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► **To cite this version:**

Bastien Bourlier, Franck Taillandier, Charlotte Heinzlef, Damien Serre, Corinne Curt. Spatial Assessment of Territorial Resilience to Floods Using Comprehensive Indicators: Application to Greater Papeete (French Polynesia). *Journal of Flood Risk Management*, 2025, 18 (1), 10.1111/jfr3.70005 . hal-04960119

HAL Id: hal-04960119

<https://uvsq.hal.science/hal-04960119v1>

Submitted on 21 Feb 2025

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SPECIAL ISSUE PAPER OPEN ACCESS

Spatial Assessment of Territorial Resilience to Floods Using Comprehensive Indicators: Application to Greater Papeete (French Polynesia)

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Received: 1 May 2022 | **Revised:** 9 December 2024 | **Accepted:** 16 December 2024

Funding: This work was supported by Projet ILOTS Défi CNRS IRD.

Keywords: decision-making | flooding | Polynesian High Islands | resilience modelling | spatial analysis | spatial decision support system

ABSTRACT

Flash floods and coastal flooding are more and more frequent and damaging in the context of climate change. In addition, the concentration of the population in urban areas contributes to increasing flood risk in these areas. Furthermore, not all territories are at the same level in their risk and resilience management approaches. Regarding this, the French overseas territories have been identified as particularly vulnerable to flood risk. This is the case for Tahiti, the main island of French Polynesia where the capital is located. It is a dense urban area subject to coastal and river flooding hazards, largely exacerbated by the physical environment. Our goal is to propose a method to assess flood resilience in Tahiti. We developed an indicator-based method and used GIS to produce and represent a spatial analysis of territorial resilience. We developed a list of comprehensive spatial indicators that take into account three main dimensions: a structural dimension (e.g., building resilience), an organisational dimension (e.g., the resilience of actions during crisis) and a socio-economic dimension (e.g., human economic capital). The final objective of this research is to design decision-making tools for territorial stakeholders to help them in long-term reflection and collaboration.

1 | Introduction

Disasters due to natural hazards have increased exponentially for half a century: whereas 711 disasters were recorded from 1970 to 1979, 3536 were recorded between 2000 and 2009 (WMO 2021). Flooding is largely responsible for this major increase. In 2020, major flood events were more than 20% above the annual average of the past 20 years (WMO 2021). We focus here on the human, material and financial aspects, as floods remain very damaging events (Vinet et al. 2012). Indeed, floods are the costliest disasters, since 1980 economic losses from flooding have averaged around 26 billion dollars a year (Marsh et al. 2021).

In the context of populations concentrated in urban areas because of a lack of available land, these areas become vulnerable to risk (Ehrlich et al. 2018). Furthermore, the complexity of urban systems makes the organisation of flood management more complicated (Heilemann et al. 2013). In this context, researchers and managers have developed new approaches for managing natural hazards. These methods try to reduce vulnerability, defined here as the propensity of territory to suffer damage, but also take into consideration the long-term challenges of sustainability and quality of life (Quenault 2014; United Nations 2021; Vigier et al. 2019). Some build their actions around the concept of urban resilience (Serre 2011). This can be extended to the concept of territorial

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resilience. Territorial resilience can be defined as the set of capacities of a territory and its physical and community components (population, institutions) to anticipate, respond, recover and adapt, following a disruptive event (Lhomme et al. 2010a; Propeck-Zimmermann et al. 2018; Serre 2011). Urban resilience and community resilience often focus on specific objects, even when considered broadly. Our approach to territorial resilience offers a broader perspective that captures the diversity inherent in the studied territory. This term enhances operational relevance to better address the challenges of spatial planning and governance within this territory (Brunetta et al. 2019).

Furthermore, these global observations are cumulated in certain territories, in particular tropical islands such as those of the French overseas territories. Many of these territories are particularly exposed to hazards and have very limited and incomplete risk management systems, in addition to strong structural and economic dependencies and social vulnerabilities (Heinzlef and Serre 2019; Nicolas et al. 2018). A French inter-ministerial report (Bourgeois et al. 2015) and a senatorial report (Arnell, Darnaud, and Jasmin 2018), dealing with flash flood risks in French overseas territories, concluded that these territories are highly affected by these hazards. However, this risk is poorly addressed by the national government and local authorities.

These characteristics can be found in the French Polynesian islands in the South Pacific area. French Polynesia is a territory largely subject to risks of flooding in the case of cyclonic events and heavy rainfall. Historically, the major events that have occurred go back several decades. In 1983, in Tahiti, during the cyclones Veena and Reva, the rivers overflowed their banks, causing much property damage. In 1998, there were two deaths and significant damage (bridges and roads) amounting to around US\$ 70 million and 600 inhabitants of the Hamuta valley were evacuated to Papeete (Larrue and Chiron 2010). On the other hand, the risk of river overflow is, although less damaging, very frequent in this territory, causing significant damage and regular functional blockages; the last major event was in 2017 and impacted economic activities and the operations of the international airport.

Given these observations of increasing risk and the limitations of risk management approaches, it is therefore relevant to work on methods of improving the territories' resilience to these risks with specific decision support systems (Heinzlef and Serre 2019; Jessin et al. 2022, 2024; Serre and Heinzlef 2021). The lack of information and the very specific characteristics of these areas require the development of a specific method (Meerow and Newell 2019). In order to answer this need, this paper seeks to answer the question: how to assess territorial resilience to flood risk in French Polynesia and in particular the island of Tahiti?

The aim of our study is to provide an account of the specific and systemic challenges facing the Polynesian territory. The concept of territorial resilience should enable us to integrate them into our thinking on land-use planning. Ultimately, the aim of this research is to help stakeholders to better rationalise their land-use planning options, manage the territory's critical infrastructures (CIs) and improve crisis management processes, so that they are better able to face risks by improving the resilience of their territory.

The approach proposed by this study relies on the development of spatially represented indicators by asking whether we can rely on spatial data and geomatic tools to evaluate territorial resilience components. Indeed, as highlighted in the literature and through the various practices of stakeholders exposed to risk, GIS tools and cartographic support are very relevant and operational tools in the study of risks and disaster management (Fekete et al. 2015; Kerguillec et al. 2019; Tomaszewski et al. 2020; Tzavella, Fekete, and Fiedrich 2017), and for assessing the exposure of territories to natural risks (Cariolet, Vuillet, and Diab 2019; Chen et al. 2016; Fekete 2020; Hissel et al. 2014; Lhomme et al. 2013; Rus, Kilar, and Koren 2018; Xiong et al. 2019). The main complexity of this work lies essentially in the ability to produce an evaluation that reflects the concept of resilience on a specific territory by producing results with an operational purpose.

The first section deals with the assessment of territorial flood resilience and the analysing of existing spatial methods and their operationalisation. Secondly, this study presents the assessment framework and methodology proposed while introducing the local context of French Polynesia in terms of risk management as well as organisational and socio-economic issues. Subsequently, this paper presents and analyses the results obtained from the method. Finally, the results are discussed and several research perspectives are described.

2 | Literature Review: Assessing Flood Resilience Using Indicators and Spatial Approaches

2.1 | Resilience Framework and Spatialised Assessment

Territorial resilience in the context of risk management implies taking into account all aspects of risk and crisis management. Moreover this notion is relevant to the understanding of temporalities, scales, territories and their components (Dauphiné et al. 2007; Koren, Kilar, and Rus 2017; Meerow, Newell, and Stults 2016; Ribeiro and Pena Jardim Gonçalves 2019). Resilience is an all-encompassing concept and allows for the consideration of different phases of the risk (before, during and after), with notably a particular focus on the post-crisis recovery and adaptation processes (Davoudi et al. 2012; Helfgott 2018; Klein, Nicholls, and Thomalla 2003; Quenault 2015). The multiplicity of definitions of the concept of resilience (Lhomme et al. 2010b; McClymont et al. 2020; Meerow and Newell 2019; Provitolo and Reghezza-Zitt 2015; Ribeiro and Pena Jardim Gonçalves 2019) implies that we must situate the concept in the study context to establish a precise conceptual framework that can be effectively operationalised. We define the concept of territorial resilience here as the set of capacities of a territory and its physical and community components (population, institutions) to anticipate, respond, recover and adapt, following a disruptive event.

All the elements of this definition provide a framework to build a resilience assessment methodology. Indeed, assessing resilience is of great interest for understanding territorial issues and creating new data and information to assist reflection. This assessment may involve mapping, which offers strong added value

in terms of operationalisation and decision support (Cariolet, Vuillet, and Diab 2019; Fekete 2020; Haraguchi and Kim 2016; Heinzlef, Becue, and Serre 2019a; Malczewski 2007; Propeck-Zimmermann et al. 2018; Saint-Marc et al. 2018). Because resilience is a multidimensional concept (Dos Santos 2020; MacAskill and Guthrie 2014), mapping is a relevant tool for studying various territorial components, representing social, economic and technical data.

The indicator-based approach has long been used for assessing geographical phenomena (Beccari 2016; Cutter, Burton, and Emrich 2010; Gallopin 1997; Lafitte et al. 2012; Merkle and Kaupenjohann 2000). An indicator fulfils two main functions: to synthesise the numerous parameters necessary to account for a situation and to simplify the understanding and interpretation of the results for the user. It is a relevant tool for territorial decision-making (de Sède-Marceau and Moine 2012; Heinzlef, Becue, and Serre 2019a; Joerin, Lebreton, and Desthieux 2005; Peacock et al. 2010; Quillet et al. 2019; Schumann 2016). Our assessment model will therefore be based on various indicators of resilience which will then be represented spatially.

