmental settings may call for different risk control options, which typically range from structural measures ('hard' structures belonging to the repertoire of civil engineering) to nonstructural measures (land-use planning, ecological restoration, hazard risk zoning, education, awareness campaigns, early warning systems, affordable disaster insurance, and other regulatory policy measures). Those approaches, whether structural or nonstructural, tend to be top–down and technocratic, but community-based holistic and integrative approaches are also emerging, where civil society, scientists, the state and/or third-sector organizations (and thus the private marketplace) endeavor to co-construct the safety of their own futures (on community-based disaster risk reduction, or CBDRR, see [12]).

New Caledonia is a 18,575 km^2 archipelago located in the South West Pacific Ocean, about 200 km west of the seismically highly active Vanuatu subduction zone (Fig. 1). This region is frequently subject to earthquakes of magnitude M_w up to 7.0 and more. The earthquakes pose a threat to the island's population, particularly when a tsunami, as on December 5, 2018 (Maré, M_w 7.5) [13] and February 10, 2021 (Matthew Island, M_w 7.7), is triggered. Distant earthquakes can also affect the archipelago through transoceanic tsunamis, with potential impacts on coastal communities on the other side of the ocean. New Caledonia is fully concerned by this, and destructive tsunamis have been reported during the 19th and 20th centuries. New Caledonia's vulnerability to tsunami, its ethnographically and culturally diverse population, its appeal as a destination for seaside tourism, and its imperfect emergency planning and management policy, make this group of islands an ideal laboratory for (i) probing why the region is underprepared for natural disasters, (ii) formulating policy recommendations towards setting up an effectual disaster management system, and (iii) showcasing its relevance to other similar tropical insular regions concerned by tsunami risk assessment. The coasts of New Caledonia are also vulnerable to other inundation produced by events such as wind waves, strong swells [14], and storm surges [15]. Given that these processes also expose New Caledonia to coastal erosion [16,17,18] and thus enhance baseline threats to human life and infrastructure, the risks related to these hazards call for being assessed while also bearing in mind the threats of sea-level rise associated with global climate change (for its impact on tsunamis, see [19]; impact on waves, see [20]; impact on surges, see [21,22]).

Ideally, full tsunami hazard assessment includes predicting the likely maximum heights reached by tsunami waves while taking account of the location and magnitude of the source; of geometry of shorelines, straits and bays that may be affected; of seafloor morphology; of the occurrence of natural features such as reefs and mangroves; and of the distribution of low-lying land. The finer detail of some of these aspects, however, is still work in progress for New Caledonia [23]. A recent update of the tsunami catalog of New Caledonia documents 37 tsunamis triggered by local, regional, and distant earthquakes between 1875 and 2018 [24]. The two largest local earthquakes generated at the southern Vanuatu subduction zone on March 28, 1875 and September 20, 1920, with respective magnitudes M_w 8.1–8.2 and M_w 8.0, triggered two destructive tsunamis in New Caledonia and Vanuatu. Wave heights reached 5 m at specific locations, and the first event killed 25 people in the south of Lifou Island (Loyalty Islands), while also causing various levels of damage and human injury [25]. These earthquakes are directly linked to high tectonic compression rates along the Vanuatu Trench ranging between 5 and 12 cm/yr horizontally in the central and southern part (maximum at the latitudes of the Loyalty Islands [26]). A seismic gap between the Loyalty Islands and the southern Islands of the Vanuatu arc (Erromango, Tanna, Aneytium) suggests the forthcoming possibility of a major rupture [27], potentially triggering catastrophic tsunamis in the coming years or decades. Finally, 20% of recorded/reported wave heights were more than 1 m, two of them ranged between 2 and 5 m [24], justifying the relevance of an island-wide, DRR-focused investigation of New Caledonia.

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

Figure 1

These general features lay the foundations for a marine inundation hazard assessment that includes defining protection priorities along the coastline—typically housing and critical infrastructure such as hospitals, fire stations, polluting industries, etc. In most countries, however, the exact number of residents close to the shoreline is commonly unknown. Such is the case in New Caledonia, where, furthermore, 25% of the population was not born on the island and 16% are expatriates from mainland France [36]. Such situations vary but are not uncommon among island nations. As a result, cultures and traditions vary within the population, depending on geographic origin, social background, and education level [37]. The same is true for risk culture (way a community handles questions of safety and security), which varies on an international scale and within a population as a function of past and current exposure to hazards [38]. In New Zealand, for example, the Māori have developed their own knowledge about local hazards. It is typically based on environmental indicators and geographic place names remembered as high-risk and is passed on through oral tradition [39]. It is, therefore, relevant to know how much of the population is aware of impending tsunami hazards, and what knowledge people have about these hazards and about existing safety measures to guard against them [40,41,42,43]. This emphasizes the need to conduct a vulnerability analysis of the island's coastal fringe, which has a potential for exposure to tsunami-related hazards along its entire length.

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

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

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

(iii) Mangroves cover 359 km^2 of New Caledonia's coastline [50]. These forests function as an important buffer between the world's largest natural coralline lagoon [51] and the high sediment and heavy-metal loads of rivers conveying opencast mine tailings to the coast. Some mangrove forests are even advancing seaward because of sediment accretion in estuaries [52]. Whether in the case of tsunamis [53,54,55,56] or storms [45,56,57], mangroves have repeatedly demonstrated their protective effect on coastlines [58], with a proven reduction in human casualties when forming barriers seaward of human settlements.

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

Figure 2

This paper focuses on a low-cost toolbox for vulnerability and hazard-perception mapping crafted in the context of studying tsunami-related hazards in New Caledonia. It relies on a mixed methods approach [60,61] involving an opensource geographical information system, dasymetric population mapping, rapid field interviews (combination of structured and semi-structured), and hazard perception analysis. The HFA recognizes that governments have the primary responsibility to guide and implement measures for achieving DRR (priority 1); accordingly, this comprehensive study is framed under a national focus and presents the methodology and its associated toolbox primarily as a basis for creating a national DRR platform. However, New Caledonia is also held here as representative of other coastal environments and communities in the Tropics, where the toolbox could be also adopted and adapted for framing proactive risk reduction policies in those settings. We begin by presenting a methodology for systematic mapping of the archipelago's coastal population in order to quantify the magnitude of its vulnerability to tsunami-related hazards. Given that the analysis covers a vast territory based on a standard set of criteria and low-cost tools, a tradeoff also occurs between geographic range — the larger the better for preliminary strategic planning — and site-specific analytical precision, which for some variables (e.g., building height, or digital elevation in the absence of LiDAR coverage) is limited or unavailable compared to what may exist in wealthier countries. We subsequently report the results of a rapid assessment survey of tsunami hazard perception by residents of the capital Nouméa and by visitors from other parts of the islands. Using a quota sampling approach, the rapid survey was crafted as a means of assessing behavioral patterns among a cross-section of the population in the event of a tsunami, and of identifying future policy priorities for optimizing DRR on that basis. The potential for existing coastal ecosystems to efficiently protect exposed residents is discussed, and the effectiveness of an alarm siren network, currently being deployed throughout the islands by the regional emergency management agency (*Direction de la Sécurité Civile et de la Gestion des Risques*), is assessed. Conclusions advocate the advantages of jointly developing a map-based and social science approach to disaster risk management in coastal areas exposed to tsunamis, with potential for transferability of the methodology to other island settings where standards of preparedness are still limited.

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

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

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

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

2.2. Step 2: inventorying buildings and population distribution

2.2.1. Buildings: location and function

New Caledonia has a mean population density of 14 inhab./km^2, with buildings spread all over the land (many often isolated and usually low-rise). For this study, the DITTT provided a vector-format database which includes all infrastructure data located with a precision of ~1 m. It currently serves as the database for New Caledonia (BDTOPO NC) and is used in all environmental and urban planning studies on the islands. Easy to work with using GIS tools, it consists of 8 vector families: buildings, drainage network, elevation, place names, roads, other networks, administrative boundaries, and vegetation cover. It additionally provides a special layer of ‘remarkable buildings’, including public, industrial and commercial buildings. Figure 3 illustrates these different types of buildings in Hienghène, Northern Province. This additional layer was used to locate all potential buildings of this nature within the coastal fringe exposed to tsunami-related hazards. The layer was first simplified by regrouping some entities, such as all the buildings belonging to a same school. It was also updated for this study by adding dialysis centers (diabetes is widespread in Pacific island communities [67,68]) and facilities which may present health and environmental hazards in case of damage by inundation. Lastly, a new attribute was created to code the utility of each building and determine its function in connection with healthcare, transportation, energy supply, administration, education, or leisure activities.

Figure 3

2.2.2. Population distribution

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

This census also provides mean population distribution by municipality. With 33 municipalities in the country (average size: 562 km^2), this makes the proportion of population living within the coastal fringe difficult to locate. The statistics also do not provide information about residential addresses for confidentiality reason, and thus altitude and distance to the coastline of individual households is unknown. However, the census does break down its accounting into 2,392 smaller census wards, each municipality consisting of several such units [35]. In low-density areas, these units can, however, be quite extensive. The largest, Pourina Kouakoué (west of Yaté), covers 982 km^2 but has only 3 reported inhabitants (Fig. 4).