2.2 | Multidimensional Assessment Models

A variety of studies are based on the systemic assessment of resilience using a cartographic approach based on spatial information and spatialised indicators (Alberico, Iavarone, and Petrosino 2020; Cariolet, Vuillet, and Diab 2019; Cimellaro et al. 2016; Cutter, Ash, and Emrich 2014; Rus, Kilar, and Koren 2018; Serre and Heinzlef 2018). Many of these works focused on assessing resilience in a holistic way and proposed a categorisation of resilience indicators into several broad dimensions. The main dimensions used are as follows:

- The social dimension deals with the social characteristics of a population, their capacities to face risk and their risk perceptions (Asadzadeh et al. 2017; Cai et al. 2016; Cimellaro et al. 2016; Cutter 2016; Cutter, Ash, and Emrich 2014; Fekete 2018; Heinzlef, Becue, and Serre 2019b; Joerin et al. 2014; Peacock et al. 2010; Saja et al. 2019; Zheng et al. 2018).
- The community dimension encompasses collective resilience processes and self-organisation (Cai et al. 2016; Cutter, Ash, and Emrich 2014; Frazier et al. 2013; Peacock et al. 2010).
- The economic dimension is often approached from the point of view of potential economic losses related to a crisis considering business and property damage (reactivation) (Asadzadeh et al. 2017; Cai et al. 2016; Cimellaro et al. 2016; Cutter 2016; Cutter, Ash, and Emrich 2014; Heinzlef, Becue, and Serre 2019b; Joerin et al. 2014; Martinelli et al. 2014; Peacock et al. 2010; Saja et al. 2019).
- The technical and urban environment dimensions cover the building characteristics of the technical networks and CI of the territory (Alberico, Iavarone, and Petrosino 2020; Asadzadeh et al. 2017; Cimellaro et al. 2016; Cutter, Ash, and Emrich 2014; Serre and Heinzlef 2018).

- The environmental dimension considered in some works includes the environmental and physical characteristics of the territories (Alberico, Iavarone, and Petrosino 2020; Cutter et al. 2008; Cutter, Ash, and Emrich 2014; Moghadas et al. 2019; Zheng et al. 2018).
- The organisational or governance dimension focuses on the risk management process of the territory (management and development plan) (Cutter, Burton, and Emrich 2010; Cutter, Ash, and Emrich 2014; Saja et al. 2019).

The common objective of these works is to produce mappable data (priority use of GIS) using indicators available in institutional or non-institutional databases of the territory. Most often the logic is therefore top-down (Alberico, Iavarone, and Petrosino 2020; Cariolet, Vuillet, and Diab 2019; Cutter 2016; Moghadas et al. 2019) using data available at the administrative or census scales. While interesting, these methods of calculation and representation have some shortcomings (the completeness of the indicators selected, the detail of the information (spatial scale), the risk-specificity of the method or data available to feed these models). Most often these studies give a vision of the inherent resilience of the territory rather than the so-called adaptive resilience. In other words, it gives an instant picture of a territory and makes it more difficult to assess long-term dynamics. Nevertheless, they provide a comprehensive understanding of the territory.

2.3 | Monodimensional Models

Other works with a cartographic focus address more specific domains of resilience, especially in the context of flood resilience studies. These thematic studies give a more detailed account of certain processes. Regarding technical and infrastructural resilience, urban and CI studies propose to identify the consequences of failures on urban networks (movement of people, emergency services, economic impacts) such as the road network (Dierich et al. 2019; Tzavella, Fekete, and Fiedrich 2017) and electricity networks (Pant et al. 2018; Russo et al. 2020; Sánchez-Muñoz et al. 2020). Firstly, the road network is studied as a vector of movement in the territory before or during the crisis, with intrinsic vulnerabilities (roadway, bridges), while highlighting the vulnerability of certain neighbourhoods or CI accessibility (hospitals, fire stations, sewerage system). Secondly, regarding the electricity network, failures are most often studied at the level of punctual CIs as transformers, considered as critical nodes. Finally, the study of technical networks makes it possible to consider the question of domino effects in times of crisis, causing direct and indirect impacts (Fekete 2019).

On the other hand, the consideration of governance in risk management is an aspect of resilience rarely present in operational assessment strategies. Disaster governance consists of 'the interrelated set of norms, organisational and institutional actors and practices [...] that are designed to reduce the impacts and losses associated with disasters' (Tierney 2012). Risk governance will therefore influence community resilience, as effective disaster governance produces resilience (Djalante, Holley, and Thomalla 2011). Sometimes, this organisational dimension can be observed through the territorial reality of the action of

risk actors (Toubin et al. 2015; Villagra and Quintana 2017). It seems relevant to explore these spatial approaches to organisational resilience.

2.4 | Lessons Drawn From the Literature Review

The application of these specific spatialised methods to technical and organisational aspects allows us to deepen the concept of territorial resilience. We can even go further and assume that they can be associated with holistic spatialised index methods and with socio-economic indicators frequently implemented in the holistic designs presented above (population characteristics, economic resources, etc.). It should be noted that we do not retain an environmental dimension which seems to be a contextual aspect, relevant in the case of a generic multirisk assessment, but less in our context with specific territorial characteristics for a particular risk. Thus, we synthesise our framework through three main dimensions: socio-economic, technical and organisational (Figure 1), identified as the main vectors of a global understanding of the concept of territorial resilience. We propose a comprehensive spatialised approach for several methods specific to the different domains of resilience studies.

3 | Case Study

3.1 | Case Study Description

The archipelago of French Polynesia is located in the middle of the Pacific Ocean, south of the equator. The island of Tahiti, located between 17°40'S and 149°28'W, is in the southeast of the Society Archipelago. It is a high island characterised by a marked relief and low coastal plains where problems are concentrated, with poorly controlled urbanisation and therefore subject to strong pressure on ecosystems (Duvat 2015; Oppenheimer et al. 2019). Thus, several major risks are concentrated in these areas, notably flood and submersion. Submersion can be caused by seasonal swells (winter) or cyclonic swells (cyclone season). Flood events are due to torrential flows (frequent flash floods but occasionally exceptional overflowing). Downstream on the

coastal plain, the flood risk is more extensive due to the more even morphology.

Risk management in the Polynesian territory has many limitations at the political and organisational levels. The territory is characterised by a number of shortcomings in terms of management planning policies, the organisation of prevention and in the post-crisis period with the absence of insurance processes, for example. The original institutional framework of French Polynesia makes risk management more complex than elsewhere due to its highly autonomous status (Bambridge et al. 2012; Stahl 2018). Indeed, the administration and, as a result, the risk management process have a dual dimension with competences shared between the central government (France) and local government (French Polynesia). Therefore, the French government is responsible for crisis management while the local government (French Polynesia) deals with land-use planning and waterway management. This complex division leads to organisational uncertainties.

3.2 | Levels of Analysis

The assessment of resilience can be understood at several levels, requiring varying assessment and analysis scales. In this work, a territory is first highlighted and studied in priority, Greater Papeete located on the western coast of Tahiti Island. It is of interest because of CI concentration, a dense population, high-risk neighbourhoods and therefore major development issues. Moreover, it is the only gateway to the whole territory for goods and people are located here (commercial port and airport). Finally, the whole island of Tahiti will also be studied due to issues such as commuting, territorial continuity and the accessibility of isolated areas.

We distinguish two dimensions: a scale of analysis (the territory studied) and an assessment scale (the information mesh). The main assessment scale chosen is the census district developed by ISPF (Statistical Institute of French Polynesia) due to the accessibility, quality and territorial scope of the data. Thus, through the census districts, we analyse the dynamics within neighbourhoods, municipalities and the agglomeration as a whole (Figure 2).

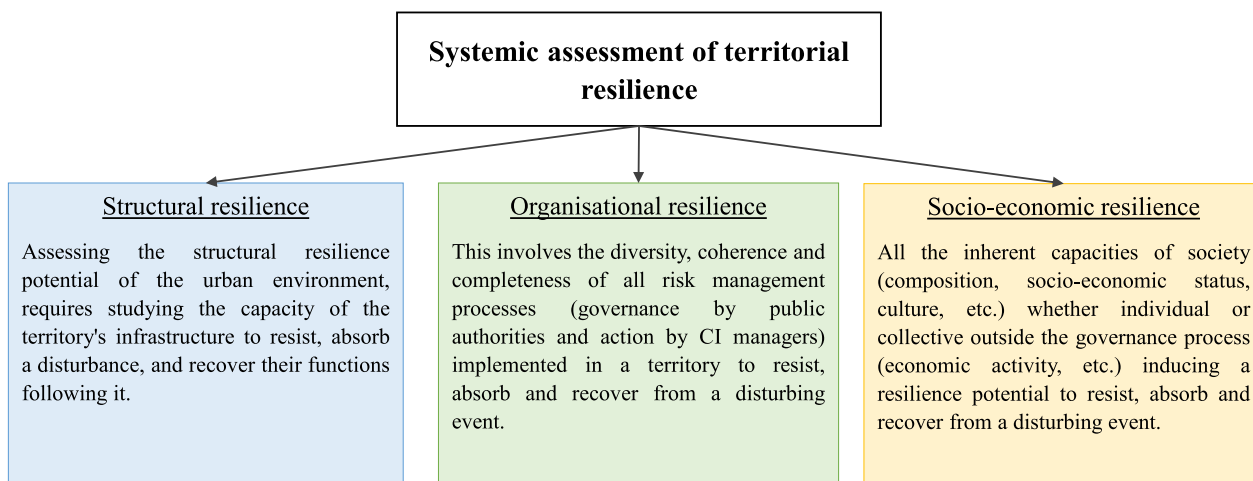


FIGURE 1 | Conceptual framework for resilience assessment.

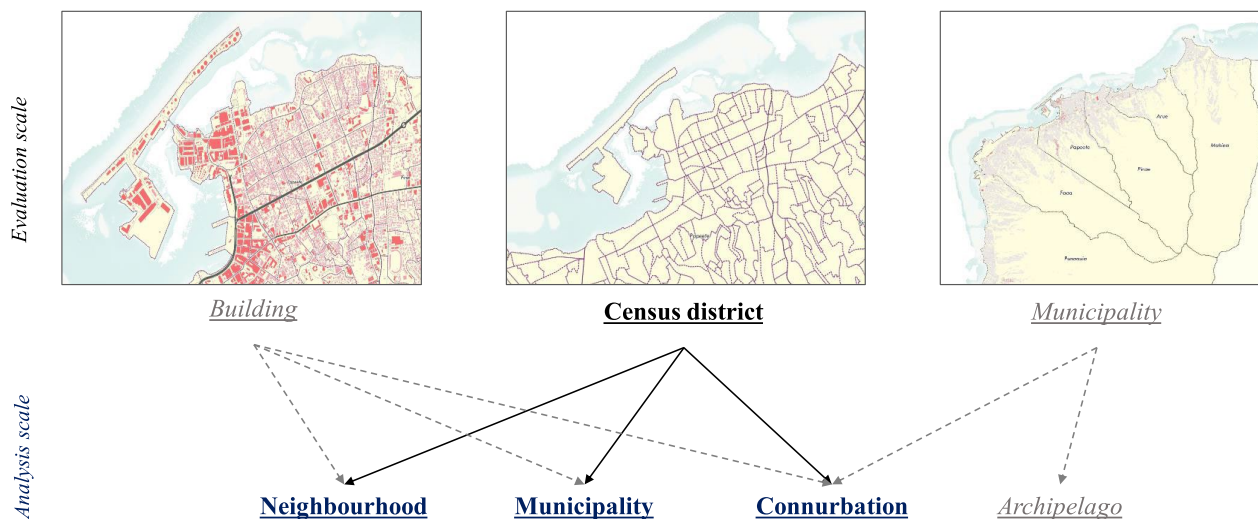


FIGURE 2 | Organisation of scales of assessment and analysis, implementation and perspectives.

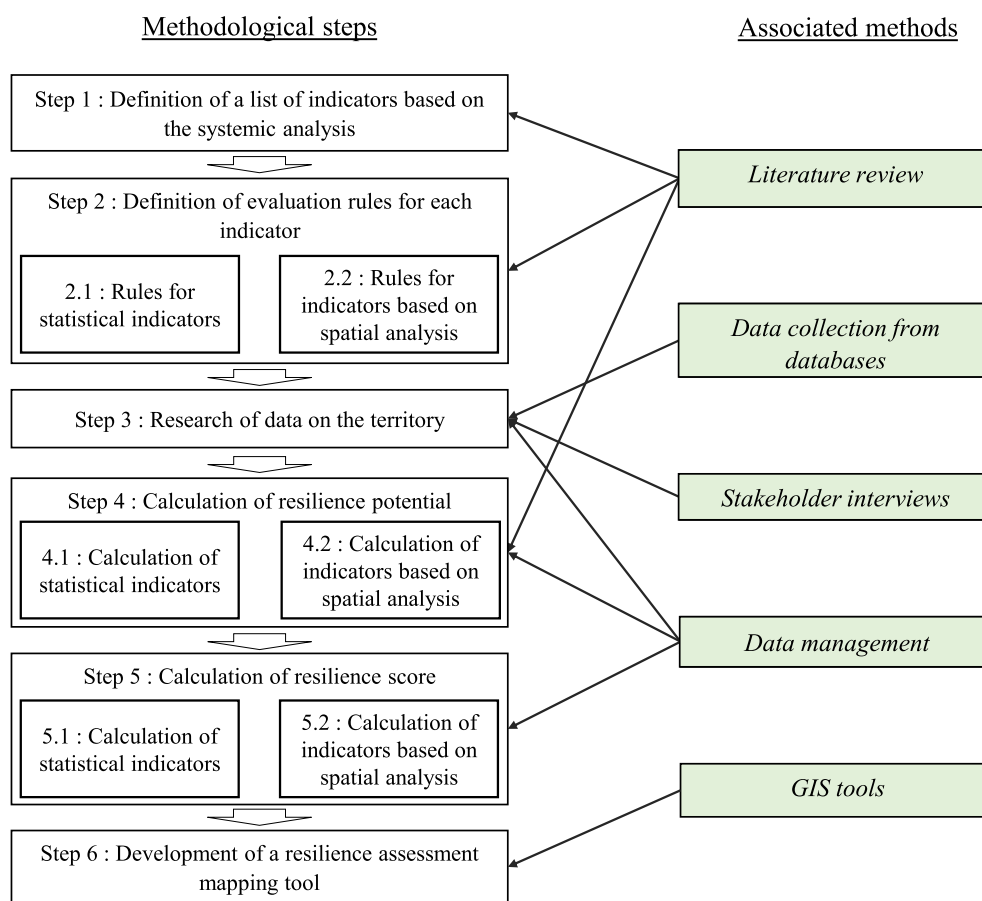


FIGURE 3 | Development of a map-based resilience assessment model.

4 | Methodology to Assess Territorial Resilience

4.1 | General Assessment Methodology

The approach relies on the spatialisation and the use of mapping tools to represent this territorial resilience specifically on the Greater Papeete. The method is composed of six successive steps (Figure 3).

The first step is the identification and formalisation of indicators based on the existing literature and their consistency regarding the perspective chosen (spatialised, adapted to the territory studied). The second step consists of the definition of assessment rules for each indicator based on existing models and by analysing the positive and negative impacts of each indicator according to its value for resilience. The third step is to collect data on the territory to assess the indicators (Step 3). This step

TABLE 1 | List of territorial resilience indicators.

Resilience dimension	Indicator	Definition	Homogeneous sub-set	Impact on resilience	Reference
Socio-economic resilience of communities	(1) Age of the population	The age categories of people will influence their ability to react during a disruptive event	0–10 years old 11–60 years old Over 60 years old	Negative Positive Negative	Cutter, Burton, and Emrich (2010), Daddoust et al. (2018), Fekete (2009), Heinzlief, Becue, and Serre (2019), Morrow (2008)
	(2) Study level	A higher level of education allows for better understanding of warning information, better access to recovery information and increased problem-solving capacity	No degree Baccalaureate and higher	Negative Positive	Cutter, Burton, and Emrich (2010), Fekete (2009), Heinzlief, Becue, and Serre (2019), Morrow (2008)
	(3) Employment status	Being active promotes access to financial and technical resources and thus promotes the resilience potential of individuals	Working Non-working	Positive Negative	Fekete (2009), Heinzlief, Becue, and Serre (2019), Moghadas et al. (2019)
	(4) Car availability	Having at least one car per household improves people's ability to travel	At least one car No car	Positive Negative	Cutter, Burton, and Emrich (2010), Heinzlief, Becue, and Serre (2019b), Tierney (2012)
	(5) Presence of floors	Floors provide a refuge in the event of flooding and increase the potential for resilience	0 One and more	Negative Positive	CEPRI (2010)
	(6) Access to running water	A household with access to water has a greater potential for resilience	Access No access	Positive Negative	Cutter, Emrich, and Burton (2010), Fekete et al. (2021)
	(7) Access to electricity	A household with access to electricity has a greater potential for resilience	Access No access	Positive Negative	Cutter, Emrich, and Burton (2010), Fekete et al. (2021)
	(8) Access to the internet	A household with access to the internet has a greater potential for resilience (access to information, communication)	Access No access	Positive Negative	Cutter, Burton, and Emrich (2010); Cutter, Emrich, and Burton (2010)

(Continues)

TABLE 1 | (Continued)