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

Figure 4

2.3. Step 3: dasymetric mapping of the coastal population

2.3.1. Available methods

Spatial resolution and population density distribution are key components for correctly assessing population numbers impacted by coastal hazards [71,72]. A variety of methods exists for quantifying the population distribution of a user-defined geographic area that differs from census unit boundaries, the latter being dictated by the convenience of data collection and suited to generating choropleth maps, but ill-suited to geolocating households precisely and for inferring spatially accurate population densities. They depend mainly on datasets initially available and on time available for the study.

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

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

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

Figure 5

2.3.2. Defining the boundaries of built-up areas

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

In summary, the built-up land cover category in this study includes every building and artificial non-agricultural green space, surrounded by a user-defined, and freely adjustable based on context 20 m buffer zone. The buffer zones make sense because the Caledonian lifestyle involves much time spent outdoors near (often small, potentially overcrowded) places of residence rather than inside them [88,89].

2.3.3. Defining the boundaries of populated areas

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

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

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

(iii) Built-up areas exceeding 0.1 km^2 — a size which, on average, hosts with 100% certainty at least 1 resident whose life may need saving in the context of a disaster — were also aggregated to the GIS layer of 'populated areas'.

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

Figure 6

2.3.4. Defining population densities

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

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

Figure 7

2.3.5. Focus on the coastal populated areas

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

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

Figure 8

2.4. Step 4: pilot survey of tsunami hazard perception

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

2.4.1. Survey methodology

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

Here, ethnographic 'thick description' and other time-consuming methods were ruled out for practical reasons, opting instead for the efficiency of a rapid assessment survey. The survey was based on quota sampling and was aimed at capturing the spontaneous feelings of people [113] in order to gain an overview of their reactions in the event of a tsunami alert, arrival or inundation. The survey was underpinned by a set of seven questions (Table 1) allowing respondents to answer as freely as possible about tsunamis as potential threats to their daily lives. The survey was conducted verbally, and IT tools were ruled out (the use of a smartphone, suited to obtaining complete answers and to automated data classification was tested at first, but was found to disturb the respondents [108]). The vocabulary used was chosen and adapted to all potential types of interviewees to avoid discomfort or misunderstanding, and therefore to avoid biased replies [106]. It was decided not to interview children under the age of 10 because of potential comprehension issues. This lowered the national target population from ~269,000 to ~227,000. The written data were subsequently entered into a spreadsheet to facilitate data classification and statistical analysis.

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

(i) country of birth. If the answer was New Caledonia: then in which town; otherwise: how long had they lived on the island.
(ii) place of residence in New Caledonia. If the answer was Nouméa: in which neighborhood.
(iii) age groups: 10–19 years old; 20–39; 40–59; 60 and over.

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

The seven questions were written, tested, and discussed among research team members before asking them in French or in English depending on the respondent's language. The effectiveness and quality of the rapid survey also hinged on sequencing the questions following a pattern that allowed smooth transitions (see 'Methodological notes' column in Table 1) so that respondents could remain engaged throughout the rapid survey [121].

Table 1

2.4.2. Organization in the field

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

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

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

3. Results

3.1. Mapping results

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

(i) Figures 9a and 10a represent all the 'populated areas' for one municipality. Note the strong contrast between Lifou, with 38 polygons totaling 1,207 km^2 but only 3.4% of them (41 km^2) counting as 'populated areas'; and Nouméa, with nearly 100% of urbanized land cover.

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

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

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

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

Figure 9

Figure 10

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

Table 2

3.2. Perception survey results

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

Figure 11

The extremely high response rate compared to rates commonly reported for questionnaires and long interviews can be explained by the fact that (i) most people were surveyed at a moment of the day when they had some time to spare, and (ii) the questions were short and limited to 7. The survey took an aggregate of 20 hours to be completed by four interviewers, and adequate time was granted to obtain detailed answers to the open questions. The questions generally interested the respondents and motivated them to develop their answers or even debate on the subject. Most people were concerned about the tsunami hazard, but some of them clearly felt insufficiently informed about the associated risks in New Caledonia. The main trends in the answers given to each question are presented below. Binary responses to closed questions are simple to classify, whereas answers to open questions require a recategorization process prior to analysis. Some proportions are given to show significant similarities or differences between native and non-native groups, or between age groups below and above 40.

3.2.1. Answers to the two open questions

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

Figure 12

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

Figure 13

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

Figure 14

3.2.2. Answers to the closed questions

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

Table 3

Table 4

3.2.3. A preliminary hazard perception map

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

Figure 15

4. Discussion: policy recommendations and toolbox adaptations

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

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

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

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

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

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

Figure 16

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

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

4.2.1. The coral reef

The survey showed how almost half of the respondents felt protected from marine inundations by the reef barrier, some of them having learned at school about the attenuating effect of reefs. Studies on this topic are scarce, and experimental results or field observations often divergent. Thus, although most of these studies estimate that friction by the coral reef would in some cases reduce the energy of the tsunami (i.e., a healthy coral reef displaying structural complexity and a high coral cover area will enhance the wave friction factor and substantially improve coastal protection [125,126]), reef distance from the coast and openings in the reef could also influence wave amplification in the lagoon before striking the shoreline (for tsunamis, see [127,128]; for storms, see [129]). Thus, a continuous coral reef can prove to be an effective barrier to the propagation of low-amplitude tsunamis if there is no disturbing gap [127,128,130]. In support of this independent evidence, Andréfouët et al. [131] mention the case of several discontinuous fringing reefs facing localities already affected by tsunamis (case of the 1875 tsunami, considerably impacting the village of Mu on Lifou). The overall conclusion is that many parameters enter the equation and further scientific investigations must be conducted. This is echoed by 11% of respondents, who explained (based on either intuition or memory) that the reef is only partly protective, or that it depends on other reef-related conditions. Four interviewees also specified that the largest tsunami risk occurred at locations facing the gaps in the reef, a response empirically consistent with the laws of wave refraction.

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

4.2.2. Mangroves

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

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

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

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

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

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

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

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

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

Reviving this risk culture and risk memory involves periodic communication to keep people updated on individual and common safety measures. The rapid risk perception survey carried out for this study was part of this communication effort: it sparks the interest of the respondents and provides insights into the disparities in culture and education within the population. It was based on a total sample of 402 respondents. Online sample-size calculators, which are based on standard equations used in statistical power analysis and survey sampling techniques [146,147], recommend surveys of representative minimum sample sizes that vary as a function of target population size. At the 95% confidence level, the sample obtained for each age or birth (native or non-native) class in this pilot study provided results with an error margin of 6 to 12%. To reduce error margins to the conventionally acceptable 5% confidence level and attain the quantitative robustness required for political decision-making, it would be necessary to increase sample sizes in each of the above statistical classes to between 100 and 300 depending on total class population, i.e., in total somewhat more than 402. Clearly, such street surveys are time consuming and labor-intensive, but the survey shows that a representative study for a total population of ~230,000 (young children excluded) can be a rewarding 'first shot' without going through major operations and could be implemented on many other islands of a similar or smaller population size in the Pacific, Indian, Caribbean and Mediterranean. To go further on communication strategies, it would be also relevant to conduct longer semi-structured interviews with a shortlist of key informants.

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

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

In light of these observations, our methodology for mapping the coastal population generates a static representation of vulnerable areas. No distinction is made, for example, between daytime and nighttime: large industrial or commercial areas are included in the 'populated areas' but are only occupied during the day. Fishing is a common activity in New Caledonia [89], but details on activity patterns are scarce. Similarly, figures about tourist frequentation of small islands vulnerable to tsunami hazards off the mainland (where $z < 5$ m) are currently unavailable. More precise statistics could also be gained from including roads in the built-up areas GIS layer, combined with day- and nighttime analysis of population presence and interaction. One solution, used in several countries during the 2020 international Covid-19 crisis, proposes to track people using data provided by their mobile phones, a way to gather data at different times of the day [78]. Should data relating to population dynamics ever become available, the work on 'populated areas' could be refined by monitoring those dynamic parameters.

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

Figure 17

5. Conclusion

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

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

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

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

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

Figure 18

The data, tools, and mixed methodologies combined in this paper can be transferred to other disaster risk reduction contexts. Topographic and bathymetric data in New Caledonia itself could, for example, be updated to very high-resolution mapping and DEM with the use of LiDAR technologies. Closed questions such as those included in this rapid survey would gain from being added to the forthcoming national census questionnaires, next scheduled for 2023. The population mapping methodology provides a broad basis for future research work on population vulnerability or in cognate fields where there is an urgent need to know more precisely where people live and what their movements are. The study also revealed a gap in the BD TOPO NC concerning slum areas ('squats'), a useful lesson for other similar studies in other parts of the world, where precarious housing settlements may be absent from spatial databases. This must be compensated by using satellite imagery calibrated against field surveys to visualize all housing types and make sure that the administration of safe spaces through risk management science is systematic and socially just.

Author contributions

BT: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing - Original draft preparation; **JR**: Conceptualization, Methodology, Resources, Writing - Original draft preparation, Visualization, Supervision; **YG**: Methodology, Resources, Writing - Review & Editing, Visualization, Supervision; **CS**: Methodology, Resources, Writing - Review & Editing; **JA**: Funding acquisition.