Resilience dimension	Indicator	Definition	Homogeneous sub-set	Impact on resilience	Reference		
Socio-economic resilience of communities	(9) Access time to health facilities	The closer people are to health facilities, the more resilient they will be to flooding in times of crisis	0–3 min	Positive	Asadzadeh et al. (2017), Cutter, Burton, and Emrich (2010), Heinzlief, Becue, and Serre (2019a), Moghadas et al. (2019), Tzavella, Fekete, and Friedrich (2017)		
			3–6 min	Positive			
	(10) Access time to infrastructure providing basic necessities	The closer people are to an infrastructure that provides basic necessities, the greater their potential for resilience	6–10 min	Negative			
			+ of 10 min	Negative			
			0–3 min	Positive		Fekete, Tzavella, and Baumhauer (2017)	
			3–6 min	Positive			
	(11) Density of commercial structures	The more commercial structures an area has, the more resilient the area has the potential to be due to its dynamism	6–10 min	Negative			
			+ of 10 min	Negative			
	Infrastructure resilience	(12) Balance of business start-ups and closures	A territory with a high rate of business creation is a dynamic territory and therefore with greater potential for resilience	Number of infrastructures	Impact according to the classification	Asadzadeh et al. (2017), Cutter, Burton, and Emrich (2010), Heinzlief, Becue, and Serre (2019), Martinelli et al. (2014), Tierney (2012)	
				Creation/ Breakdown rate	Impact according to the classification	Cutter, Burton, and Emrich 2010, Heinzlief, Becue, and Serre (2019)	
		(13) Date of construction of the buildings	Older buildings have less resilience potential than newer buildings	Before 1997	Negative		Alberico, Iavarone, and Petrosino (2020), Chao, Ghansah, and Grant (2021), Cutter, Burton, and Emrich (2010), Heinzlief, Becue, and Serre (2019)
				After 1997	Positive		
	(14) Building material	A building constructed with 'heavy' materials has a better resistance capacity and resilience potential	Hard	Positive		Alberico, Iavarone, and Petrosino (2020), Cutter, Burton, and Emrich (2010), Franco et al. (2010), Heinzlief, Becue, and Serre (2019), Xian et al. (2018)	
			Other (wood, plywood, bamboo ...)	Negative			
			No foundation	Negative		Chao, Ghansah, and Grant (2021), Franco et al. (2010)	
	(15) Building foundation	A building with a 'solid' foundation will be more resistant in the event of flooding and improve its resilience potential	Presence of foundation	Positive			
Areas affected by network failure			Negative		Lhomme et al. (2013), Russo et al. (2020), Sánchez-Muñoz et al. (2020)		
(16) Vulnerability of the electricity network	The level of recovery of the electricity network will influence the resilience of the territory	Non-affected areas	Positive				

(Continues)

TABLE 1 | (Continued)

Resilience dimension	Indicator	Definition	Homogeneous sub-set	Impact on resilience	Reference
Organisational resilience	(17) Redundancy of the road network and critical nodes	The more redundant the network, the fewer critical nodes are flooded. And the more redundant the road network, the easier it is to move people around	High proportion of vulnerable network Low proportion of vulnerable network	Negative Positive	Cutter, Burton, and Emrich (2010); Cutter, Emrich, and Burton (2010), Heinzlief et al. (2019), Tzavella, Fekete, and Fiedrich (2017)
	(18) Availability of risk management and crisis management plans	A territory with risk management plans has better potential for resilience (PPR, PCS)	No management plan Presence of a management plan	Negative Positive	Meur-Ferec et al. (2020), Quillet et al. (2019)
	(19) Updating of risk management plans and crisis management	A territory with recent risk management plans (PPR and PCS) has better potential for resilience	Ancient management plan Recent management plan	Negative Positive	Meur-Ferec et al. (2020), Quillet et al. (2019)
	(20) Action time of emergency services	Districts with easy access to emergency services have better resilience potential	0–3 min 3–6 min 6–10 min + of 10 min	Positive Positive Negative Negative	Cutter, Burton, and Emrich (2010); Cutter, Emrich, and Burton (2010), Tzavella, Fekete, and Fiedrich (2017)
	(21) Access time to reach refuge areas	Proximity to refuge areas for people improves resilience potential	0–3 min 3–6 min 6–10 min + of 10 min	Positive Positive Negative Negative	Villagra and Quintana (2017), Tzavella, Fekete, and Fiedrich (2017)
	(22) Location of the actors' preferred areas of action	The action of crisis management actors is unequal across the territory	Fuzzy zones and classification of action zones	Impact according to the classification	Djalante, Holley, and Thomalla (2011), Villagra and Quintana (2017)

may highlight the lack of data available on the territory and the need to produce new data. The resilience potential indicators are calculated in step 4. The resilience potential is the intrinsic resilience of the territory, without considering the intensity of the hazard considered (e.g., 10-year or 100-year flood). Step 5 consists of using the resilience potential and considering different hazard scenarios to compute the resilience scores. Finally, we format the indicator values, resilience potentials and resilience scores at various analysis scales in a GIS (Step 6).

4.2 | Indicator Selection (Step 1), Rule Assessment (Step 2) and Data Collect (Step 3) to Assess Resilience Potential

Based on the literature analysis (Cutter, Emrich, and Burton 2010; Fekete 2018; Pant et al. 2018; Tzavella, Fekete, and Fiedrich 2017), we selected 22 indicators distributed in the three main dimensions (socio-economic resilience of communities, infrastructural resilience and organisational resilience), as set out in Table 1. This corresponds to step 1 of the method proposed. For each of these indicators and based on the literature, we identified the homogeneous sub-set values that have a positive or negative impact on resilience (Table 1). The socio-economic status of people is one of the dimensions most taken into account in the assessment process. For example, behind the standard of living, we can identify differentiated resilience potentials such as resistance and recovery. However, these interpretations are sensitive and vary according to context. The choice of indicators is based on relative unanimity in the literature. For instance, people with lower levels of education are identified as having lower resilience potential. On the other hand, for spatial analysis, proximity to infrastructure is the preferred criterion of resilience. The definition of these positive/negative impacts corresponds to step 2 of the method. Finally, the final selection of indicators was made according to the data available on the territory. It was collected not only from the main institutional providers, in particular the Statistical Institute of French Polynesia and planning department services but also from the few available opensource data. This allowed the creation of a spatial information database.

4.3 | Resilience Potential Computation of Statistical Indicators (Step 4.1)

This step aims at computing the resilience potential related to each indicator. The impact potential is built from the different sub-sets related to each indicator and their impact on resilience. It is computed from the equation (1).

$$R_i = \frac{\sum_{j=1}^M N_{ij} * W_{ij}}{N_{tot}} \quad (1)$$

where R_i is the resilience potential evaluated for indicator i , j is a territorial element (such as a building), M is the number of different sub-sets of the element considered, N_{ij} is the number of elements in the territory considered (number of buildings for example) belonging to the same homogeneous sub-set, W_{ij} is the resilience value of this sub-set, depending on whether the impact of

resilience is positive or negative (value of -1 if negative or 1 if positive) and N_{tot} is the total number of elements at the district level.

There are many different methods available for standardising the indicators, and they can also vary according to the indicators selected (Asadzadeh et al. 2017; Cutter, Emrich, and Burton 2010; Heinzlef, Becue, and Serre 2019a; Moreira, de Brito, and Kobiyama 2021). The final objective is to move towards a progressive classification into several resilience potentials ranging from 'low resilience' to 'high resilience' based on the proportion of each variable in the census districts. The calculation consists in, for each sub-set ('working people' for example for the 'employment status' indicator), associating a resilience potential value (W) (1 in this case). This method of characterising resilience potential has an advantage in that it can be adapted to any type of variable with a positive or negative potential. It allows for removing variables with an uncharacterised impact from the calculation. Finally, it allows us to obtain an index ranging from -1 to 1 allowing districts to be compared with each other.

For instance, the resilience potential related to the socio-economic indicator 'Employment Status' of a census district is computed by Equation (2).

$$R \text{ "Employment Status"} = \frac{\text{Number of "working people"} * 1}{\text{All people}} + \frac{\text{Number of "non-working people"} * (-1)}{\text{All people}} \quad (2)$$

4.4 | Using Spatial Analysis to Develop Specific Indicators Related to Technical Resilience (Step 4.2)

We have seen that many resilience assessments are based on the assessment of the resilience of CI and technical networks. We rely on spatial analysis rather than statistical data processing and develop the spatial analysis for the study of electricity and road networks. Firstly, we study the electrical network on the basis of potential dysfunctions. Secondly, we consider the road network as a vector of mobility at all stages of the crisis. This allows for highlighting spatial inequalities and providing strategic information for managers. The study of interdependencies will therefore be fairly simplified; we identify four main types of CI (Figure 4) (Fekete, Tzavella, and Baumhauer 2017):

- Networks as interface infrastructures enabling action (Net.)
- Infrastructure for the provision of basic daily needs (Prov.)
- Infrastructure enabling service provision. This category covers a wide range of examples, but we will focus on emergency services (Emg.)
- Shelter (or health infrastructure) (She.)

The study of the interactions between these different infrastructures allows a simplified consideration of interdependencies, for example between road network and other CI (Figure 4). In this way, we develop indicators representing organisational resilience (proximity to shelters of the population and action from relief centres by emergency services) and socio-economic resilience (access to basic resources and health infrastructures for people).

4.5 | Computing the Resilience Score by Taking Into Account Hazard Zones (Step 5)

The methodology for calculating resilience potential (Equation 1) does not take into account hazards, only an intrinsic resilience of the territory. However, depending on the hazard scenario, some areas will be more or less vulnerable than others to direct flood impacts. We observe that hazard areas are sometimes taken into account in spatialised resilience assessment indexes as an additional indicator (Cai et al. 2016; Cutter, Ash, and Emrich 2014; Kontokosta and Malik 2018). However, we chose to supplement the assessment of resilience by taking into account the hazard within our framework; the resilience score combines the resilience potential and the hazard map.