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Figures

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

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

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

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

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

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

Figure 7. Schematic dasymetric evaluation of residents in ‘populated areas’ and ‘coastal populated areas’.

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

Figure 9. Population distribution on Lifou island.

Figure 10. Population distribution in Nouméa.

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

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

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

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

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

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

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

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

Table 1. Question sequence for the risk perception survey

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

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

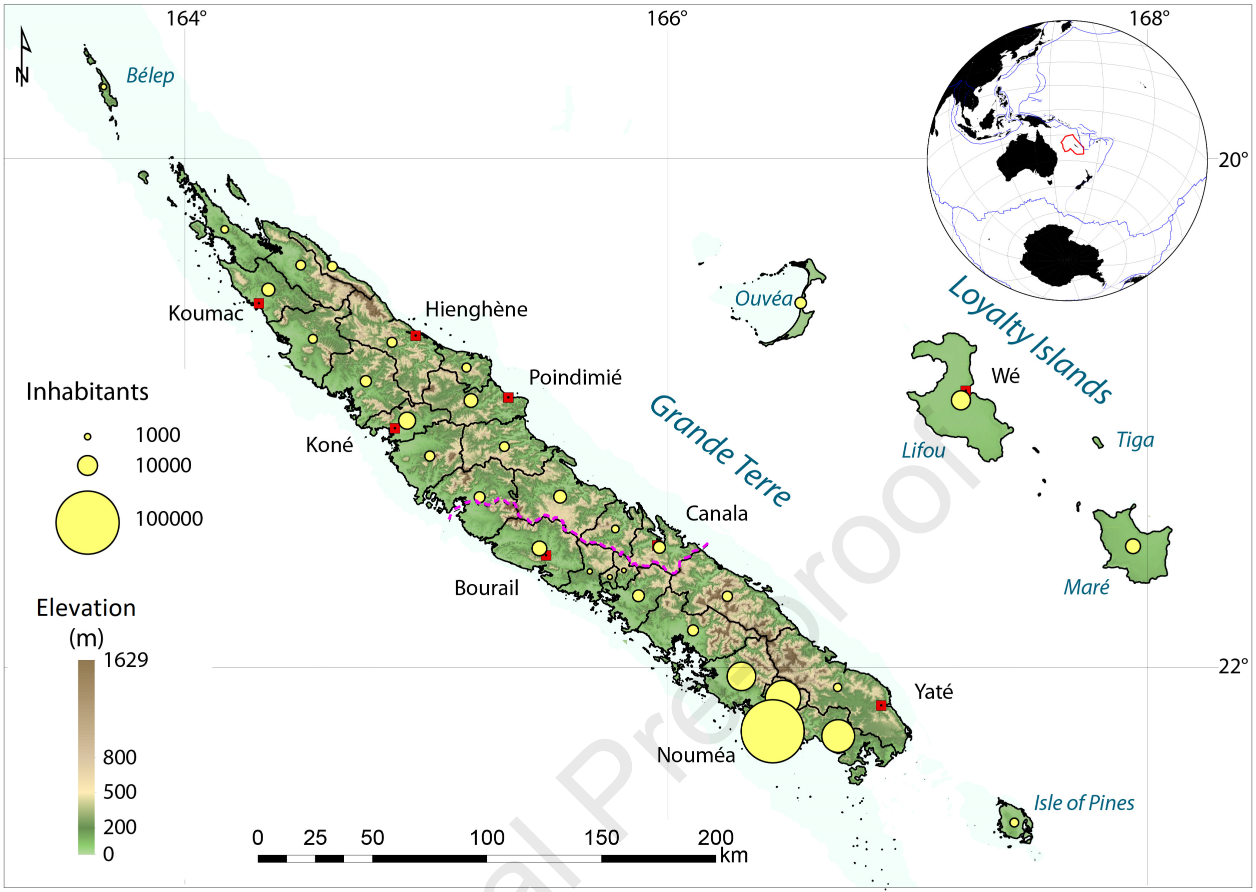
(e) The first response concerns coral reef protection, and the second mangrove protection: for example, “Yes – No” in column 3 means “yes, the coral reef protects, and no, the mangroves do not protect”.

(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)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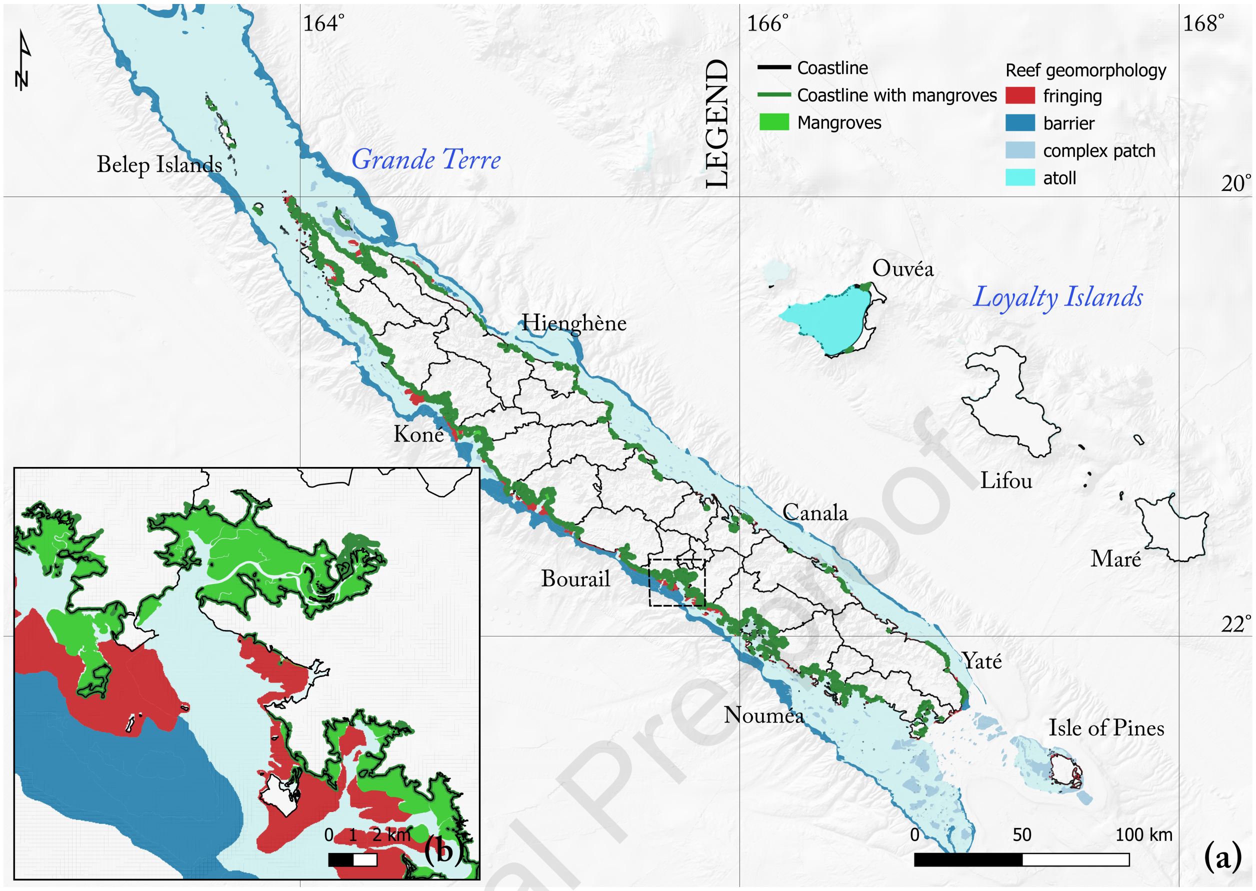

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Coastline
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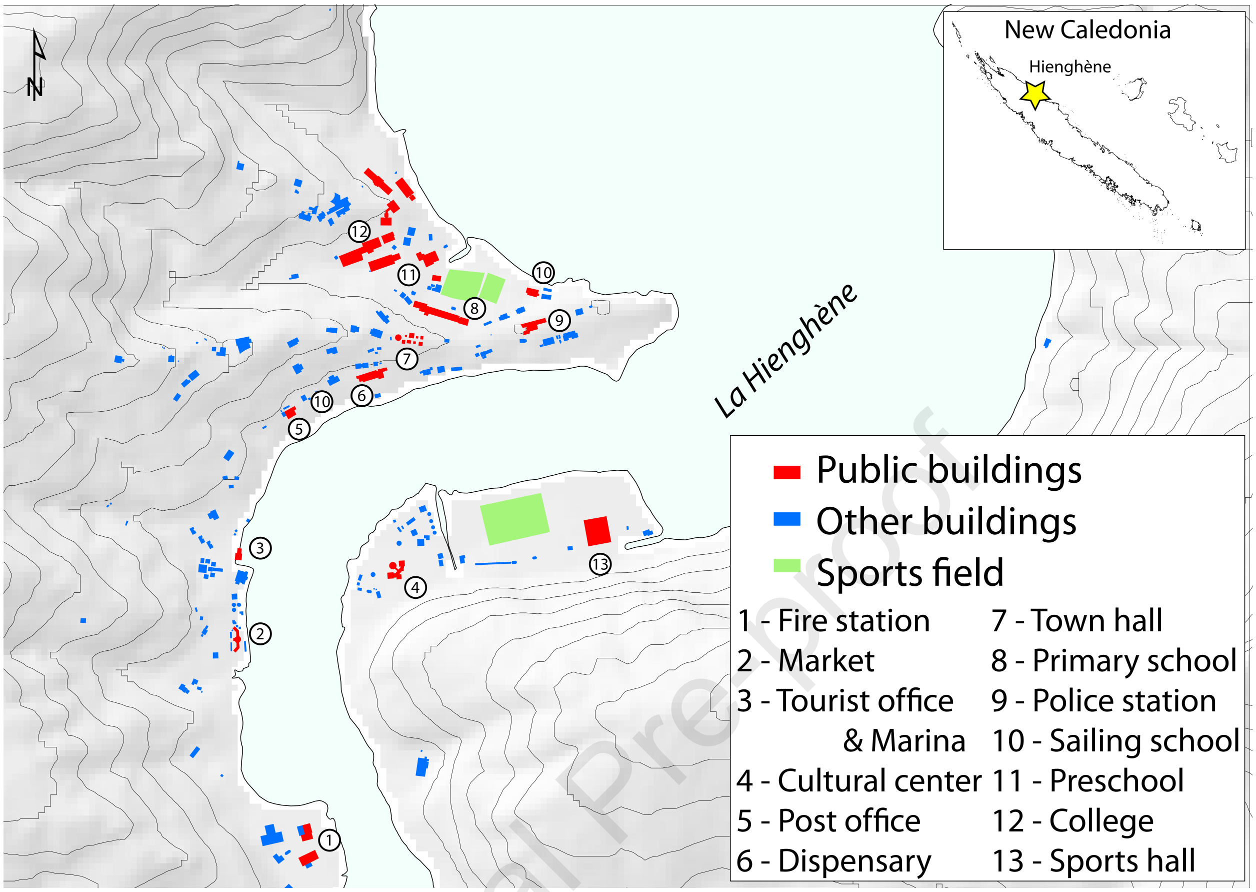
New Caledonia
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1 - Fire station
2 - Market
3 - Tourist office & Marina
4 - Cultural center
5 - Post office
6 - Dispensary
7 - Town hall
8 - Primary school
9 - Police station
10 - Sailing school
11 - Preschool
12 - College