4.6 | Resilience Score Based on Statistical Indicators (Step 5.1)

For statistical data, it is envisaged to calculate these resilience scores based on the resilience potential calculation. The main interest is to look at the intrinsic resilience of territories clearly identified as exposed to hazards. This representation method is based on flood and submersion hazard zones of the risk prevention plan taken into account in planning and crisis management policies. In terms of objective, this indicator is interesting for sharing and transferring information to risk stakeholders and as part of a tool to assist them in reflection. From a scientific point of view, our method aims at taking into account the compounded effect of multiple flood hazards on the same territory (Moftakhari et al. 2017); this is part of a multirisk approach (Curt 2020).

From the standpoint of calculation, a scenario-based logic will be favoured. The reference hazards on which we will work are the flood and submersion hazards. However, some meteorological configurations can give a combination of these two hazards (in cyclonic periods) causing both heavy rainfall and flooding as well as swells on the coast causing flooding and overflows. Thus, a scenario adding the zoning of the two hazards will also be considered. Finally, we will have four distinct results: one independent from the hazard (resilience potential described above) and three hazard scenarios (flash flood scenario, a submersion scenario and a scenario combining both) for the calculation of three resilience scores (Figure 5).

The resilience score should consider that:

1. the higher the proportion of the district that is flooded, the more damage is expected;
2. a good level of initial resilience mitigates the impact of the hazard. In contrast, a low initial resilience level worsens the impact of the hazard;
3. if the resilience level is maximum (i.e., 1) then it remains one regardless of the proportion of the district flooded

The equation is:

$$SR_i = R_i - \left(\frac{\text{Max}(RT_i) - R_i}{\text{Max}(RT_i) - \text{Min}(RT_i)} \right) * A_{\text{inond}} \quad (3)$$

where SR_i is the resilience score which is a weighting of the initial resilience potential R_i by hazard, $\text{Min}(RT_i)$ and $\text{Max}(RT_i)$ are, respectively, the minimum and maximum R_i scores of the different census districts in the whole study area, for indicator i . Finally, A_{inond} is the proportion of the neighbourhood flooded (from 0 to 1).

4.7 | Resilience Score for Indicators Based on Spatial Analysis (Step 5.2)

Furthermore, the hazard will be taken into account during the spatial analysis of technical networks and their malfunctioning with crisis scenarios. To assess the flood resilience of the electricity network (Fekete, Tzavella, and Baumhauer 2017; Pant et al. 2018), we identify areas potentially affected by the malfunctioning of electrical transformers, neuralgic points of the network. The zones of dysfunctions will be calculated according to the exposure to flood hazards for each of the transformers depending on geographical proximity by a Voronoi tessellation method (Pant et al. 2018). Regarding the road network calculation, a three-fold reduction in travel time on flooded sections has been established based on the literature (Tzavella, Fekete, and Fiedrich 2017). This measure is difficult to establish with finesse and remains rather indicative, depending in reality on the capacity of the vehicles. A slow travel speed for all is the most relevant assumption in the territory. However, this point could be the subject of further work in order to better take into account local realities. The latter indicators have been represented on a 200-m grid for greater representational finesse.

5 | Application

The application of the method results in 18 maps related to the resilience potential of the 18 indicators. Some indicators are still difficult to construct due to a lack of data. Economic development data for the territory is not available with a sufficient level of accuracy. The census of the management plans is not exhaustive and requires a thorough collection. The lack of data on the actions of the different local actors had prevented the construction of a dedicated spatial indicator. The choice of presenting the indicators separately allows us to have precise information on all the territorial characteristics and avoid the limitations of synthetic indicators that make interpretation difficult.

5.1 | The Resilience Potential of Greater Papeete Through Several Key Indicators

Figure 6 presents the resilience potential of four indicators which are representative of the territorial disparities. The first map describes the resilience potential according to the date of construction (13) (Figure 6a). Here, we generally observe older buildings closer to the coast and newer buildings on the more recently urbanised slopes. This highlights a relatively interesting territorial reality, with buildings constructed according to stricter standards in the face of flooding (earthworks, elevation), implying greater resilience (resistance and absorption capacities).

The second indicator studied is building materials (Figure 6b) (14). This indicator is particularly interesting as it sheds light on the poorest neighbourhoods of the conurbation built with light materials (sheet metal or bamboo house structure). These neighbourhoods are in the heart of the city in Papeete (Figure 7) and largely in the municipality of Faa'a (hosting the international airport). Thus, this municipality with its high concentration of low-income neighbourhoods has many visible social inequalities, whether in terms of the type of buildings or socio-economic characteristics. This implies a low level of resilience in many areas, as shown by the resilience potential based on the level of education (Figure 6c) (2) and level of employment (Figure 6d) (3) in the population census districts. Finally, the comparison between structural and socio-economic indicators allows us to highlight a concentration of neighbourhoods with a low potential for resilience in the face of risk, combining building vulnerability and socio-economic vulnerabilities.

Regarding territorial accessibility, if we look at the accessibility of emergency services in the territory, it is interesting to analyse the whole island (Figure 8). We first observe that the dense urban areas at the top of the slopes, which are furthest from the coast, are difficult to access and therefore less resilient. In addition, some municipalities are much further away from emergency services, particularly on the northeast coast of the main island and in the municipalities of Tiarei, Hitiaa and Mahaena as well as in the south (Mataiea).

The following map of these selected results shows that the socio-economic disparities of the Papeete conurbation are significant. According to these indicators, people living in the urban area of Papeete are closer to the main infrastructures favouring crisis management processes, for example. A certain number of neighbourhoods are identified with several vulnerability factors, such as being built with light materials. Thus, between the different municipalities but also within them, there are areas that are much more vulnerable than others. Considerable inequalities are a prevalent territorial characteristic and the lack of space is also an important parameter of construction in vulnerable spaces in the urban area.

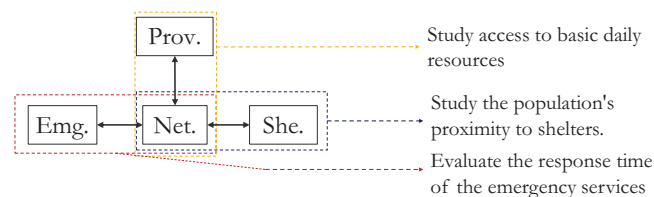


FIGURE 4 | Interdependencies of critical infrastructures and examples of translation by indicators for the road network.

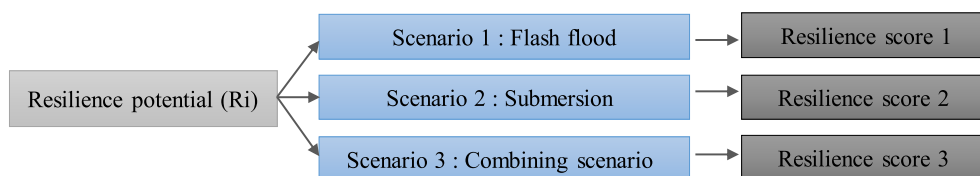


FIGURE 5 | Articulation of the territorial resilience calculation.

5.2 | The Resilience Score

The results on the resilience potential give us particularly interesting indications of the territory's vulnerability and spatial inequalities; however, it seems particularly interesting to focus on the areas that have been identified previously as vulnerable to flooding and submersion hazards. This work allows us to have a more oriented reading of the territory and emphasise certain territories that are more vulnerable than others. Figure 9 is a representation of the resilience score according to building materials (14) for the three hazard scenarios: flooding from river, marine submersion and a combined hazard representative of the cyclone hazard.

There are many areas at risk in the urban area due to the many watercourses crossing the territory. The city centre of Papeete is largely affected by flooding, with many vulnerable areas. Moreover, if we take the example of the Papeava River, which can be responsible for the most significant overflows in this sector, the combined risk of a rise in the water level on the sea side plus an increase in the flow rate due to precipitation makes the risk of overflow all the greater. At the same time, in the seaside areas, some neighbourhoods have a rather low material resilience (wooden and sheet metal construction), so these areas will change from an already low resilience potential to a very low resilience score. In general, these neighbourhoods are confronted with a double vulnerability, as the population with low income is concentrated in certain at-risk areas, in particular on the banks of waterways sensitive to flash flooding. Valley bottoms are also vulnerable areas in this sense although this phenomenon is less marked on the coast.

Furthermore, if we look at the indicators relating to the response times of the emergency services (20), the maps of Figures 10 and 11 show us the potential resilience and the resilience score for a flood hazard with an increase in travel time. The difficult-to-access spaces are much more numerous and correspond to the tops of the slopes and the bottoms of the urbanised valleys. Logically, recent neighbourhood have a lower resilience score, which in some places will involve entire valleys that are otherwise very vulnerable. These spaces cover several realities, some favoured neighbourhoods were built on the first heights, but most of these difficult-to-access spaces are often occupied by precarious housing. In particular, the valley bottoms are inhabited by poorer populations pushed out of the central districts and who, in addition, are at the front line of the overflows.

6 | Discussion

Through this article, we have made several contributions. The objective was to respond to the lack of operationalisation of resilience and develop a method adapted to a specific territory.

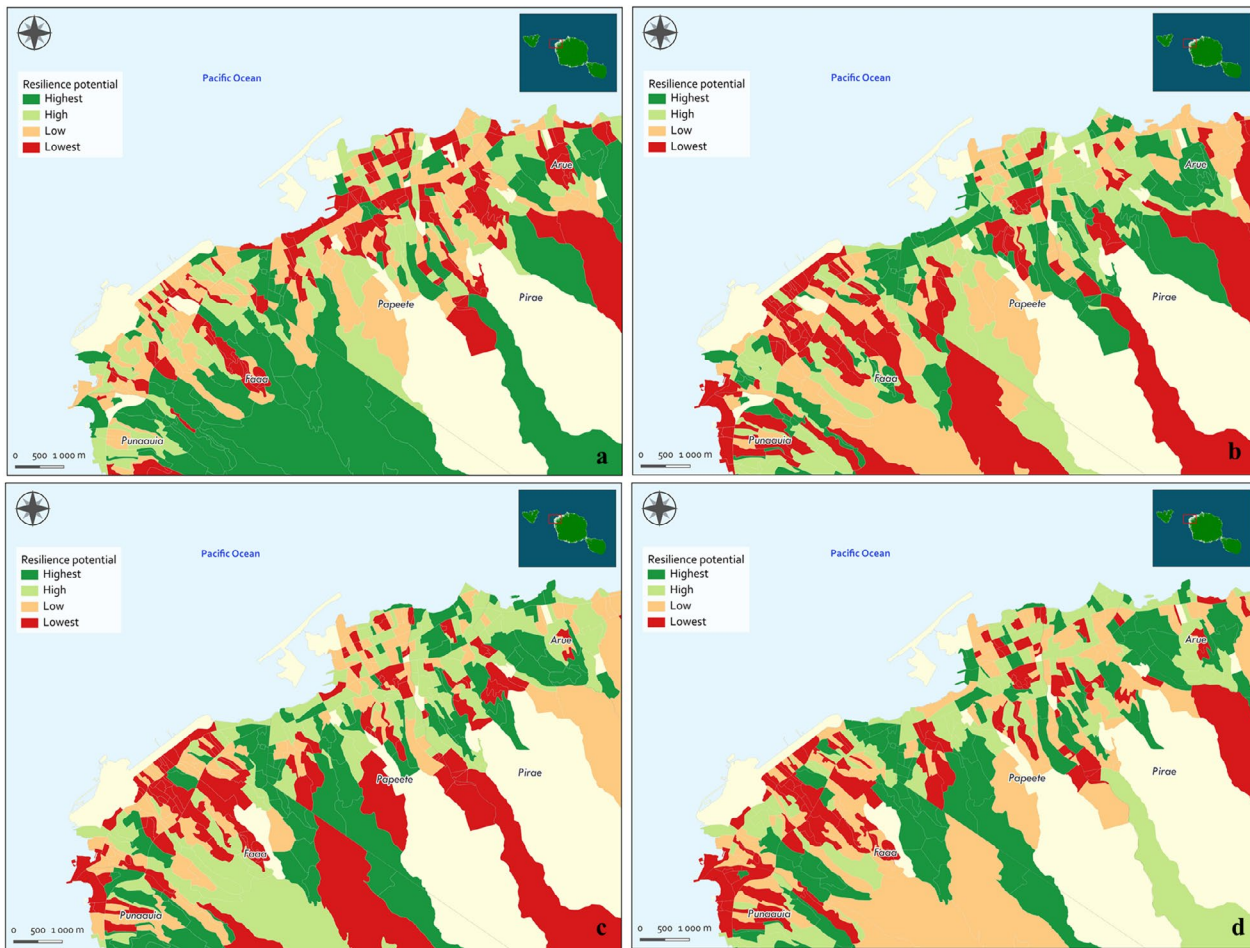


FIGURE 6 | Resilience potential for four indicators: Building date (a), building material (b), study level (c) and employment (d).



FIGURE 7 | Low-income habitats in Papeete city centre (photography: Bastien Bourlier).

The method we proposed results in a set of maps formalising territorial resilience. The objective was to move towards spatial representation and mapping-based methods, reflecting multiple spatial distribution phenomena of territorial resilience to risk. The indicators reflect significant spatial inequalities, both between municipalities and neighbouring districts, and highlight the specific exposure of certain areas. This constitutes a knowledge base that provides an operational perspective on territorial resilience, fostering reflection on development policies.

Based on a systemic vision of resilience to flood, we proposed a method for assessing resilience across three complementary dimensions: infrastructural, organisational and socio-economic. At the same time, we have combined spatialisation methods from different approaches to resilience, either urban (Fekete 2020) or community-based (Forrest, Trell, and Woltjer 2020). It provides a basis for reflection in various decision-making contexts within the territory (urban planning, crisis management), and thus, addresses a wide range of stakeholders, thereby enhancing the operational relevance of the method. The adopted model aims to take into account risk management policies implemented by actors with diverse expertise (network management, urban planning, protection of goods and people, etc.), operating at different territorial and temporal scales. This approach enables these processes to be viewed as a continuum before, during and after crisis, a critical element of the resilience concept.

We have highlighted the challenges of managing risk through dual governance between the French state and local government. Each dimension in this framework is designed to be cross-functional in both its structure and operability. Indeed, French state's approach to crisis management will be more focused on the technical and organisational dimensions, while local government will strongly integrate the socio-economic dimension into its planning. Nevertheless, this model aims to limit the current silo approach and share specific indicators.

Moreover, the two levels of analysis (potential and resilience score) enable us to answer the question 'resilience to what?' (Meerow and Newell 2019). The framework starts with a broad approach to territorial resilience, emphasising the interconnectedness of risk management, spatial planning and socio-economic policies. It then transitions to a more focused, flood-specific approach, addressing critical aspects such as building exposure and crisis management strategies. Beyond only identifying a type of hazard, the method can also incorporate specific hazard levels, enabling a more practical and operational approach.

Nonetheless, the method and its application raise a number of questions that can be discussed, constituting both limitations and perspectives:

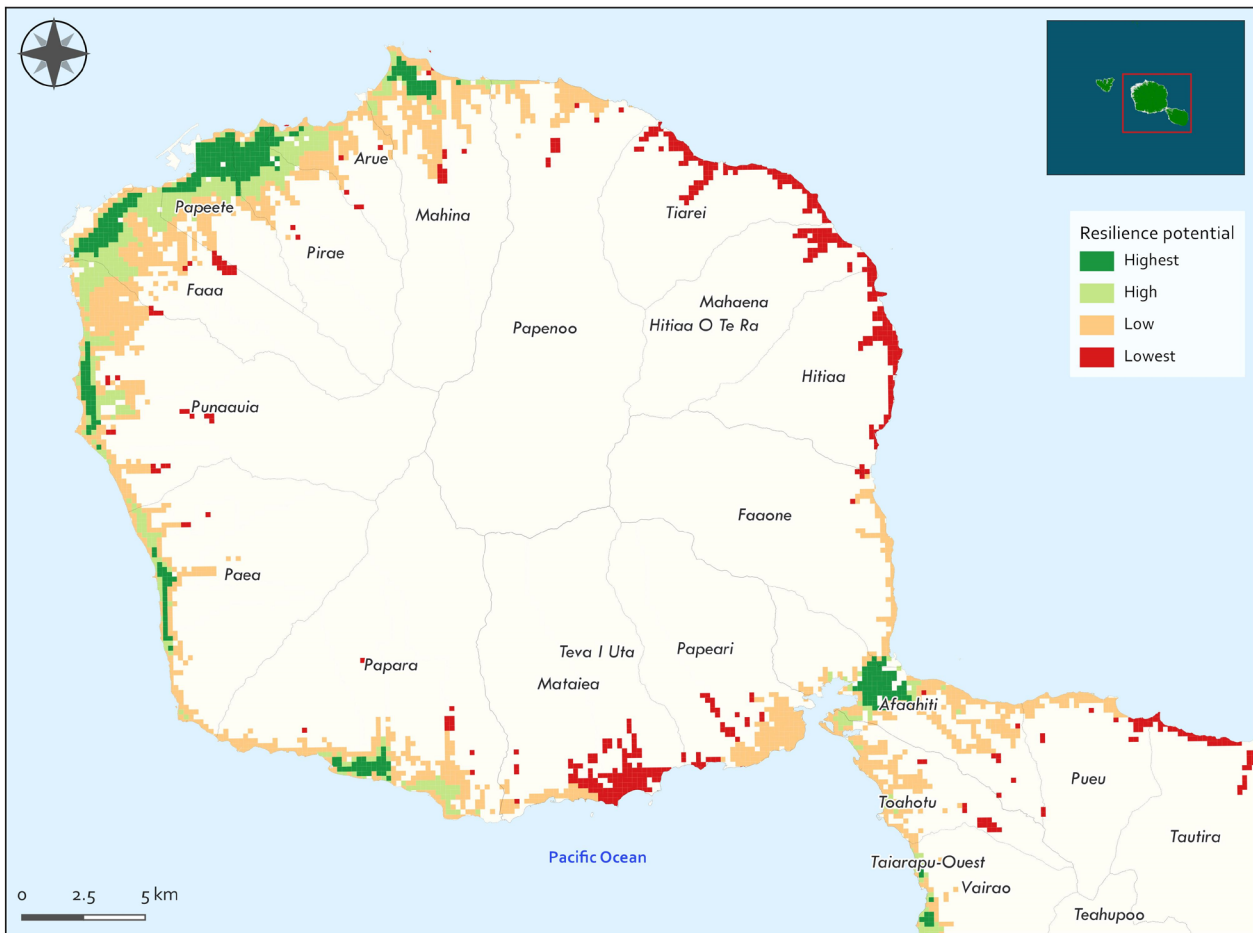


FIGURE 8 | Resilience potential for emergency access in Tahiti at the grid cell level.