13 - Sports hall
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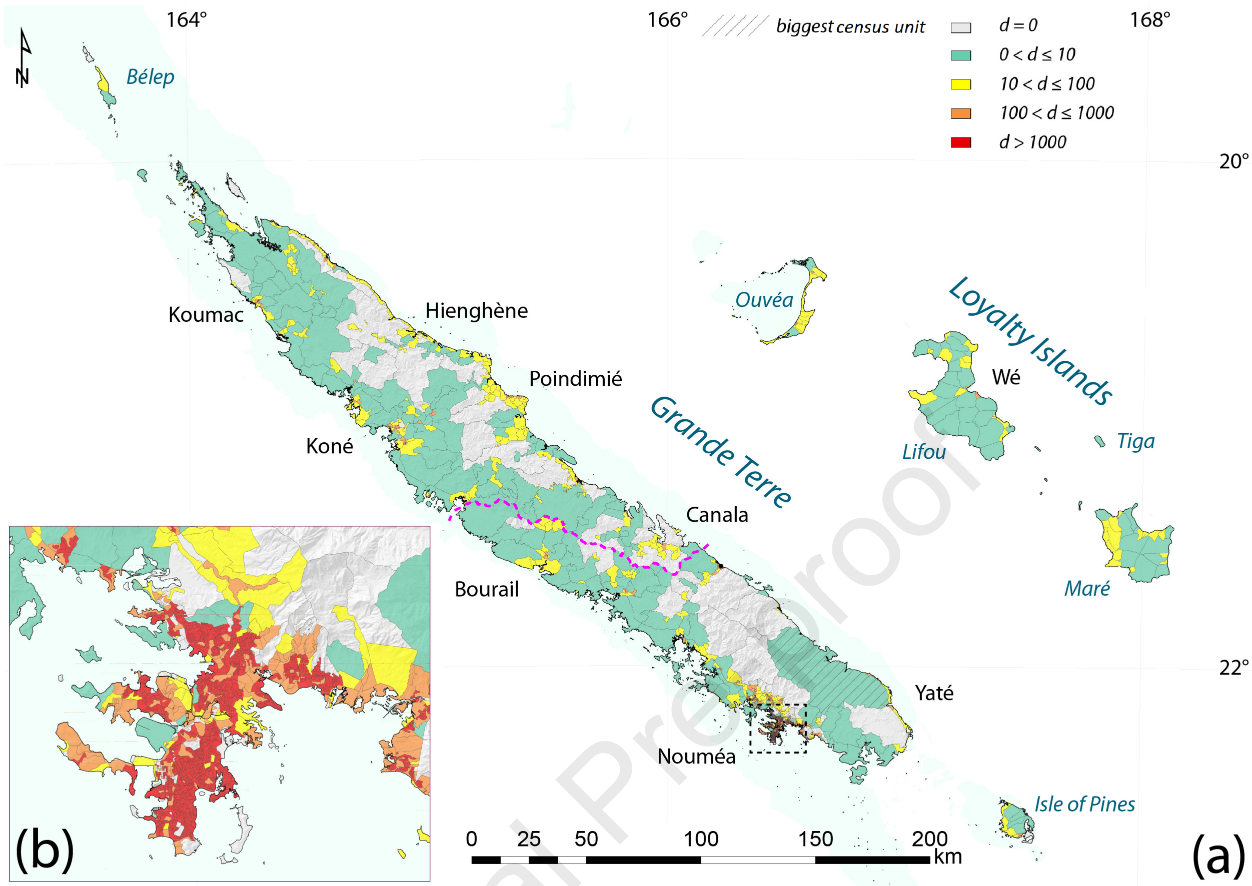
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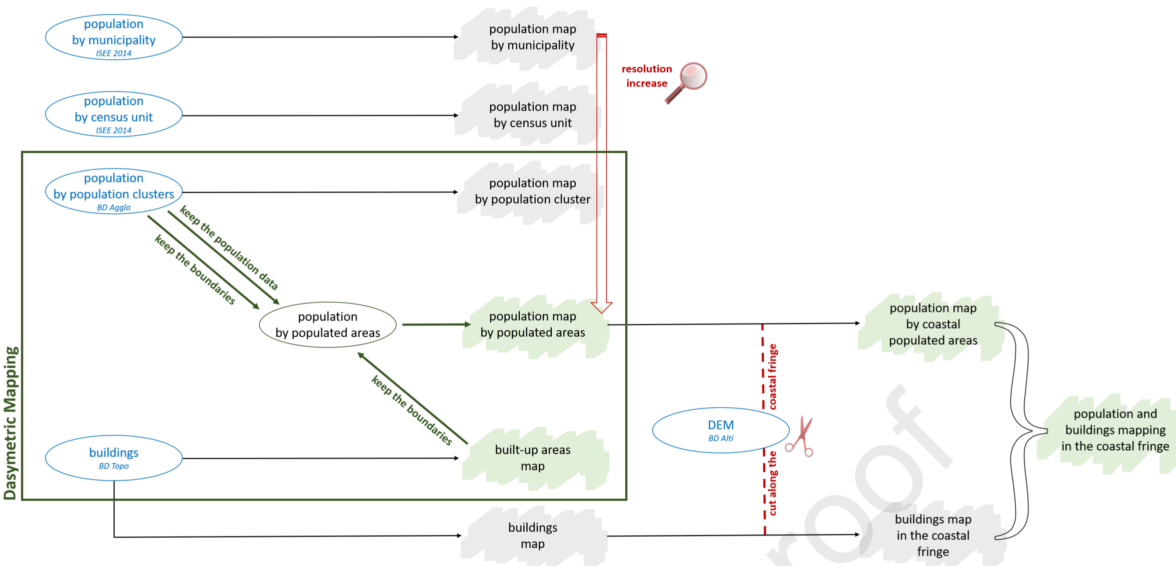
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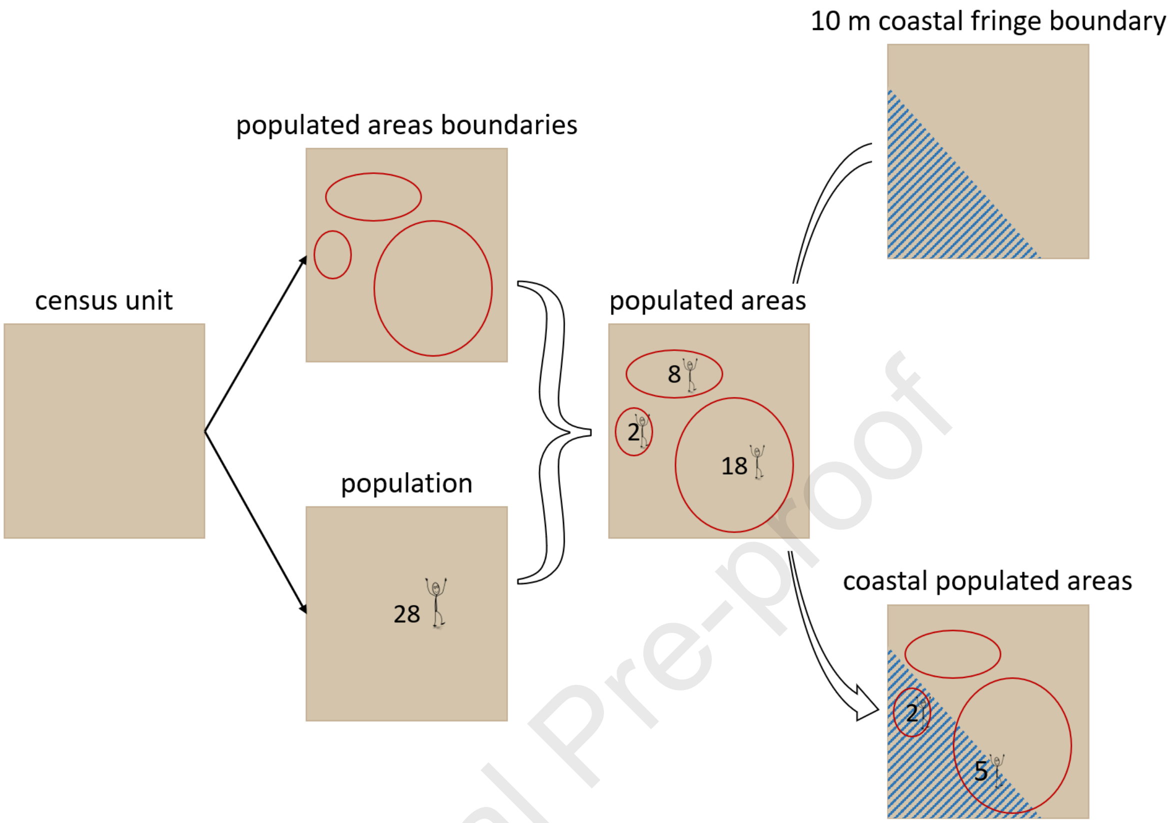
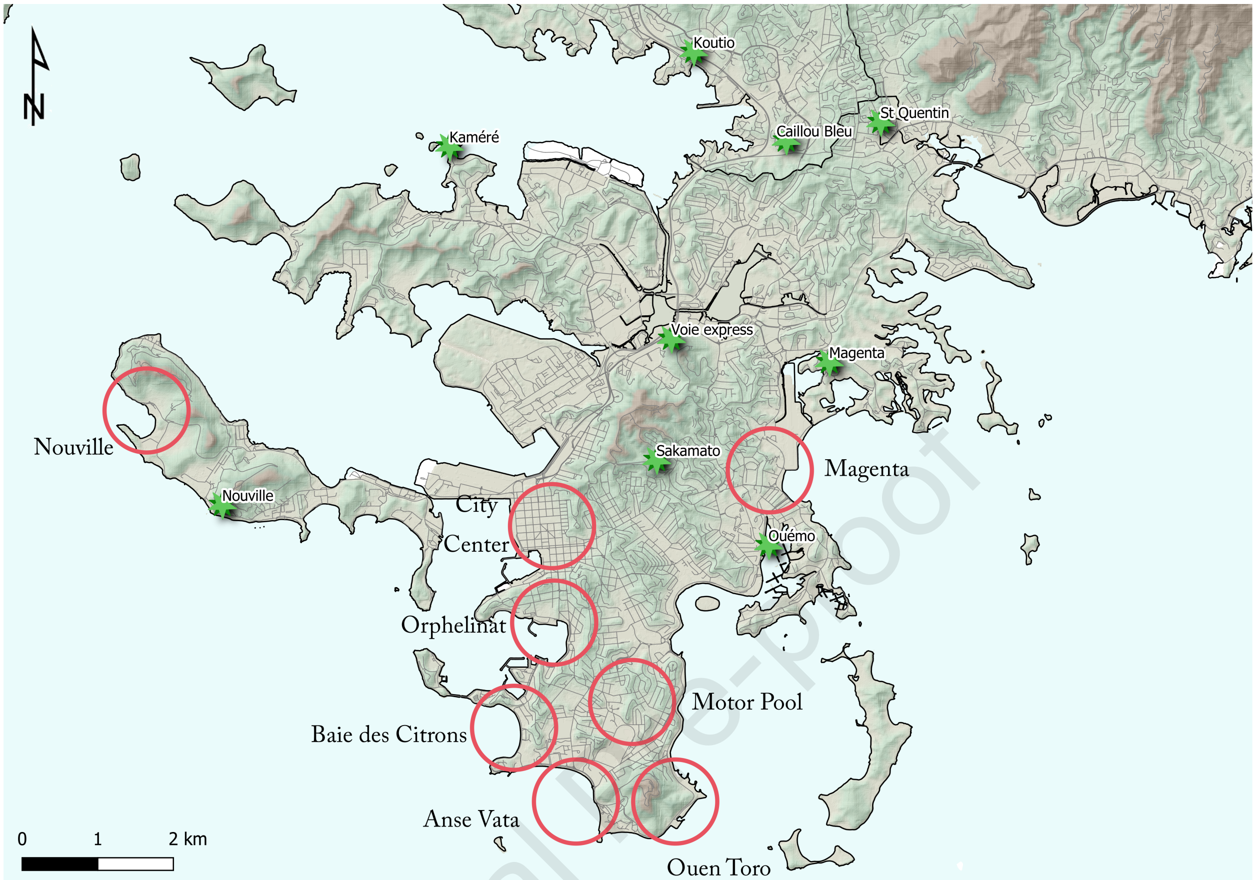
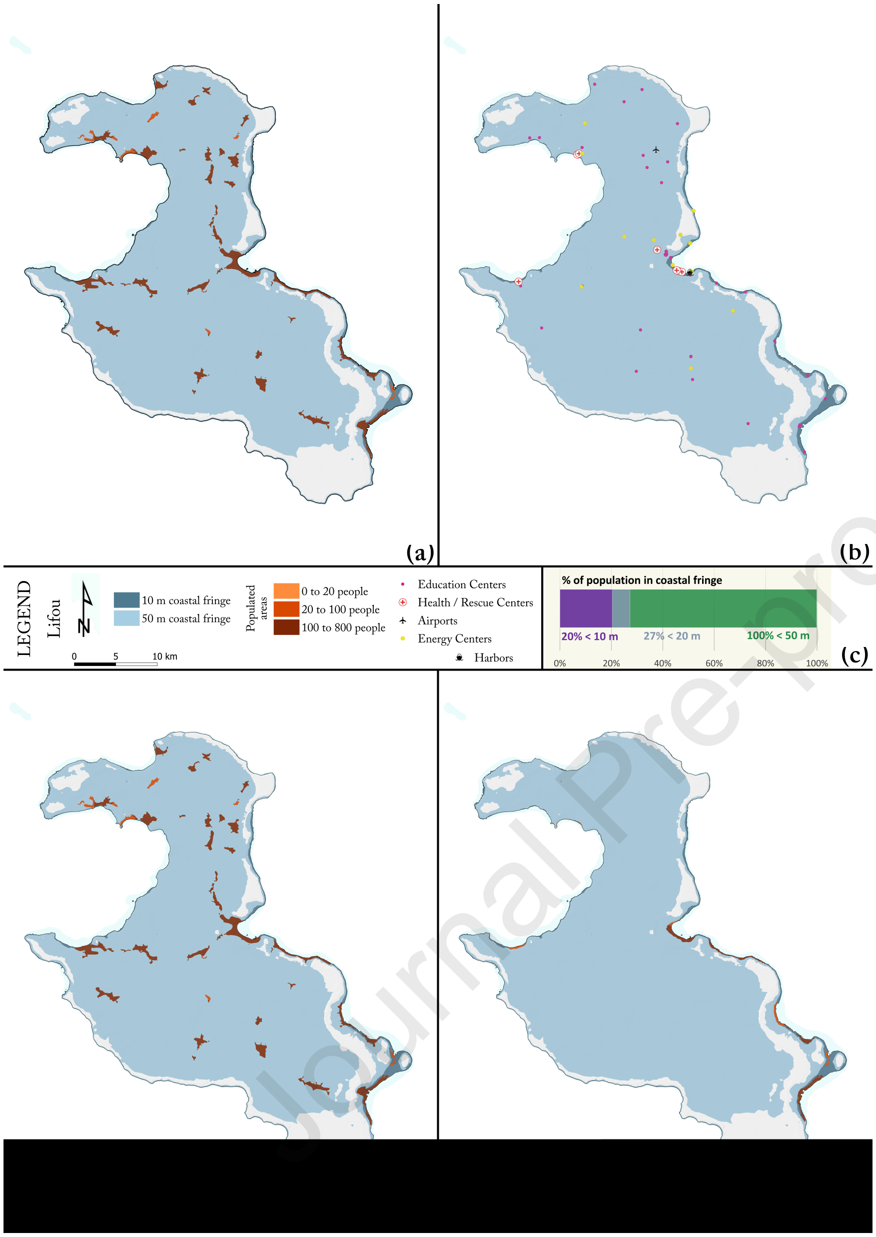
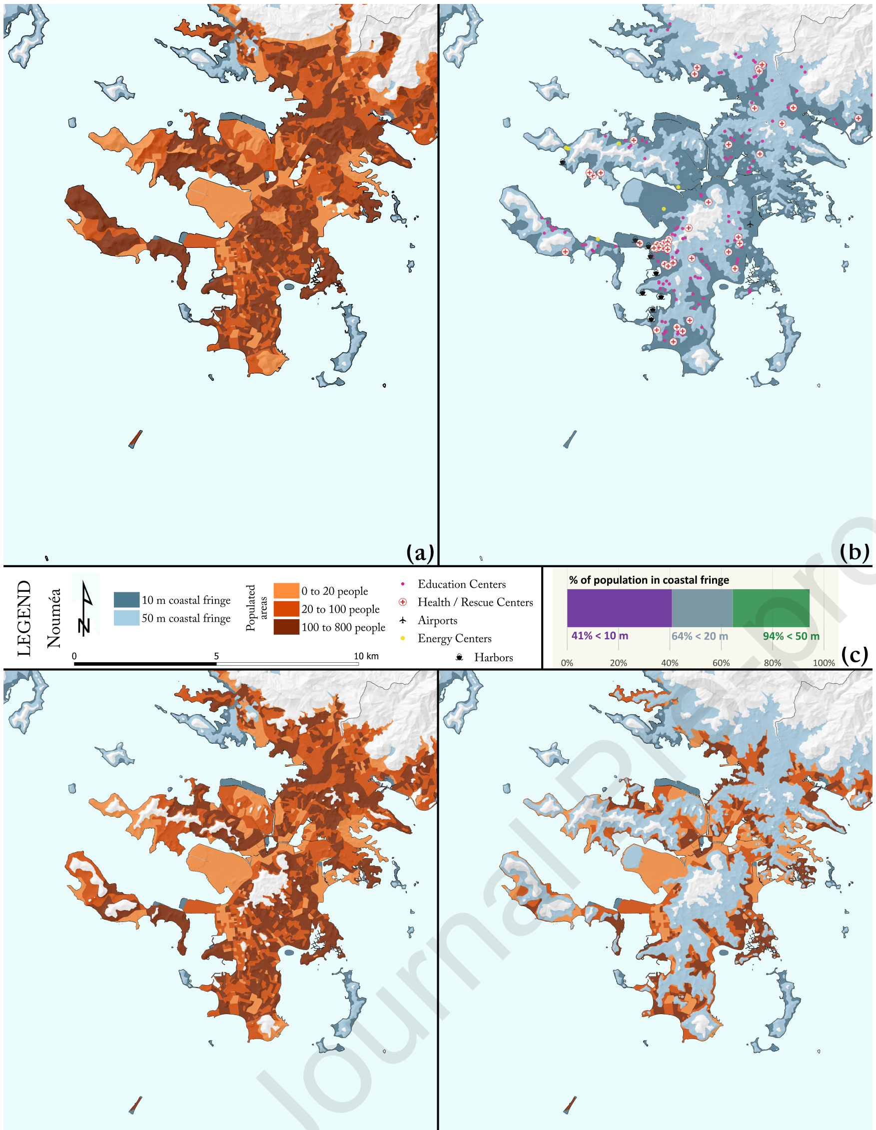
250
500 m