- The operational framework was designed with an operational focus, which inherently introduces a degree of rigidity into the model.
- The methodological choices of spatialised assessment show its interest in several aspects but have several constraints.
- The interpretation of socio-economic data is highly dependent on local context and it impacts analysis accuracy.
- The lack of data is a constraint in the methodological construction and the production of operational data.

First of all, the division into several large dimensions has certain limits and tends to erase the systemic character of the concept of territorial resilience. Indeed, three thematic categories overlap and indicators can be considered at the border between these dimensions.

Ultimately, this division facilitates the reading of the concept by local stakeholders and the users of the assessment model. In addition, the model's aim is to respond to the territory's challenges by targeting previously identified sensitive issues: the vulnerability of technical networks, socio-economic vulnerability and governance difficulties specific to the politico-historical system.

Secondly, indicators provide relevant information but are not exhaustive mainly due to methodological limitations. Resilience

assessment methodologies cover a much wider range of methods which can be complementary, such as methods based on operational safety and the study of malfunctions, particularly in the field of CI interdependencies. Maps primarily reflect spatial interdependencies but are more difficult to use for functional interdependencies. Our study of CI dependencies will be able to partially respond to these aspects with considerable simplification (indicative speed reduction on road networks) (Toubin et al. 2013). Concerning the study of the electrical network, there is no data associated with the role of transformers, even though electrical networks are made up of several strata depending on the type of service. Finally, the impacts are simplified, and data on transformer location heights are needed. Nevertheless, all these indicators reflect a certain reality and strike a balance between the availability of data, the accuracy of information and methodological simplification in order to situate the model in a comprehensive territorial context.

Moreover, regarding socio-economic data treatment, numerous choices are possible. In this work, the indicators simply identify negative or positive impacts on resilience. This is a rather simplified relationship, but it is the most accurate possible, as the literature shows that the interpretation of socio-economic characteristics can lead to different or even contradictory interpretations depending on the spatial, political and cultural contexts. For example, the indicator based on the age of the population can be taken into account in different ways. Older or very old people,

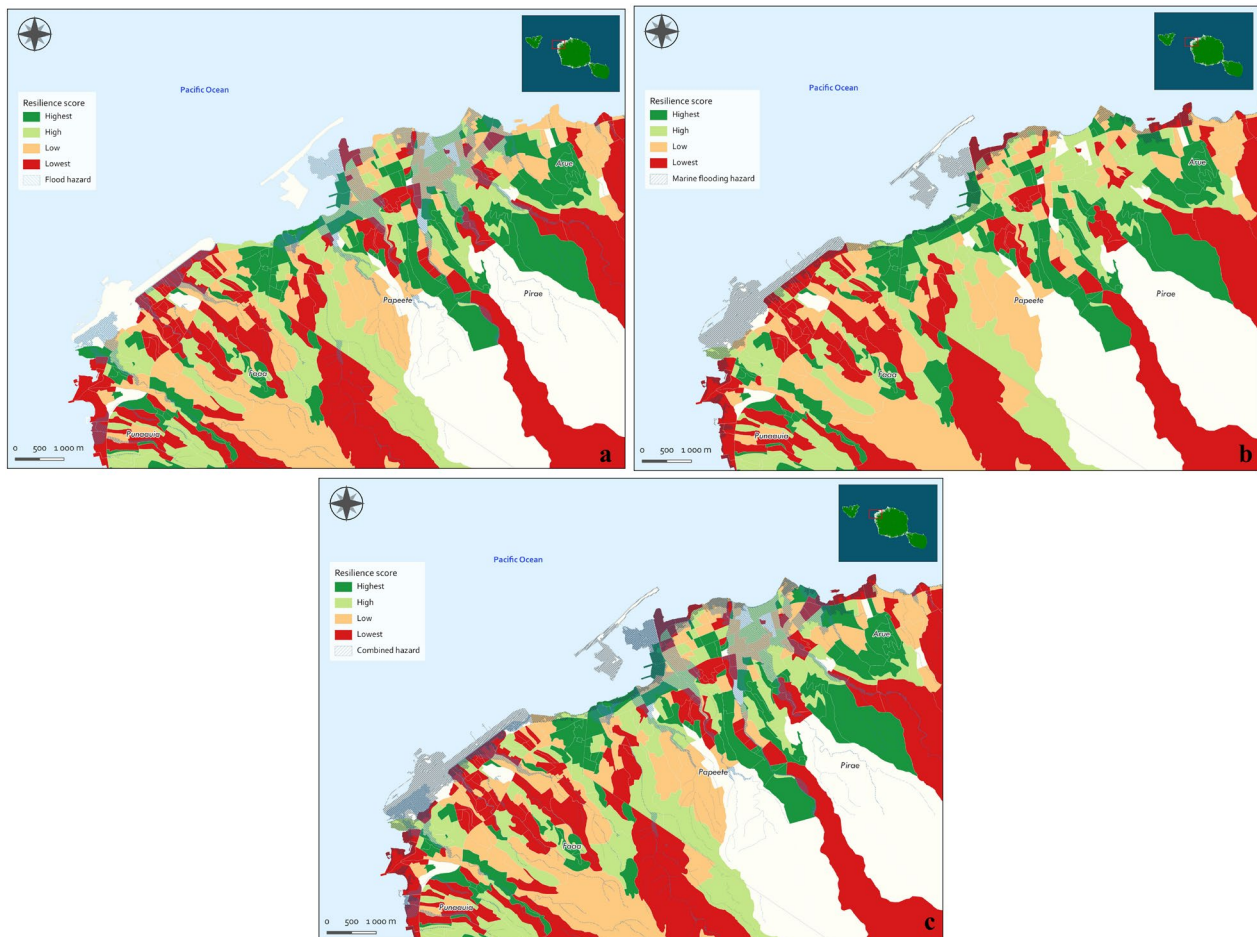


FIGURE 9 | Material resilience score for flood hazard (a), marine flooding hazard (b) and combined hazard (c).

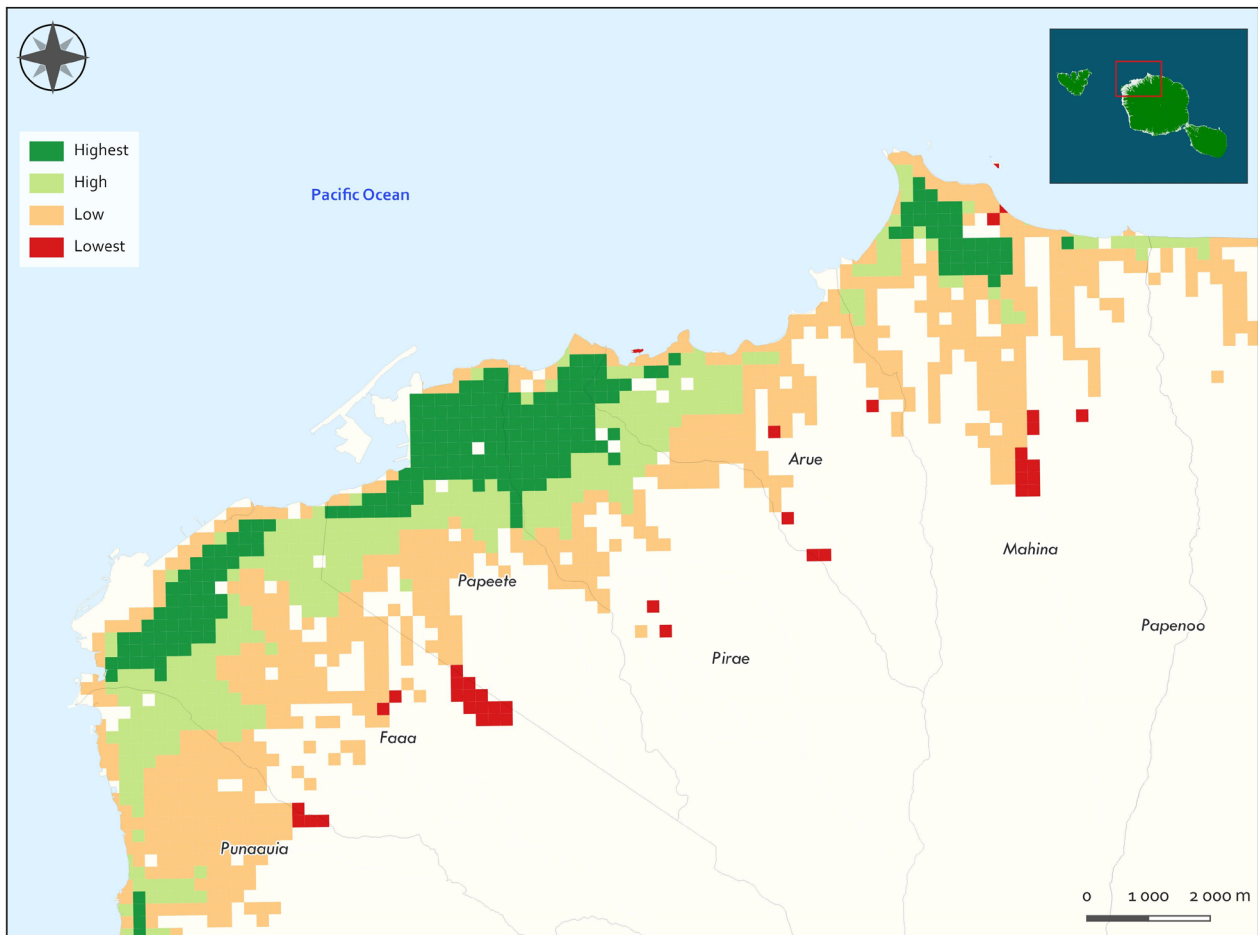


FIGURE 10 | Resilience potential for emergency access in the Papeete conurbation at the grid cell level.

as well as children who are not self-sufficient facing a crisis situation, will be identified as either less resilient or more vulnerable (Chau et al. 2014; Green, Bates, and Smyth 2007; Jonkman et al. 2009; Lowe, Ebi, and Forsberg 2013; Weiner, Harris, and Craig 2002). On the other hand, people who are considered fully mobile and healthy are described as more resilient. But this understanding of age is obviously much more complex. Thus, it has been pointed out that older people may also be more informed about the risks facing their territory and have a better perception of risks than younger people who sometimes moved to the territory more recently (Soetanto, Mullins, and Achour 2016). Finally, it was considered that, when adapted to the territorial context of French Polynesia, the indicators selected were relatively robust with regard to the literature.

Lastly, the construction of indicators has a major limitation, which is the availability of input data in a given territory. Exchanges with local Polynesian actors highlighted the fact that data was very rarely available or even non-existent. The dynamics of open data are only embryonic in the territory. Thus, domains such as building infrastructures or health data do not have available or complete databases. More complete data at the scale of the building (size, function, etc.) would offer new perspectives of analysis within the different districts. This observation poses a strong constraint on the construction of spatialised indicators while offering important perspectives in the improvement of territorial knowledge for the public authorities. It will

also allow their involvement and exchange in the construction of the data (Serre and Heinzlef 2021).

Finally, to look at the bigger picture, how can this model and its results be effectively applied within the specific context of local governance in French Polynesia?

We have highlighted the fact that the spatialisation of risk management offers significant added value as an explanatory tool but is also operational, providing robust decision-making support (Cariolet, Vuillet, and Diab 2019; Heinzlef, Becue, and Serre, 2019a). Thus, our model enables a comprehensive understanding of the territory's inherent resilience, serving as a foundation for more informed and context-sensitive governance strategies. As seen above, concerning the administrative duality, the approach facilitates the centralisation, organisation and integration of data and methods from various sources, aiming to bridge the gap between crisis management (led by the French state) and spatial planning (managed by local governments). For example, in urban renewal projects, it enables the consideration of key indicators such as evacuation routes and building vulnerability. Similarly, in crisis management, it supports the adaptation of responses based on a neighbourhood's socio-economic resilience.

In addition, the model includes several features that make it adaptable for use by local stakeholders and tailored to specific

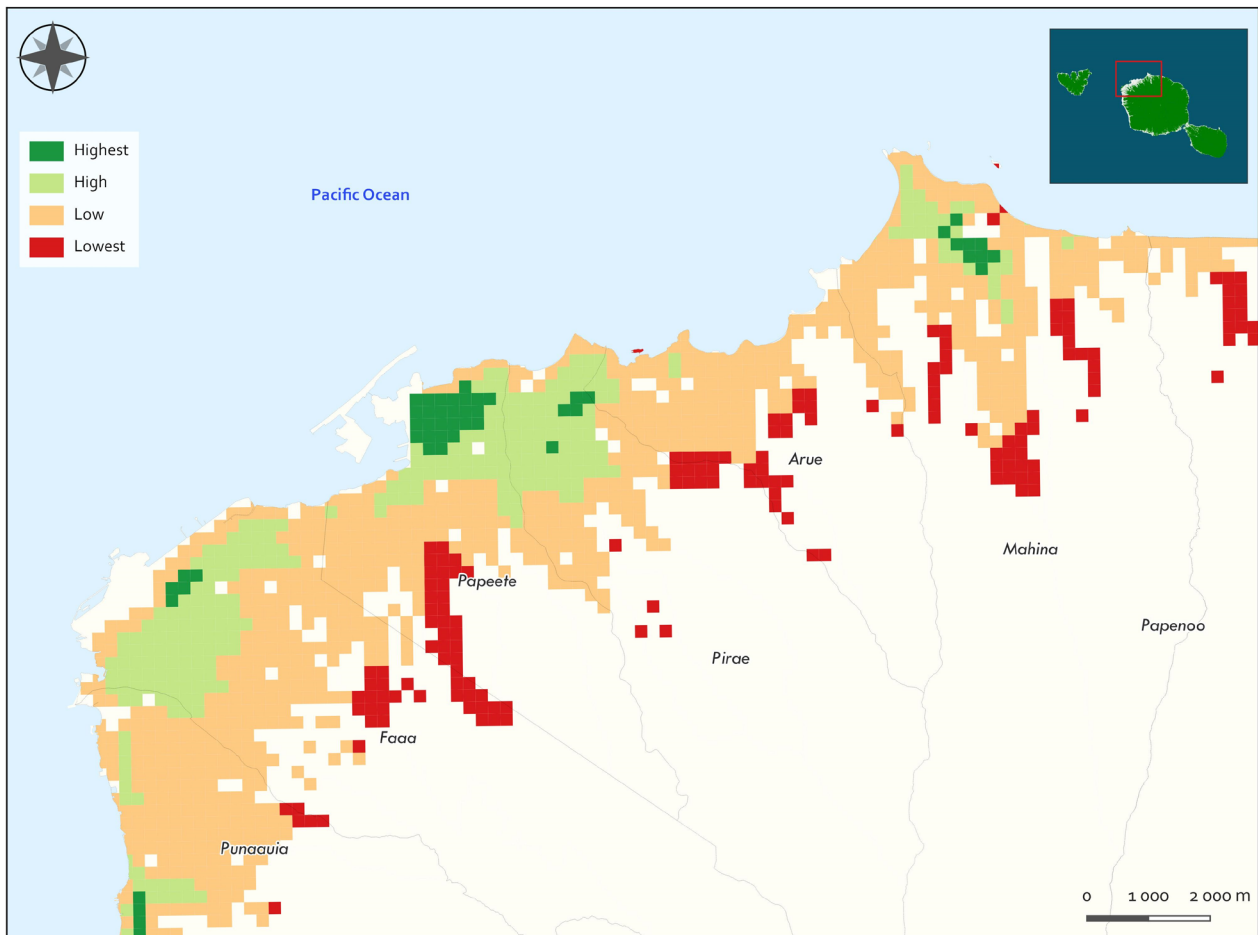


FIGURE 11 | Resilience score for flash flood scenario for emergency access in the Papeete conurbation at the grid cell level.

operational contexts. Certain calculation thresholds can be adjusted to reflect new developments affecting the territory or meet the needs of specific studies. Moreover, the hazards analysed can be modified to assess the resilience score in response to more exceptional events, for example.

To go beyond the strict production of data, it has been shown that spatialised information promotes decision-making processes (Heinzle et al. 2022). This operational and cross-sectoral model is designed to serve as a shared tool for various stakeholders and has the potential to evolve into a collaborative resource, fully integrated into decision-making processes such as future land-use projects. It emphasises the concept of adaptive management, focusing on assessing the impacts generated by projects across different scales (e.g., built environment, socio-economic conditions, environmental dynamics) and evaluating how specific projects or policies contribute to enhancing resilience.

7 | Conclusion and Perspectives

The aim of this work was to respond to the challenge of operationalising the concept of resilience in a tropical island territory such as Tahiti. This study provides a spatialised model to assess territorial resilience more in terms of an encompassing vision of resilience. The main contributions of this work are as follows:

- The composition of a comprehensive spatial model of resilience assessment can lay the foundations for decision support on flood risk applied to a territory with particular characteristics.
- The initial results provide a basis for reflection in various decision-making contexts in the territory (development, crisis management) and are therefore aimed at a wide range of actors, thereby reinforcing the operability of the method highlighting the interdependence of risk management policies across spatial and temporal scales.
- This model is applied to a particular context, a territory that is vulnerable as much from the physical point of view as from its organisational, societal and technical aspects. Consequently, the tool is intended to respond to the important need to promote the coordination and articulation of different risk management policies between the state, local government and municipalities.
- This production of information attempts to respond to the context of a global lack of data available in the territory on these issues by linking existing data from different sources and giving perspectives for further data collection.

The low involvement of local stakeholders is partly due to the physical and conceptual implementation of the research project. This work reports on the spatialised assessment of resilience with a view to improving knowledge of the territory. In the

second phase, the research project aims to rely on local stakeholders in a qualitative approach.

Moreover, the prospects for extending the model are multiple and may, for example, involve opening it up to other major risks in the territory, such as landslides or extending the assessment to the entire Polynesian territory, thereby broadening the spectrum of local issues in more distant territories.

Furthermore, this model is a step in the implementation of a global decision support tool. It could be materialised by a territorial observatory of flood resilience based on geographical information with the aim of helping territorial collaboration between crisis and risk management, land-use planning and economic stakeholders and communication with the local population (Heinzle and Serre 2019). This tool could be used as a dashboard, help with data sharing and geovisualisation modelling and be used to propose technical production (Serre and Heinzle 2021). This tool would provide an answer to the problem of collaboration between players who operate in silos.

Acknowledgements

The ILOTS project has received financial support from CNRS through the MITI and IRD interdisciplinary programmes.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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