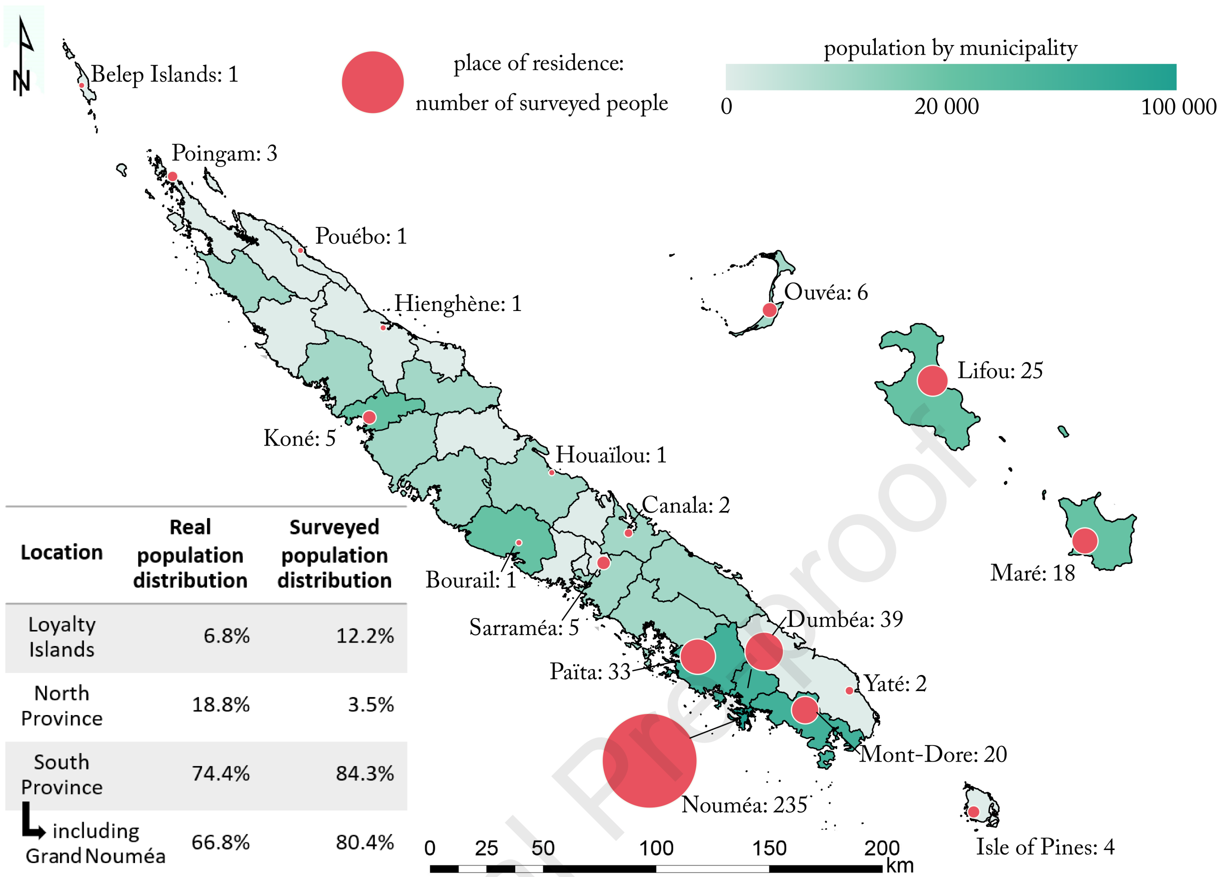

10 m coastal fringe boundary
populated areas boundaries
census unit
populated areas
8
2
18
population
28
coastal populated areas
2
5



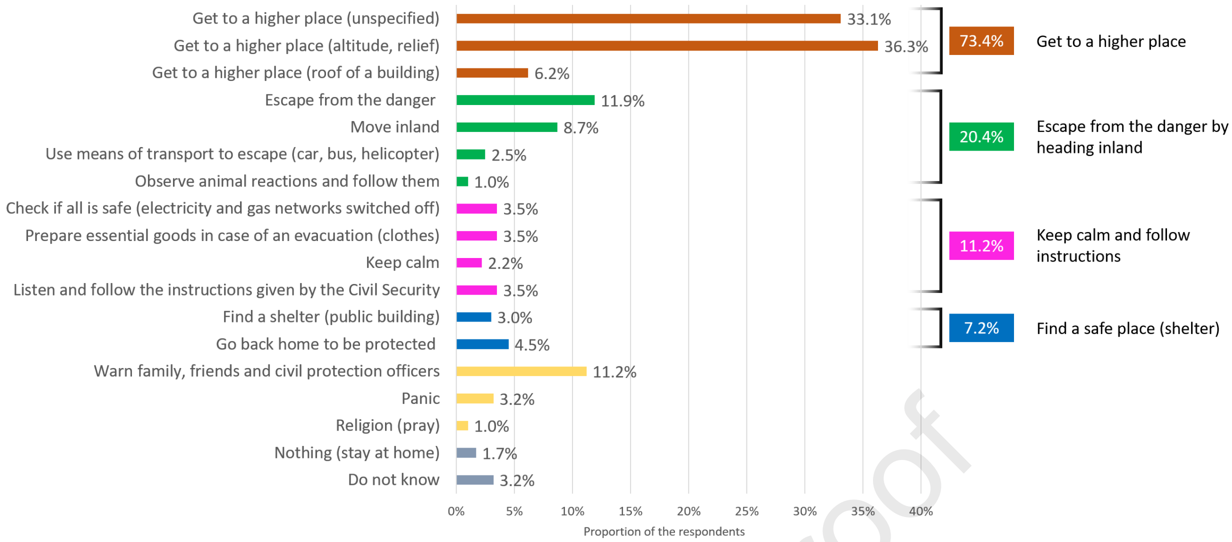
N
Koutio
St Quentin
Caillou Bleu
Kaméré
Voie express
Magenta
Nouville
Sakamato
Magenta
Nouville
City
Center
Ouémo
Orphelinat
Motor Pool
Baie des Citrons
Anse Vata
Ouen Toro
0
1
2 km

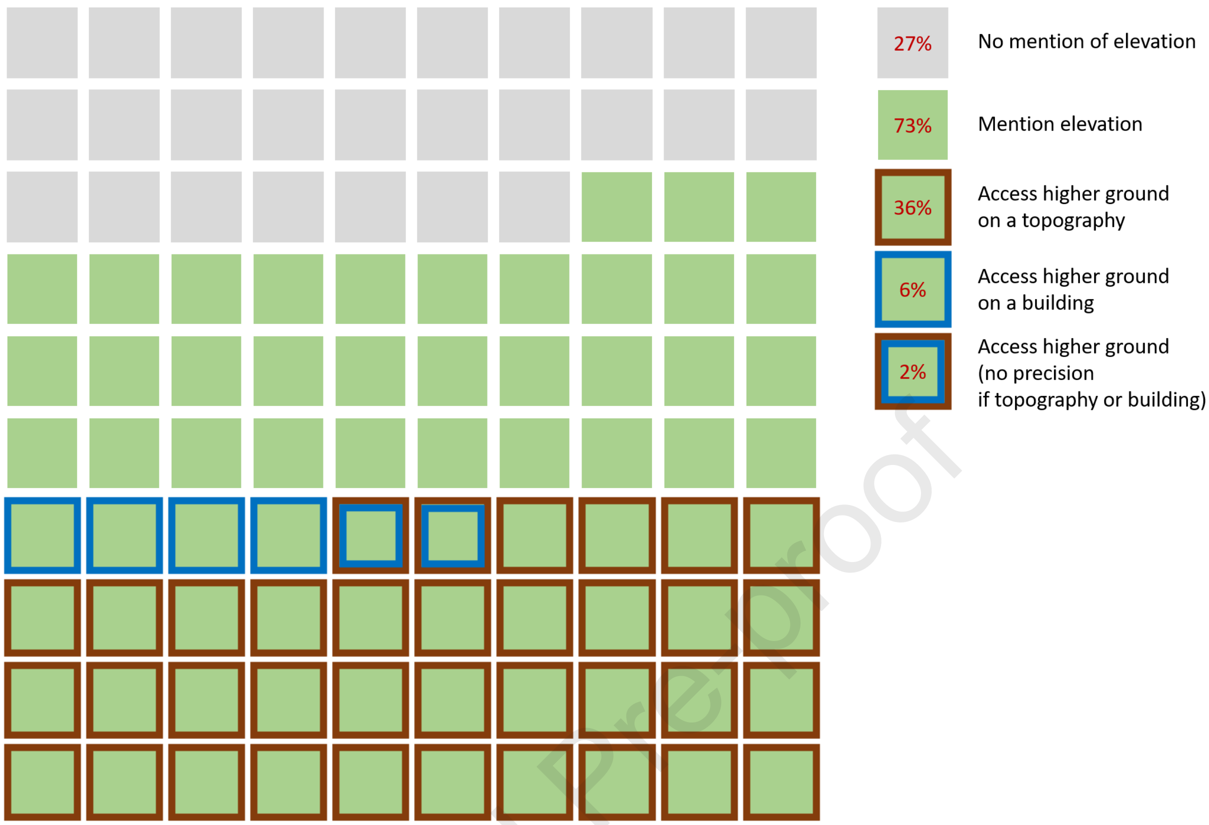

(a)
(b)
LEGEND
Lifou
N
0
5
10 km
10 m coastal fringe
50 m coastal fringe
Populated areas
0 to 20 people
20 to 100 people
100 to 800 people
Education Centers
Health / Rescue Centers
Airports
Energy Centers
Harbors
% of population in coastal fringe
20% < 10 m
27% < 20 m
100% < 50 m
0%
20%
40%
60%
80%
100%
(c)

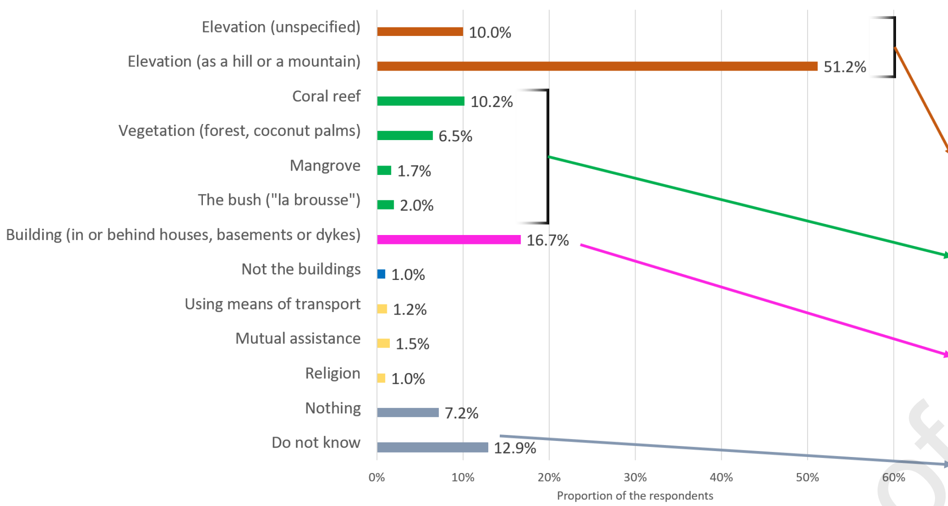

(a)
(b)
LEGEND
Nouméa
10 m coastal fringe
50 m coastal fringe
Populated areas
0 to 20 people
20 to 100 people
100 to 800 people
Education Centers
Health / Rescue Centers
Airports
Energy Centers
Harbors
0
5
10 km
% of population in coastal fringe
41% < 10 m
64% < 20 m
94% < 50 m
0%
20%
40%
60%
80%
100%
(c)



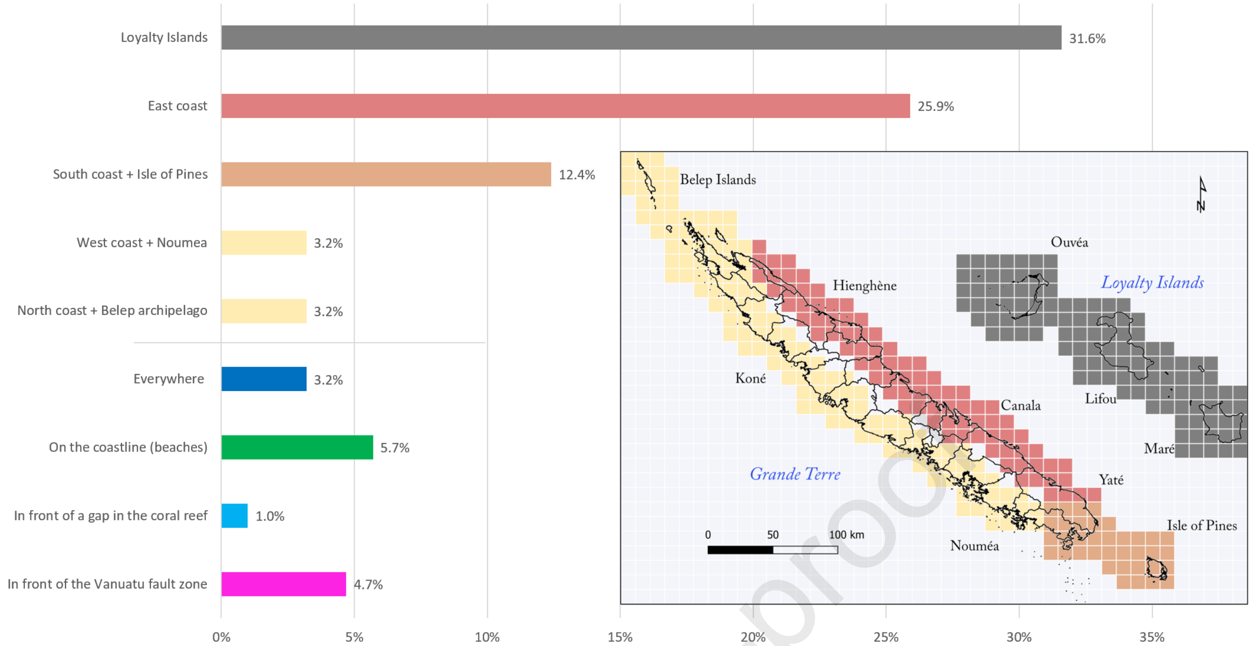
Location	Real population distribution	Surveyed population distribution
Loyalty Islands	6.8%	12.2%
North Province	18.8%	3.5%
South Province	74.4%	84.3%
↳ including Grand Nouméa	66.8%	80.4%


Get to a higher place (unspecified)
33.1%
Get to a higher place (altitude, relief)
36.3%
Get to a higher place (roof of a building)
6.2%
Escape from the danger
11.9%
Move inland
8.7%
Use means of transport to escape (car, bus, helicopter)
2.5%
Observe animal reactions and follow them
1.0%
Check if all is safe (electricity and gas networks switched off)
3.5%
Prepare essential goods in case of an evacuation (clothes)
3.5%
Keep calm
2.2%
Listen and follow the instructions given by the Civil Security
3.5%
Find a shelter (public building)
3.0%
Go back home to be protected
4.5%
Warn family, friends and civil protection officers
11.2%
Panic
3.2%
Religion (pray)
1.0%
Nothing (stay at home)
1.7%
Do not know
3.2%
0%
5%
10%
15%
20%
25%
30%
35%
40%
Proportion of the respondents
73.4%
Get to a higher place
20.4%
Escape from the danger by heading inland
11.2%
Keep calm and follow instructions
7.2%
Find a safe place (shelter)

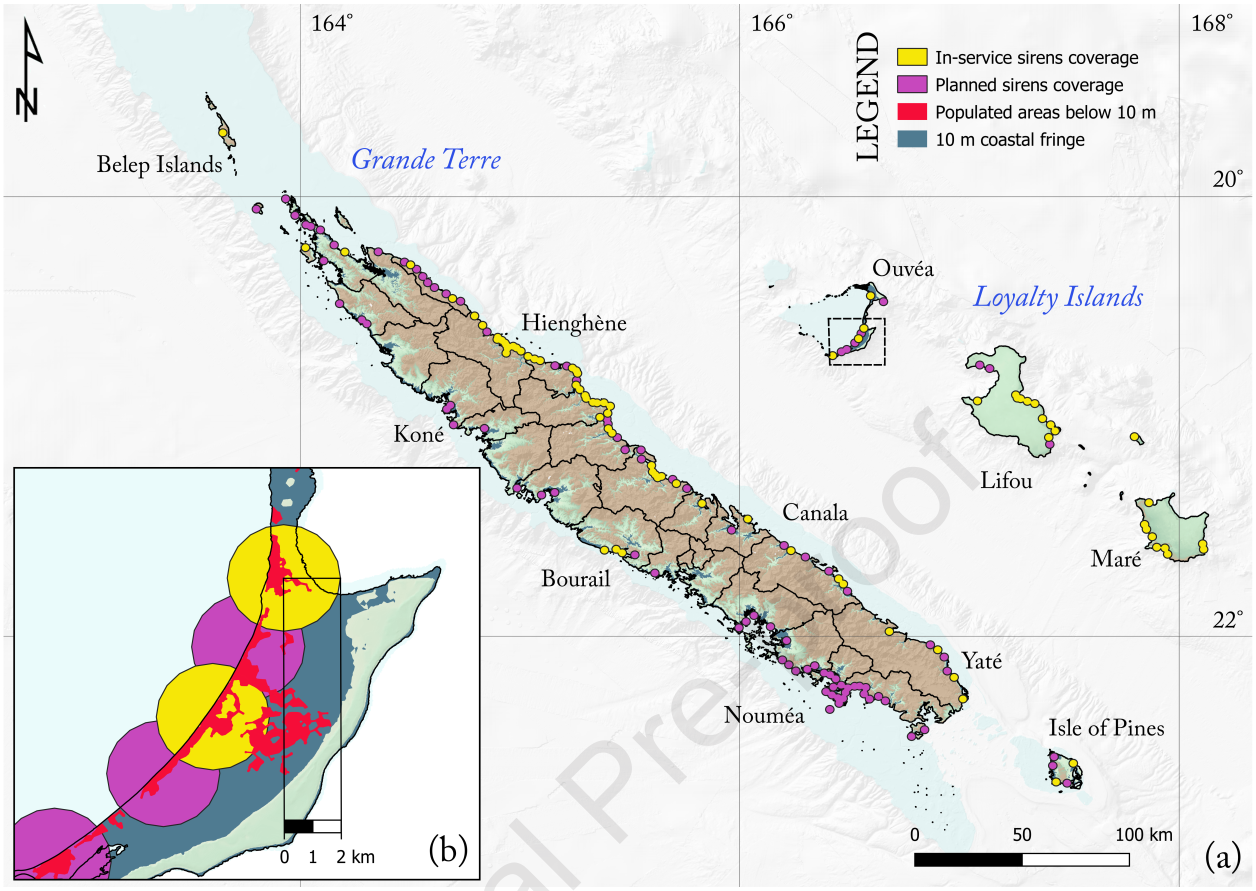

27%
No mention of elevation
73%
Mention elevation
36%
Access higher ground on a topography
6%
Access higher ground on a building
2%
Access higher ground (no precision if topography or building)



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

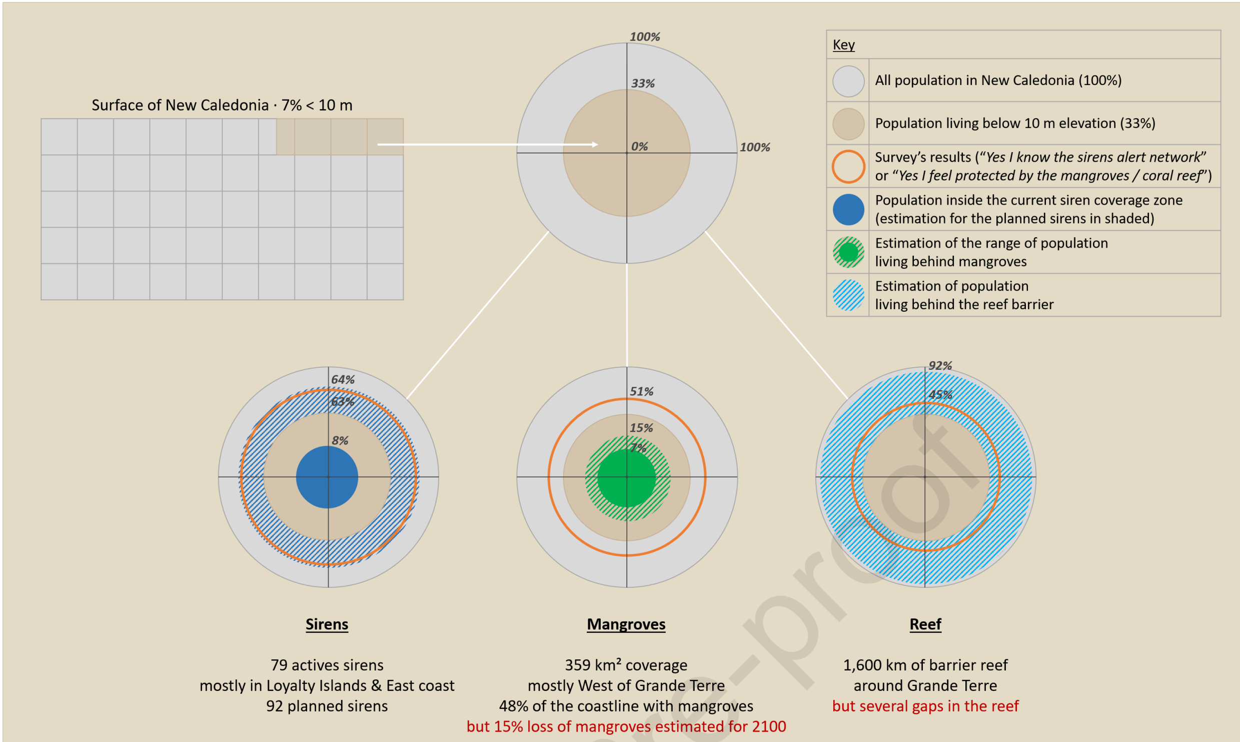


Loyalty Islands
31.6%
East coast
25.9%
South coast + Isle of Pines
12.4%
West coast + Noumea
3.2%
North coast + Belep archipelago
3.2%
Everywhere
3.2%
On the coastline (beaches)
5.7%
In front of a gap in the coral reef
1.0%
In front of the Vanuatu fault zone
4.7%
0%
5%
10%
15%
20%
25%
30%
35%
Belep Islands
Ouvéa
Hienghène
Loyalty Islands
Koné
Canala
Lifou
Maré
Grande Terre
Yaté
Isle of Pines
Nouméa
0
50
100 km



164°
166°
168°
20°
22°
LEGEND
In-service sirens coverage
Planned sirens coverage
Populated areas below 10 m
10 m coastal fringe
N
Belep Islands
Grande Terre
Ouvéa
Loyalty Islands
Hienghène
Koné
Lifou
Canala
Maré
Bourail
Yaté
Nouméa
Isle of Pines
0
50
100 km
(a)
0
1
2 km
(b)


COMMENT
LUTTER CONTRE
L'AEDES
AEGYPTI ?
PRÉVENTION DES RISQUES MAJEURS
ESSAI DU SIGNAL
D'ALERTE
TSUNAMI
ZONE A RISQUE DE TSUNAMI
Tous les 1er
MERCREDIS
du mois à midi
DOSSIER SUR LES
RISQUES
MAJEURS
DE LA
NOUVELLE-CALÉDONIE
NOUVEAU
Juicy
UN MAX de fruits et d'ÉNERGIE !


Surface of New Caledonia · 7% < 10 m
100%
33%
0%
100%
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
64%
63%
8%
51%
15%
7%
92%
45%
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

Highlights

- The population of New Caledonia (Western Pacific) is vulnerable to tsunami hazards
- A GIS-based mapping methodology and atlas of exposure to tsunami risk are presented
- A perception survey was conducted to assess risk awareness based on age and ethnicity
- Some mitigation options (reefs, mangroves, education, warning systems) are discussed
- The methodological package is transferable to other disaster risk reduction contexts

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: