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Assessing Socioeconomic Vulnerability after a Hurricane: A Combined Use of an Index-Based approach and Principal Components Analysis

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Abstract: Small Island Developing States (SIDS) are vulnerable to sea-level rise and hydro-meteorological hazards. In addition to the efforts to reduce the hazards, a holistic strategy that also addresses the vulnerability and exposure of residents and their assets is essential to mitigate the impacts of such hazards. Evaluating the socioeconomic vulnerability of SIDS can serve the purpose of identification of the root drivers of risk. In this paper, we present a methodology to assess and map socioeconomic vulnerability at a neighbourhood scale using an index-based approach and principal component analysis (PCA). The index-based vulnerability assessment approach has a modular and hierarchical structure with three components: susceptibility, lack of coping capacities and lack of adaptation, which are further composed of factors and variables. To compute the index, we use census data in combination with data coming from a survey we performed in the aftermath of Irma. PCA is used to screen the variables, to identify the most important variables that drive vulnerability and to cluster neighbourhoods based on the common factors. The methods are applied to the case study of Sint Maarten in the context of the disaster caused by Hurricane Irma in 2017. Applying the combined analysis of index-based approach with PCA allows us to identify the critical neighbourhoods on the island and to identify the main variables or drivers of vulnerability. Results show that the lack of coping capacities is the most influential component of vulnerability in Sint Maarten. From this component, the "immediate action" and the "economic coverage" are the most critical factors. Such analysis also enables decision-makers to focus their (often limited) resources more efficiently and have a more significant impact concerning disaster risk reduction.

Keywords: vulnerability assessment; vulnerability index; PCA; extreme weather; hurricane irma; SIDS; sint marten

1. Introduction

In a changing climate, natural disasters associated to weather-related hazards such as storms, storm surge, flash floods, hurricanes, heatwaves, and droughts are estimated to increase both in severity and frequency [1]. Changes in climate are of special importance in the context of Small Island Developing States (SIDS), because they are especially vulnerable to the associated impacts due to their location, fragile economies and more vulnerable environments [2,3]. Impacts in SIDS can turn in significant loss of life and damage to property and infrastructure that can easily damage the entire economy of small economies [4]. Hence, in order to mitigate such impacts, SIDS need to adapt to the effects of climate change.

Implementation of climate change adaptation measures should include planning programs, such as disaster risk reduction and community-based development strategies, assessment of the critical physical, social, economic, and environmental issues in combination with raising awareness, and communicating future risks to local communities [3,5]. In that regard, socioeconomic vulnerability assessment can play a vital role in the adaptation of SIDS to the effects of a changing climate.

There is no unique definition of vulnerability in the scientific community [6]. The definition of vulnerability for scientific assessment depends on the purpose of the study and can only be considered meaningful regarding a specific at-risk situation [7–9]. Regarding socioeconomic vulnerability to natural hazards, as the scope of this paper, one of the most widely used definitions is the one given by the Intergovernmental Panel on Climate Change (IPCC). The IPCC defines vulnerability as "the propensity or predisposition to be adversely affected, and it encompasses a variety of three dimensions susceptibility to harm, lack of capacity to cope and lack of capacity to adapt" [1]. In summary, the IPCC concept of vulnerability is the degree to which a system is susceptible to, and is unable to cope and recover from the adverse effects [10].

Based on the above definition, a methodology that allows capturing the three dimensions of vulnerability and that facilitate its spatial representation is essential. Vulnerability assessments to natural hazards are vast in the literature. Nguyen et al. [9] present an extensive review of 50 studies on the use of vulnerability indices associated with the impacts of climate change on coastal areas across a range of hazards. Nguyen et al. [9] concluded that there is a lack of standardisation of concepts and methods to assess vulnerability, making them difficult to compare for different areas and calls for an adoption of a consistent and standard methodology and justifies pursuing indicator-based vulnerability assessments. The call for the use of indexes to have a consistent set of metrics to assess vulnerability is not new; similar recommendations are also presented in Comfort, et al. [11] and Cutter et al. [7]. Accordingly, a vulnerability assessment based on indices was selected for this research.

An index based vulnerability assessment approach has been extensively used and reported for flood and weather-related events [7,12–18]. The results and conclusions of those studies suggest and support the feasibility of using an index-based approach for the assessment of socioeconomic vulnerability in the context of SIDS. In Sorg et al. [17], an index-based framework to assess vulnerability is presented. The assessment method called PeVI is based on multiple indicators and is composed of three major components, susceptibility, lack of coping capacity and lack of adaptation capacities. PeVI was conceived to be flexible and easy to adapt to properly reflect the information available and the needs of a case study. In such a way, the current study has expanded PeVI to capture key components of vulnerability in an island prone to frequent hurricane and floods [19] and to capture how these components can alter the island vulnerability after a major disaster by incorporating a household survey in the aftermath of Hurricane Irma. Our approach is taking into account the changing in dynamics after a disaster, offers a different view on vulnerability assessment to extreme weather events and is aligned with recommendations in literature [20].

We have expanded PeVI by adding elements that can change after a disaster such as elements of risk awareness and perception and access to information. We also include elements related to the possible immediate actions to face the potential hazard, which are essential in the context of a small island due to the impossibility to move completely away from the possible threat. Finally, we use information collected in the aftermath of a hurricane that can be associated with the direct impact (building and infrastructure damage) and how the society was adapting to the disaster (speed of recovery and construction methods and materials).

The methodology presented in this study is applied in the case study of Sint Maarten, one of the Leeward Islands on the northeast Caribbean Sea. Despite the general agreement among stakeholders and academia on the importance of having a vulnerability assessment for small islands in order to have a proper strategy to reduce risk to climate associated events, the island of Sint Maarten lack such a study for the whole island to date. The need for a vulnerability assessment in Sint Maarten was evident after the disaster caused by Hurricane Irma in September 2017. Vulnerability and risk assessments are an essential input for disaster risk reduction and adaptation planning to climate-related hazards and to support the island's reconstruction efforts.

In addition to expanding the vulnerability index, we have extended the analysis and interpretability of results by combining the index-based result of PeVI, with the use of Principal Components Analysis (PCA) into the methodology. Aggregate indices of vulnerability, such as the one computed in this research are useful in identifying where the hotspots of vulnerability occur. Moreover, it gives decision-makers a powerful tool to focus their efforts for disaster risk reduction. However, the generation of a single composite vulnerability index can be problematic, because information regarding the relations between the original variables is averaged in the resulting aggregated index (i.e., from many variables to a single number). Two different locations may have a similar vulnerability index value, but the driving variables may differ [21]. To overcome this issue, we use the PCA technique that allows returning to the original variables to understand and interpret the aggregate vulnerability index.

PCA is a multivariate statistical technique that can be used to analyse several dependent variables (which usually are inter-correlated) in a dataset. PCA aims to draw conclusions from the linear relationship between variables by extracting the most relevant information in the dataset in the form of a (reduced) set of new orthogonal variables that are called principal components [22]. PCA reduces the number of variables by identifying the variables that account for the majority of data variance, and by identifying the similarities between individuals for all variables, and by doing so, highlighting the main contributing factors to the phenomenon under investigation [22,23]. PCA works by performing an orthogonal linear transformation in an N dimension space to identify the vector that accounts for as much as possible of the total variability. The first vector is called the first Principal Component (PC-1). After the first PC is extracted, the method continues building principal components that are also orthogonal and linearly uncorrelated to the previous component and each time accounting for as much of the maximum of the remaining variability as possible.

The remaining part of the paper proceeds as follows: In Section 2 we start by presenting the case study description, which includes a synopsis of Hurricane Irma on Sint Maarten, followed by the data collection using different sources and including the field campaign. We believe that presenting this information upfront will allow the reader to understand better which elements were essential to consider in the vulnerability assessment after a disaster and how the information was collected and later used. We continue the section laying out the theoretical dimensions of the research and the computation and mapping of the vulnerability index (PeVI). We conclude Section 2 with the description of how we implement the PCA analysis. Section 3 corresponds to the results and discussion from the PeVI assessment and from the PCA analysis. The final section draws upon the entire paper. We present here our main conclusions and how our findings can be used for future risk mitigation measures on the island of Sint Maarten.

2. Methodology and Data

2.1. Case Study Area and Hurricane Synopsis

The island of Saint Martin is located in the Leeward Islands on the northeast Caribbean Sea. The island is divided into two administrative units: the northern part called Saint-Martin with an extension of 53 km^2 is an overseas collectivite of France, and the southern part called Sint Maarten with an extension of 34 km^2 is one of the constituent countries of the Kingdom of The Netherlands [19] (see Figure 1). Due to the scope of the project that funded this research, the target population selected for this study was only those living in the Dutch part when Hurricane Irma struck on 6 September 2017. The magnitude and path of Hurricane Irma cause that the entire population of the island was directly and severely affected by the hurricane. The official population in the Dutch side was 40535 in 2017 [24]. However, the figures may not include all the undocumented immigrants, whose increase in numbers is considered as one of the most significant social issues and driver of vulnerability on the island [25]. According to non-official sources and during the interviews during the fieldwork performed after Hurricane Irma, the research team estimates that around 10,000 illegal immigrants might be living in the Dutch part of the island before Hurricane Irma struck on September 2017. Previous figures put the number of undocumented immigrants close to 20,000 people [26].

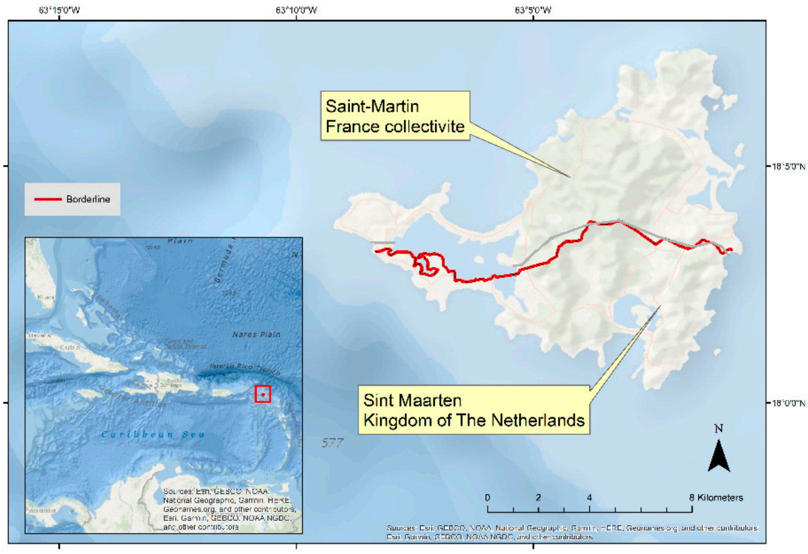

Figure 1. Location of Sint Maarten in the Caribbean Sea.

Located within the Atlantic hurricane belt, Sint Maarten is subject to numerous hazards; the most noticeable are hurricanes which can cause one or a combination of strong winds, storm surge, pluvial flooding and mudslides. Since records began in 1851, a total of 20 major hurricanes (Category 3 or higher in the Saffir-Simpson Hurricane Wind Scale) have hit Sint Maarten to date. The most notable major hurricanes that affected the island include hurricane Donna in 1960, Hurricane Luis in 1995, Hurricane Lenny in 1999 and more recently Hurricane Irma in 2017 (the most catastrophic on record to date). These hurricanes brought an enormous amount of damage to the people of Saint Martin, both economically and socially [27].

Hurricane Irma Synopsis in Sint Maarten

Hurricane Irma was the ninth named hurricane of the 2017 hurricane season, and it was originated on 27 August and weakened to a tropical storm after 14 days on 11 September in continental USA [28]. The best track of the hurricane is shown in Figure 2. During its lifetime, the catastrophic hurricane made seven landfalls, four of which occurred as Category 5 across the northern Caribbean Islands. Irma's second landfall as a Category 5 hurricane was on the Island of Saint Maarten on 6 September around 07:15 local time with maximum recorded winds of 295 km/h and a minimum pressure of 914 mb [28]. Irma was a Category 5 hurricane for 60 h, which at that moment was the second-longest duration on record (behind the 1932 Cuba Hurricane). When Irma occurred in 2017, it was considered the strongest hurricane ever observed in the open Atlantic Ocean, and one of only five storms with measured winds of 295 km/h or higher in the entire Atlantic Basin.

In terms of fatalities associated with Hurricane Irma, it is reported 11 direct deaths in Saint-Martin (French part of the island) and four in Sint Maarten (Dutch part). Furthermore, one indirect death was reported in Sint Maarten [28]. It is important to mention that during our fieldwork, the community of Sint Maarten believe that the reported number does not reflect the real number of causalities associated with Irma in the island. Their beliefs are based on the level of destruction and gossips that were circulating on the island in the aftermath of the hurricane. During the survey, we heard that the real death toll is ranging from 200 up to 1000 deaths, with Irma affecting the undocumented immigrant population primarily. Furthermore, the reports of injured people are estimated at around 250 to 300 people because of Hurricane Irma on the island [29].

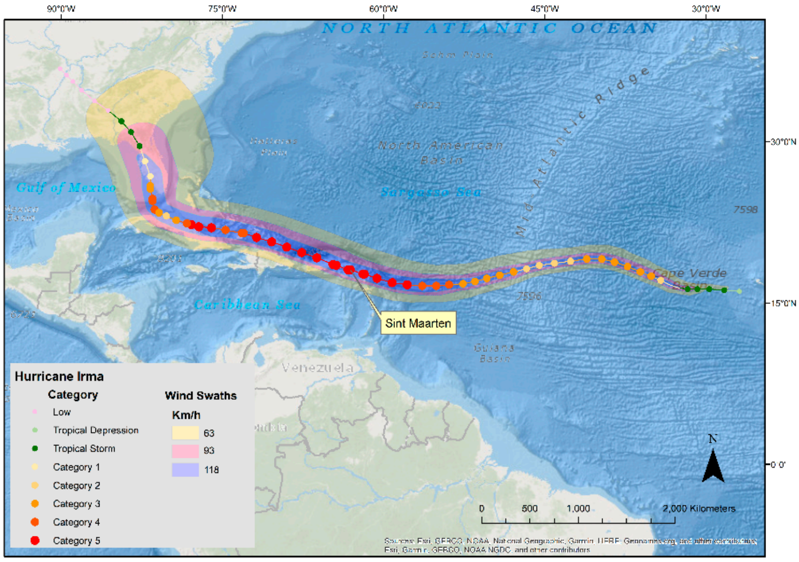

Figure 2. Best track positions, category of the storm, and wind swaths for Hurricane Irma, from 30 August to 12 September 2017. Source: Produced using data from NOAA's National Hurricane Center NHC (https://www.nhc.noaa.gov/gis/best_track/al092017_best_track.zip).

Hurricane Irma also caused significant economic damages by destroying homes, schools, public buildings, businesses, and infrastructure. It is estimated that over 90% of housing had some damage, with 50% suffering from average damage or worse. It was estimated that around one-third of the buildings were destroyed entirely [30]. The direct physical damage on the island was estimated at around USD 1 billion [29].

2.2. Data Collection

2.2.1. Field Data Collection and SURVEY

The basis to perform the vulnerability assessment on Sint Maarten, in the aftermath of Hurricane Irma was a fieldwork campaign to collect data and perform a household survey. We conducted the fieldwork five months after Hurricane Irma struck in Sint Maarten, from 12 February until 3 March of 2018. The conceptual design of the survey, which includes the data preparation, sample size, collection mode and random household selection as well as the field implementation and the statistical significance of the campaign was presented and extensively explained in a previously published work of the team [31].

The survey intended to collect information with potential use for vulnerability and risk assessment on the Island of Sint Maarten. The collected information was grouped into four categories: (i) household and demographic parameters, (ii) information, awareness, and experience with hurricanes and storms, (iii) evacuation behaviour and (iv) risk perception [31]. In addition to the survey, during the interviews, the team collected general information on the island, such as road and energy infrastructure, percentage of damage estimate per household, speed of recovery after hurricane Irma and type of construction materials.

2.2.2. Census Data

The information available regarding census data in Sint Maarten was only available at the whole island scale. This level of information is not considered sufficient when performing vulnerability analysis. Vulnerability index computation at smaller scales is advisable as they help in the identification of the most critical areas and as such be beneficial for the local government to guide the reduction of vulnerabilities to natural disasters more efficiently and to have targeted mitigation plans/measures [14,17,32].

According to the Department of Statistics of Sint Maarten, the island is divided into eight zones, 24 districts, and 54 neighbourhoods (Figure 3). For Sint Maarten, we managed to have partial access to information corresponding to the last population and census conducted in 2011 at the neighbourhood scale. Limitation to access the full extent of the census data poses a restriction to the number of variables we used in this study.

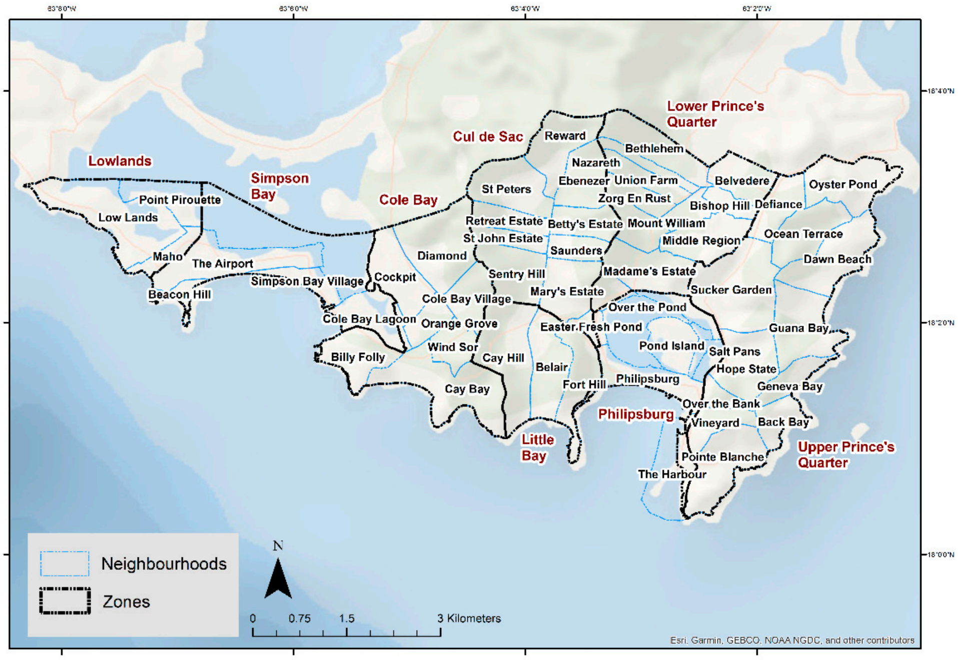

Figure 3. Administrative divisions of Sint Maarten at Neighbourhood and Zones scale. Texts in red are the zone's names, and texts in black are the names of the neighbourhoods.

2.3. Vulnerability Index

The framework selected for the computation of the vulnerability index in Sint Maarten is an extension on the work presented in Sorg et al. [17]. The PEARL vulnerability index (PeVI) aims to incorporate as many variables as possible to gain full insight into the vulnerability of a city or a region under analysis. PeVI has a modular and hierarchical structure with three main components: susceptibility, lack of coping capacities and lack of adaptation capacities. All three components consist of several factors which in turn are computed using a number of variables in a three-to-four-level hierarchy structure. The modular approach allows using any relevant and available information that captures the main components or drivers of vulnerability for the local conditions of Sint Maarten and to take into account not only the intrinsic and extrinsic factors of vulnerability but also takes into account the recent disaster caused by Hurricane Irma.

In the following subsections, the definition and computation of the three components of vulnerability, as well as the final vulnerability assessment, is presented. We recognise that some of the variables of a factor can be placed in another factor or component of the index; for example, the education variable may be used as an indicator for either the lack of adaptation capacities or in the awareness factor in the lack of coping capacities component. For this reason, we present in the following sections the explanations we used to support the rightness of use in each component based on literature review and expert knowledge. In addition, the Supplementary Material 1 contains a detailed explanation on the computation of each variable and shows all the formulas, tables, questions and values we used to compute the index.

2.3.1. Susceptibility

Susceptibility in this research is defined "as '*the current' status of a society and its likelihood to be harmed*" [17]. In the second level of the hierarchy, this component has four factors: Demography, Poverty and Income, Housing and Infrastructure, as shown in Figure 4.

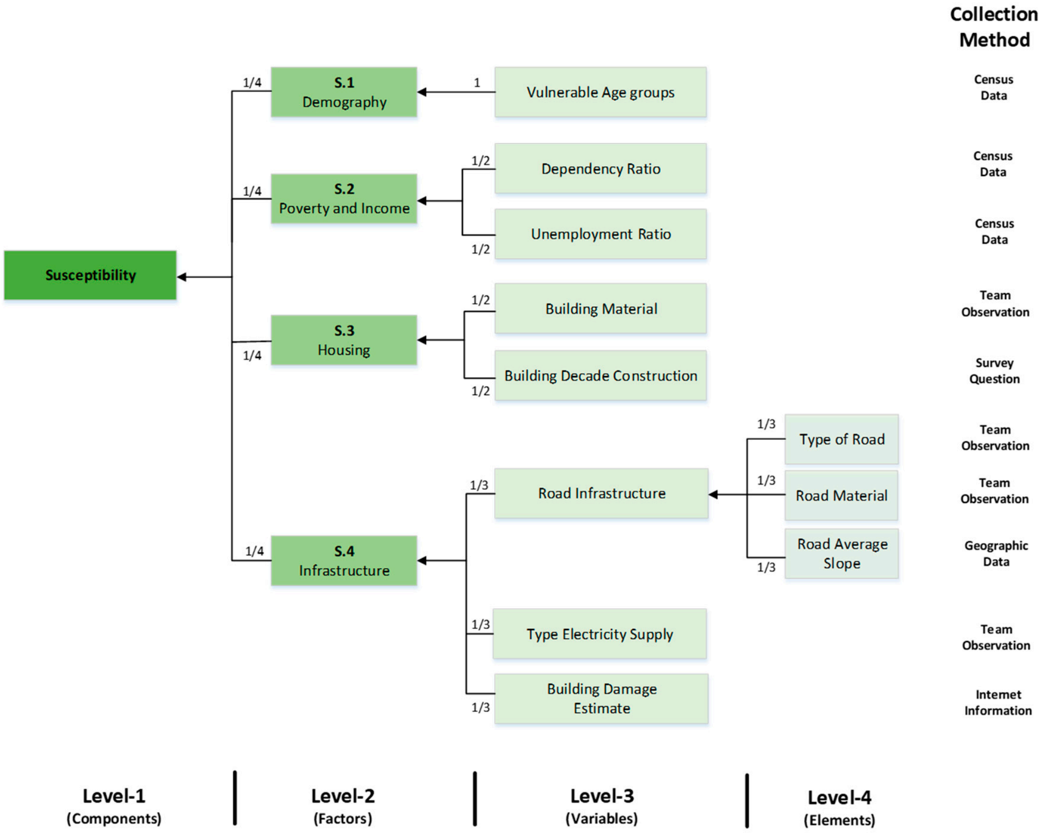

Figure 4. Structure of the Susceptibility component for the vulnerability index (PeVI), applied in the case study of Sint Maarten. The figure shows the four levels of hierarchy and the source of information used to compute each variable. The numbers next to the arrows indicate the weighting factor to compute the next level.

The **Demography** factor uses data from the 2011 census, and only one variable is used to compute it—*Vulnerable Age Groups*. This variable has been extensively used in previous vulnerability assessments for natural hazards [7,17,33,34]. In this group, it is suggested to include the segment of the population that is highly dependent (children younger than five years old) and the elderly population (older than 65 years old). These groups are more likely to require assistance, protection, transportation, financial support, and medications before and during disasters.

The factor **Poverty and Income** is a function of two variables *Dependency Ratio* and *Unemployment Ratio*, which are based on census data. *Dependency Ratio* is an economic parameter that captures the ratio between the population in a non-working age (i.e., younger than 15 years old and retirees) and the population in working age (i.e., 15 to 65 years old) [17,35]. Higher values of this variable indicate higher pressure on the working group to be able to support the dependent one. *Unemployment Ratio* is the relation concerning the number of people register as unemployed and the number of potential workers [17,33,36]. A higher rate of unemployment ratio reflects lower economic means to prepare appropriately for a disaster. This segment of the population may require external aid from the government or other humanitarian organisations during the pre-disaster and during the recovery phases.

The **Housing** factor is directly related to the physical characteristics of buildings that increases or reduces vulnerability. In this study, the variables that define the housing factor are *Building Material* and the *decade of construction* of houses. *Building material* is computed using observations we made during the fieldwork. The data collected for this variable in the surveyed houses was the walls and roof primary material. This variable is directly related to the structural strength of the building to resist adverse extreme weather conditions. As such, concrete houses are expected to have better resistance (lower susceptibility) than wooden houses (higher susceptibility) [8,37]. The *Decade of Construction* variable is of relative importance in Sint Maarten as it is a variable that has a direct relation with the construction method and material. We assumed that the older the house, the more vulnerable it is to natural hazards. As presented in Medina et al. [31], in Sint Maarten, it has been observed a significant change for better construction materials and better construction techniques after major disaster events such as those caused by hurricanes Dona (1960), Luis (1995) and Hugo (1998), and again after Irma (2017). Furthermore, we assume that the older the building, the more susceptible a building is to withstand a natural hazard. The assumption was based on the natural process of material degradation, and also from field observation and data collection, where residents do not perform regular maintenance to their houses.

The susceptibility to **Infrastructure** factor includes three variables: *Road Infrastructure*, the *Type of Electricity Supply* and the *Damage Estimate* to buildings caused by Hurricane Irma. *Road Infrastructure* is of vital importance during all phases of an extreme weather-related event, as they may get disrupted or highly damaged. *Road Infrastructure* is vital for facilitating evacuation, emergency services, relief supplies, the flow of goods and clean-up activities [38,39]. To account for *Roads Susceptibility* three elements were used: *Type of Road* (primary, secondary or tertiary), *Road Material* (Asphalt, concrete and unpaved) and *Terrain Slope* that is computed from the DEM as the average slope in percentage.

The *type of road* is extracted directly from *OpenStreetMap* attributes. Primary roads were considered more vulnerable since the few that exist are already working on full capacity and the limited redundancy on the transportation network make them almost mandatory to drive under any possible evacuation plan. This situation makes the primary roads more susceptible to collapse under an extreme weather event [40,41]. It is essential to include the road material in the index because more susceptible materials such as roads built-in natural terrain or asphalt can be easily erodible during rainfalls. The slope of the roads is important because the road's susceptibility increases in high steep areas due to poor or non-existing drainage [40,42], and the average slope of the road also influences the feasibility to access it [43,44].

The second variable used to compute susceptibility to **Infrastructure** is the *Type of Electricity Supply*. Electricity is a critical component in the recovery phase as societies depend significantly on the use of it, from household use to its vital use in other critical facilities such as hospitals and airports [45–47]. The importance of this variable in Sint Maarten lies on the high destruction potential of hurricanes and floods to electric power system components, causing widespread outages over a long period of restoration and recovery. Furthermore, blackouts are costly and entail considerable disruption to a society [48–50]. In Sint Maarten, the type of electricity supply was collected during the fieldwork at the street level and later the length was measured in the office using a map of the island. The categories of electricity supply on the island are aerial and underground. Aerial distribution lines were considered to have high susceptibility value to weather-related events. Hence, areas with underground electricity supply have low susceptibility compared to areas with aerial supply. Areas with no electricity supply did not account in the computation of the variable. We acknowledged that underground electricity distribution lines could also be affected by floods. However, for the Sint Maarten vulnerability assessment, this is simplified to include only the effects of wind on the electric system based on the observed effects of Hurricane Irma.

Finally, the third variable on the susceptibility of **Infrastructure** is the *Building Damage Estimate.* The importance of using this variable is that it can be a reasonable estimation of the proper use (or not) of building codes and administrative capacity (and willingness) to enforce regulations and to some extent to be used as predictors of damage for future hurricanes [51]. In addition, households that experience damages in the past may change their risk management behaviour to a most proactive reaction towards extreme events [52].

This variable was computed using the damage assessment for buildings done by Emergency Management Service, Copernicus [53]. The information obtained from Copernicus was a shapefile format of the buildings of Sint Maarten with the damage estimated in five categories for each building "Completely destroyed", "Highly damaged", "Moderately damaged", "Negligible to slight damage" and "not affected" by Hurricane Irma. Due to the rapid assessment performed by [53], the use of this information may have limitations of scale, resolution and data interpretation. Despite this disclaimer, the information was considered useful for rapid evaluation of the physical impacts of Hurricane Irma and how susceptible or not the building infrastructure was to the effects of a Category 5 hurricane.

2.3.2. Lack of Coping Capacities

The lack of coping capacities refers to "the strengths and resources for direct actions which potentially can lead to a reduction in the consequences of a hazardous event" [17]. In the PeVI, it is composed of six factors: Social Network, Immediate Actions, Government, Economic Coverage, Information and Awareness (see Figure 5).

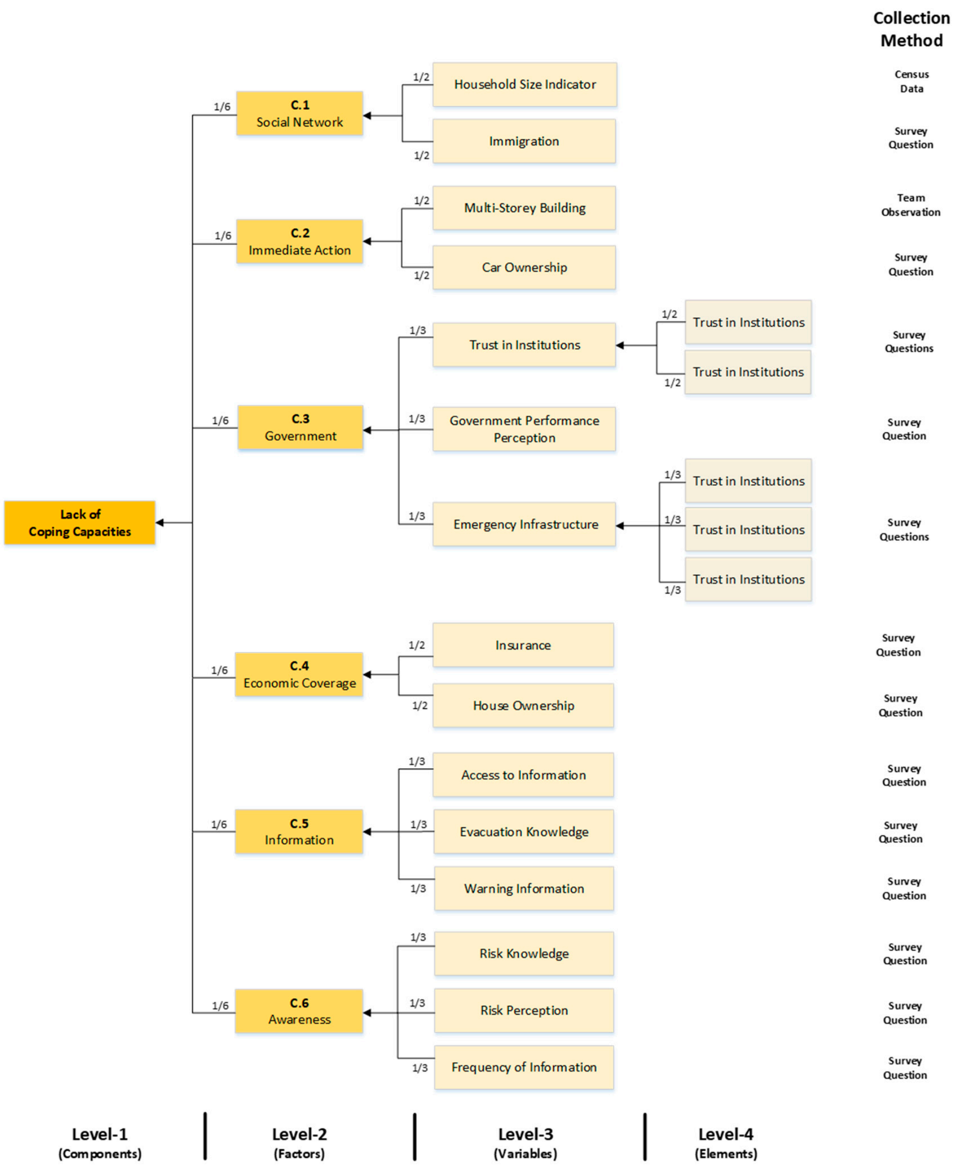

Figure 5. Structure of the Lack of Coping Capacities component for the vulnerability index (PeVI), applied in the case study of Sint Maarten. The figure shows the four levels of hierarchy and the source of information used to compute each variable. The numbers next to the arrows indicate the weighting factor to compute the next level.

The **Social Network** factor was computed using two variables, *Household size indicator* and *Immigration*. From the census data, the average number of inhabitants per household in each neighbourhood was extracted to compute the variable *Household Size*. Taking into account the formation of safety nets in the form of social networks, Welle, et al. [54] state that an increase in household size decreases vulnerability due to mutual help. The work of Lianxiao and Morimoto [55], also suggests that the more people in the family, the higher the ability to respond. For this study, a household with only one individual is considered to have a higher lack of coping capacities. In households with four or more inhabitants, this variable is considered not to influence the variable negatively. We acknowledge that expanding the household size can also affect the vulnerability by increasing the scarcity of resources, an increase in the number of care of dependants and a higher population density [7,56]. However, these associated adverse effects are accounted for in other variables of the PeVI.

To measure the lack of capacity due to the variable *Immigration*, we used a question from the survey. We asked for the number of years a respondent was living in Sint Maarten. It was decided to use the number of years lived on the island rather than the place of birth. Here we assumed that the more years a person has been living in a place could lead to a reduction of the vulnerability as they learn to cope and increase the knowledge of flood protection measures [32,57]. The number of years in a place has been previously identified to increase the general knowledge of the city, such as the best places where to evacuate and also to navigate through the bureaucracy to request and receive help from the authorities [32,58,59]. The number of years living in a place can also facilitate tighter social networks [60]. A stronger social network can increase the coping capacity through economic, social and emotional support [61] as well as increasing knowledge about past disasters and exchange information about the risk of future events [32]. On the other hand, recent migrants (less than five years living in a place), can potentially have cultural, economic and language barriers, which in turn can affect access to warning information and access to post-disaster aid [7,60,62,63].

One crucial element to increase the coping capacities is the ability to take **immediate action**, getting to safety in a fast and secure way during a weather-related event. In the case of floods, having a *multi-storey building* allows to move quickly to a higher zone and in this way avoiding direct contact with the hazard and also to protect belongings from getting damaged from the floodwaters [17,32]. During the fieldwork, we collected the number of floors of the surveyed houses. To compute this variable, we used the ratio between the number of houses with only one floor and the total number of houses in the neighbourhood.

A second variable for **Immediate Action** was related to the number of cars available in the household. It is a measure of the ability to evacuate during an emergency. We computed the variable *Car Ownership* based on a question from the survey. It was the ratio of the number of cars to the total number of inhabitants in the household. A ratio of 0.2 or bigger (i.e., having at least one car for each five-person) corresponded to a household with higher coping capacities. The smaller the ratio, the more vulnerable the household. Non-car ownership decreases the ability to move out of the hazard zone when required and closely related with low income and poverty factor [32,64,65], and not owning a car is highly correlated with non-evacuation behaviour [66].

The **Government** factor was computed using the variables, *Trust in Institutions*, the *Performance Perception* of the government during Hurricane Irma and the perception of the inhabitants about the quality of the *Emergency Infrastructure* on the island. All the variables of this factor were calculated using questions directly asked during the field survey. Previous studies such as Balica et al. [12] also used the lack of trust in institutions as a variable that lower vulnerability. Vári et al. [67], concluded that low levels of trust in institutions were highly correlated with variables that increase vulnerability such as low level of education, lower incomes and unemployed status as well as a strong relation with those who suffered the most damages. To address the trust in institutions variable, we used two questions of the survey. In the first one, we asked the participant that if based on their previous hurricane experiences, they trust in official sources of warning evacuations on the island. The second one was related to those respondents that directly expressed they did not evacuate during Hurricane

Irma because they did not trust the official warning. The higher coping capacities were assigned to those respondents that answer they have trust in authorities "to a great extent" and the lowest coping capacities for those respondents that answered they "do not trust at all" authorities. All the answers in between were assigned a proportional degree of vulnerability.

The second variable used in the **Government** factor was the *Performance Perception of the Government* in response to Hurricane Irma. Failures and inaction from governments were identified as a significant driver of present and future risk and can intensify the disaster impact [52,68]. Low-performance perception has a direct relation to households with a lower income and low level of education, houses that have shown low or non-changes in risk management at the household level [52]. Thus, they could be categorised as not being (fully) prepared in the event of new hazards events. *Government Performance Perception* was computed using a survey question indicating the relation between losses during Hurricane Irma and the responsibility of the government of the island. We used a larger coping capacity in this variable for respondents that did not blame the government for the losses in the island and lowest coping capacities to those respondents that "*strongly*" blamed authorities for the losses in the island.

As a final variable in the **Government** factor, we asked in the survey the perception of the respondent regarding the availability, location and accessibility to the existing *Emergency Infrastructure*. The questions used to build this variable were the sufficiency of shelters and if their locations were adequate, and if the road infrastructure was appropriate and sufficient to evacuate. A proper emergency infrastructure is vital for vulnerability and risk reduction. Emergency infrastructure acts as a way to mitigate the consequences of a disaster by potentially reducing exposure, especially among the socially vulnerable population [66]. In the PeVI, the higher the number of shelters available, the lower the vulnerability. For the computation, a strong agreement in the number of shelters or its adequate location or a proper road infrastructure was value as higher coping capacity (low vulnerability), and strong disagreement was ranked with lower coping capacity (higher vulnerability).

The fourth factor was the **Economic Coverage** and was calculated using two variables *Insurance* and *House Ownership*. Both variables were assessed based on survey questions, one directly asking if the household has insurance for natural disasters and another if the respondent owned or rented the house, respectively. Home *Insurance* for natural disasters can be seen as one of the most effective self-protective actions at the household level as a preventive measure in the coping strategies dimension of vulnerability [17,32,63]. Homeowners with insurance are less affected by natural disasters as they can absorb, rebuild and recover from losses more quickly once affected by a natural disaster [7,68]. For this study, having insurance was rated with high coping capacity, whereas not having one was assigned the low capacity to cope with the effects of a disaster. In the households where participants did not answer the question or expressed lack of knowledge as to whether or not the house was insured, we assigned an intermediate level of vulnerability. To those above, under the assumption that these households may not be insured, the question was avoided because in Sint Maarten it is mandatory to have home insurance when taking out mortgages [31].

House Ownership has a direct relation with vulnerability to natural disasters. First, house ownership is an indicator of available financial resources for adaptation and risk management [69]. Second, it has been linked to increasing preparedness to weather-related events due to the sense of appropriation [70]. Homeowners have shown more willingness to prepare their houses to withstand the expected magnitude of a specific hazard and more constant maintenance of the infrastructure. Furthermore, according to [71], this behaviour is associated with the local attachment effect (the emotional bonds of an individual to a specific place). As a consequence, in this study, we associated the houses with their owner living on it, with a higher coping capacity and less vulnerable to natural disasters. For those houses with renters, a lower coping capacity was used in the computation of this variable.

The factor **Information** was included as part of the coping capacities component. Warning information flow is essential to reduce vulnerability. Access to warning information needs to be received with sufficient time to react to a possible threat. The information also needs to be accurate, usable and understandable. We used three variables for this factor—*Access to Information*, *Evacuation Knowledge* and *Warning Information*. This factor was constructed entirely from survey questions.

In disaster risk management, one of the key drivers that negatively influences socioeconomic vulnerability is the lack of access to information [7]. Therefore, it is vital to acquire and disseminate the most accurate information in order to better utilise and target limited resources [18]. Population in potential risk that has access to information has at least the theoretical opportunity to reduce its vulnerability by acting accordingly to the information received [71]. Information in disaster management refers not only to have the means to distribute the warning messages to the whole population at risk but that the information transmitted contains sufficient elements that allow the population to act accordingly to minimise the impacts of a natural disaster [9].

To compute the *Access to Information* variable, we asked in the survey if the respondent knew where to get up-to-date information on early warning and actual evacuation news or instructions. We made no distinction between official sources of information and other sources. If the respondent answered that they know "to a great extent" from where to get access to warning information, we assigned a higher coping capacity value, and "not knowing" where to access information is assigned a low capacity to cope. The *Evacuation Knowledge* variable was computed based on a question asked to those who decided not to evacuate during Hurricane Irma. A low capacity to cope with the threat was given to the respondents that expressed that not knowing where to evacuate was an extremely influential reason to stay at home. We computed *Warning Information* with the number of days in advance (lead time) people receive warning information regarding the potential arrival of Hurricane Irma. The earliest the awareness regarding Hurricane Irma the highest the coping capacity.

The last factor of the lack of coping capacities component is **Awareness**. Knowledge and risk awareness of a specific hazard are good indicators of the household levels of disaster preparation [7,18]. We measured this factor using the *Risk Perception* and the *Risk Knowledge* of the respondent and the *Frequency of Getting Information* when a storm approaches. *Risk Knowledge* plays a central role in vulnerability assessment as knowledge is a necessary precursor of preparedness [7,32]. Knowledge of the hazard has been previously used as a measure of the coping capacities of a community, and it is recognised as a prerequisite to be able to trigger evacuation and coping mechanisms [72]. For Sint Maarten, this variable was evaluated using the number of hurricanes respondents who remember a hurricane that has hit the island directly while they were living on the island. A higher coping capacity was assumed for respondents that experienced more hurricanes because of the increase in risk knowledge based on first-hand experience. Similarly, the lowest coping capacity in this variable was for the respondents with no hurricane experience.

The variable *Risk Perception* was considered crucial in vulnerability and risk reduction. It is defined as "intuitive risk judgements of individuals (and social groups) in the context of limited and uncertain information" [73]. Risk perception has the potential to either mitigate or enhance the potential of a hazard [6,70]. There is a strong correlation between perceiving being at risk and vulnerability reduction behaviour. In contrast, low perception of risk in high exposed zones has proved to have catastrophic consequences in loss of life and high losses due to lack of preparation or protective behavior [32,74]. *Risk Perception* has also been reported as one of the main reasons when deciding whether or not to evacuate during an extreme weather event [31,58,59]. For those that did not evacuate during Hurricane Irma, we asked in the survey whether or not the decision to not evacuate was based on their feeling that Hurricane Irma would not be a real threat. Given the magnitude of the disaster caused by this hurricane, the minimum coping capacity value is for those respondents that ranked this question as "an extremely influential" reason not to evacuate.

How often an individual or group of individuals check for the latest updates regarding warning and evacuation information is a sign of increased awareness and readiness to cope with the adverse effects of a potential hazard. A positive effect on risk perception due to being regularly exposed to media has been extensively verified as reported in Hong, et al. [75]. Staying up-to-date to the type of hazard allows citizens to adjust their behaviour when the hazard is approaching (i.e., stay home or go to a safer place) [76,77]. *Frequency of Information* was incorporated in the coping capacities component using a survey question. We asked how often the interviewee checks for weather information when a hurricane or tropical storm is announced. Due to the high uncertainty in the path and the frequency of hurricanes in Sint Maarten, the lowest coping capacity was for respondents that check weather information with a frequency of less than once a day, and the highest one to those checking the updates throughout the whole day.

2.3.3. Lack of Adaptation Capacities

The lack of adaptation capacities "*is closely related to change and the ability to deal or recover from the negative impacts of a future disaster*" [17]. The four factors of this component are education, gender equity, level of investments and the vulnerability assessment of the critical infrastructure in the island. Each factor within this component was computed using only one variable (Figure 6).

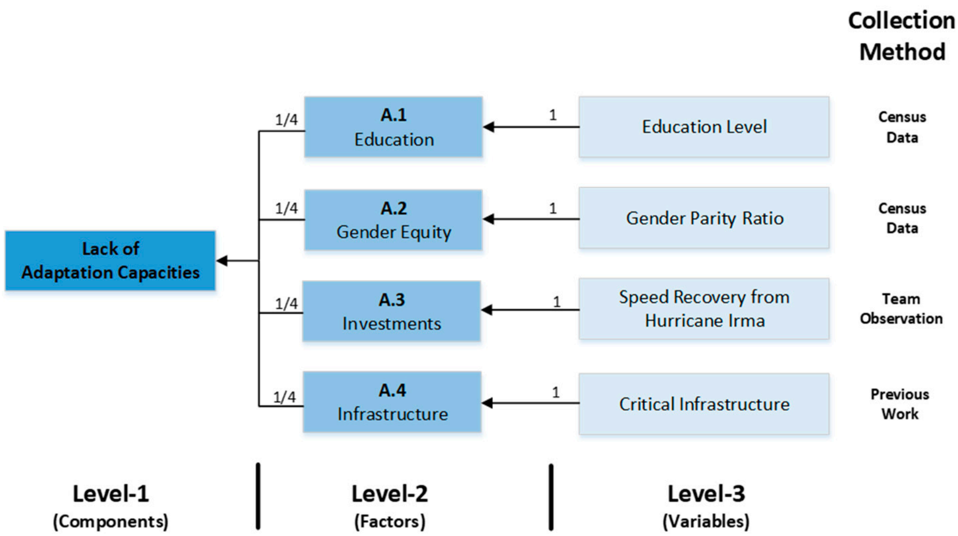

Figure 6. Structure of the Lack of Adaptation Capacities component for the vulnerability index (PeVI), applied in the case study of Sint Maarten. The figure shows the three levels of hierarchy and the source of information used to compute each variable. The numbers next to the arrows indicate the weighting factor to compute the next level.

The *Level of Education* is the variable used for **Education** factor, and it is evaluated using census data by computing the ratio between the number of people reported holding at least high school degree and the population over 18 years old. Thee follow a similar approach as the one presented in Sorg et al. [17] and Fekete [33]. Higher levels of education can be used as a measure of the economic capacities of a household as it may lead to better salaries. Wealthier households can prepare and mitigate better for disasters and are expected to recover faster, employing their economic status [7,32,58]. Besides, people with higher formal education levels have shown more access to information [71]. In contrast, people with a lower *Level of Education* has been observed to have less awareness or limited understanding of warning information towards the potentially catastrophic effects of an extreme event. Low education levels are also associated with less capability of adopting emergency measures and with limitations to access recovery information [7,54].

We used the variable *Gender Parity Ratio* in education as a measure of **Gender Equity**. Adopted from Sorg et al. [17], this variable is calculated using the ratio of the number of females holding primary, secondary or tertiary education and the respective number of males with the same levels of education. A ratio of 1 on this indicator means equity in access to education and is the desired value; therefore, we assigned the highest adaptation capacity in the computation. Advantages for men in the parity ratio ranged from zero to one and larger than one represents an advantage for women. We assign low adaptation capacity to both of the extreme values of this variable. As summarised in Smith and Pilifosova [78], it is frequently argued that adaptive capacity will have a more significant (positive) impact if the access to resources is distributed equally. Without equity, adaptive actions for vulnerability reduction may benefit only those sectors or individuals best placed in society [79]. Hence, integrating elements of equity in the identification of vulnerability is key to achieve effective implementation of vulnerability reduction programs that include the marginalised sectors [80].

The variable *Speed of Recovery* was observed by the research team five months after Irma impacted in the island. Though a subjective observation made by the field team, the compiled information is of great use to detect which areas were bouncing back faster (and stronger) in the reconstruction phase as a sign of adaptive capacities. The assessment of *Recovery Speed* was made for the entire Dutch part of the island, and averaged by neighbourhood and classified into five categories from very slow to very fast recovery, assigning from low to high adaptive capacities respectively. The capacity of a city to rebound from destruction has been used as a measure of resilience and adaptation capacities by several authors; a summary of those can be review in Gunderson [81].

The variable *Critical infrastructure* is defined in the context of this research as physical assets that play an essential role in the functioning of the society and the economy. We include in this category facilities for electricity generation, access to water and food, public health, telecommunication, sheltering, education and transport. Damage to critical infrastructure can impede or limit access to disaster relief and are crucial in restoring essential services to normalise lives and mitigate the impacts of the disaster [82–84]. Hence, evaluating the vulnerability of the critical infrastructure of a city or region can be a good indicator of how fast the city will recover. For Sint Maarten, such evaluation already existed from a previous work of the research team in a total of 200 buildings [85]. Vulnerability to critical infrastructure took into account the physical condition of the buildings and the flooding potentiality. Each building then was assigned a vulnerability value in a five point scale—low, medium, high, very high and extreme vulnerability.

2.3.4. Vulnerability Computation

The implementation of the vulnerability index consisted in the computation in Microsoft Excel© of each one of the 27 variables described above. This process was performed in 49 out of the 54 neighbourhoods of Sint Maarten. Five neighbourhoods did not have enough information to compute the vulnerability index or its components. Those were: Back Bay, Geneva Bay, Salt Pans, The Harbour and The Airport (Figures 3 and 9). Then, the variables are combined to produce every factor using the associated weight, and by combining factors, each one of the components is computed. Finally, by using equal weight, the three main components of the vulnerability index are added to produce the PeVI for each neighbourhood (Equation (1) and Figure 7).

$$Vulnerability = \frac{1}{3}\,Susceptibility + \frac{1}{3}\,Lack\ of\ Coping\ Capacities + \frac{1}{3}\,Lack\ of\ Adaptation \quad (1)$$

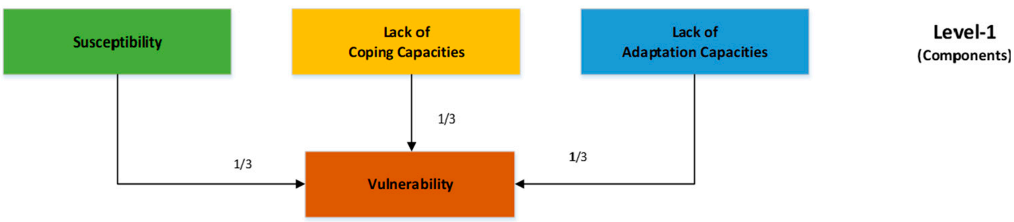

Figure 7. Composition of the vulnerability index (PeVI), for the case study of Sint Maarten with the three main components in the level-1 of hierarchy. The number next to the arrows correspond to the weight of each component in the computation of the PeVI index.

Variables used in the computation are of different nature and characteristics, ranging from quantitative to qualitative values and from different data sources (census, survey, observation and third parties). Such heterogeneity on the input data requires a standardisation of the data to ensure uniformity in scales and units [18]. The data used in the computation of the PeVI can be categorised into four data types:

Type-1 —**Census data:** Variable of quantitative nature. Data (a number) in this category represent the total number of inhabitants in each neighbourhood for a specific variable; for example, the number of people five years old or younger, and the number of residents per household.

Type-2 —**Categorical variables:** A variable that can take on one of a limited, and a usually fixed number of possible values; for example, building wall materials (Concrete, brick, wood, others) and type of electricity supply (aerial, underground and no electricity).

Type-3 —**Likert scale questions:** Measures how people feel about a question of the survey, based on a rating scale. There are three different ranges of this type of questions. One ranging from "Not at all influential" to "Extremely influential", other from "Strongly disagree" to "Strongly agree" and the third one from "To a great extent" to "Not at all". Examples in this category are the perception of the sufficiency in the number of shelters in the island and the influence of particular variables to not evacuate during Hurricane Irma.

Type-4 —**Binary questions:** Questions in the survey in which the answer is of the type Yes or No. An example is house ownership.

All variables were standardised in numeric and dimensionless values, ranging from 0 to 100 (from lowest vulnerability to highest vulnerability). This standardisation allowed us to perform operations among the different units and magnitudes of variables, to weight them and to make comparisons. For Type-1 variables, the standardisation was done by multiplying the ratios or numbers obtained in the computation by 100, except for gender parity ratio, which was obtained using a min-max normalisation method. For Type-2 variables, a specific value of vulnerability from 0 to 100 was assigned to each possible answer the categorical variable can take. In the Type-3 variables, for the answers "*strong agreement*", "*extremely influential*" and "*not at all*", a value of 100 was assigned. Similarly, a value of 0 was used to answers strongly disagree, not at all influential and to a great extent. With an exception in the variable emergency infrastructure where the Likert scale was inverted (strongly agree = 0 and strongly disagree = 100). The intermediate possibilities of the Likert scale were assumed to be evenly distributed over the minimum and maximum value. Type-4 variables are standardised with a high value of vulnerability (80) to negative answers (absence of) and a low vulnerability value of 20 to affirmative answers (presence of). The complete set of formulas and values used for the 27 variables is presented in the Supplementary Material 1 that accompanies this paper.

2.3.5. Vulnerability Mapping

The PeVI for Sint Maarten and its primary three components susceptibility, lack of coping capacities and lack of adaptation, were cartographically displayed using GIS software (ArcMap 10.5). We mapped each one of the components in five classes of vulnerability (Very low, Low, Medium, High and Very high) using natural breaks classification method. The selection of the classification method is not a trivial choice. The resulting vulnerability maps and future decisions made, based on the maps, are very dependent on the classification method to be employed. The choice needs to be closely related to the aim of the vulnerability assessment (i.e., support for decision making, prioritising, and funding allocation). A poor choice in the method can be misleading [86]. We select natural breaks (Jenks) as a classification method for the spatial representation of vulnerability and its components.

With natural breaks classification, classes are based on natural groupings inherent in the data. Breaking points between classes are identified that best group similar values, and that maximise the differences between classes. The features are divided into classes whose boundaries are set where there are relatively significant gaps in the data values [87,88]. The properties of the natural breaks classification method make it the most suitable for dividing neighbourhoods whose vulnerability is similar because it reduces the variance within each class [13]. It is important to note that natural breaks are a data-specific classification method, and hence it is not useful for comparing multiple maps that use different underlying information.

For the reason mentioned above, it is not possible to make quantitative comparisons amongst the maps we produce. However, this does not necessarily mean that no comparison can be made, for example, all neighbours classified in the "very low" (dark green) group, viewed relatively, they all have a lower priority concerning the component or index it represents. Furthermore, having a "Very low" value in one of the maps does not mean that a specific neighbourhood is not vulnerable (or another component) it just has somewhat a lower priority than other neighbourhoods.

2.4. Principal Components Analysis (PCA)

To run the PCA, we select the level 2 of the hierarchy structure, corresponding to the **factor** level. PCA was run using a total of 14 factors. PCA analysis in this research was carried out using a package in R called factomineR [89]. The first step in the PCA analysis is the analysis of missing data, which was done using an R package called missMDA [90]. This package uses an iterative method to impute data in the missing values by taking into account both similarities between individuals and relationships between variables. It works in a way that the PCA is constructed from observed data only (i.e., no contribution from the imputed data). [23,90]. The dataset we used consisted of 49 individuals (neighbourhoods), 14 variables (factors), one quantitative illustrative variable (vulnerability) and one qualitative illustrative variable (administrative zones).

After this step, all variables were normalised using z-scores. It is advisable to perform such standardisation for comparisons of data across variables. Standardisation generates variables with a mean of 0 and a standard deviation of 1. Even when the units of measurement do not differ, this operation is generally preferable as it attaches the same importance to each variable [23,91]. Then, we run the PCA on the standardised data using varimax rotation. This step is done to simplify the relationships among the variables and to clarify the interpretation of the factors [92].

3. Results and Discussion

3.1. Correlation Analysis and Selection of Number of Principal Components

3.1.1. Variables and Factors Screening

We screen all the variables of the PeVI for singularity and collinearity. This procedure is done in order to reduce the problems when analysing the data. The data screening on the entire set of original variables is done using the correlation and covariance matrices produced with the Principal Components Analysis (PCA). This step ensured that highly correlated variables are removed before the computation of the index. We found that a variable named economic status (of each neighbourhood) which was subjective based on field observations, had a strong correlation ($R^2 = 0.86$) with other variables of the index and therefore creating data redundancy. For that reason, we decided to remove it from the analysis.

We re-run the correlation test with the remaining variables to reassure their relevance. We found a strong positive correlation ($R^2 = 0.76$) between two factors of the coping capacities, immediate action (C.2) and economic coverage (C.4). This high correlation can be explained because the immediate action factor in this index has elements that could be directly related to the wealthy of households such as car ownership. Data from the survey reveals that in Sint Maarten the possession of cars on the island is not limited to wealthy households. Hence, we decided to keep both factors in the vulnerability assessment to adequately capture the effect of car ownership on the island's vulnerability.

For this study, 27 variables were used to compute the final PeVI of Sint Maarten. Eight for susceptibility, 15 in the lack of coping capacities and four in the lack of adaptation capacities. Based on this conceptual approach, the socioeconomic vulnerability to floods and hurricanes in Sint Maarten was computed and analysed from a spatial point of view, through a vulnerability index integrated into GIS, but within the limits of data availability from census, field data collection and data from third parties.

3.1.2. Selection of the Number of Principal Components

The selection of how many components to include in PCA is an arbitrary decision but must follow some guidelines. For this research, we define the number of PC in two steps. First, we decide to only keep factors with eigenvalues (contribution) greater than 1, using the Kaiser criterion as reported in Husson, Lê and Pagès [23], and second, that the minimum number of PC selected explain at least 60% of the variation of the original data. The first plane of analysis, composed by the first two dimensions of the PCA run in Sint Maarten dataset account for 40.7% of the total dataset inertia or individual's total variability. The percentage explained by the first two PC, is an intermediate percentage, and the first plane represents only part of the data variability; thus, we consider the next dimensions (PC-3 and PC-4). The cumulative variability explained in the first four dimensions is 62.5%. Hence, for Sint Maarten, we select four principal components for the PCA (Figure 8).

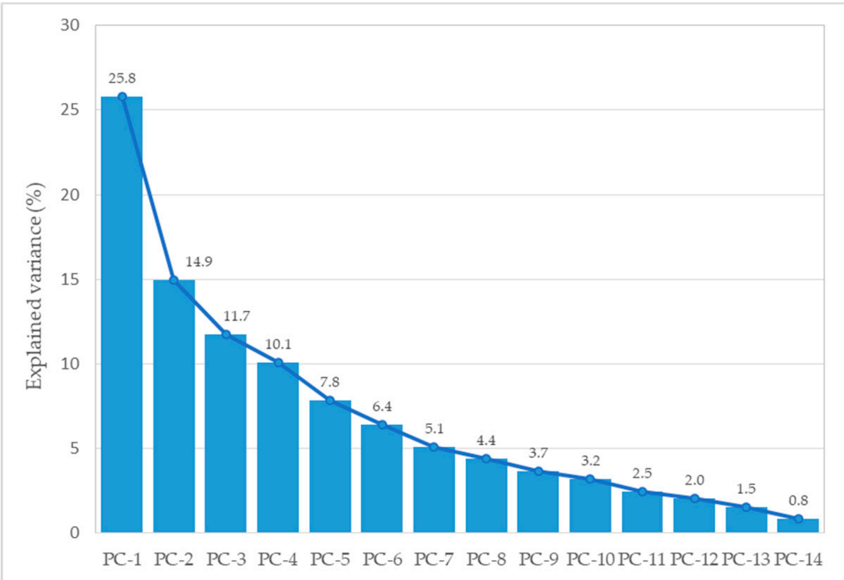

Figure 8. Scree plot with the decomposition of the total inertia on the component of the analysis. The first four principal components explain 62.5% of the inertia in the data.

3.2. *Vulnerability Index and Components*

The resulting vulnerability index (PeVI) is presented in Figure 9d and combine the three main elements on which vulnerability can be decomposed Susceptibility (Figure 9a), Lack of coping Capacities (Figure 9b), and Lack of Adaption (Figure 9c). Furthermore, in Table 1, we present the top 5 most critical neighbourhoods for the PeVI and for each component of the vulnerability index. The complete table with the computed values for all neighbourhoods is presented in Appendix A. Figure 10 presents a closer look at the top five driving factors for each one of the critical neighbourhoods.

In terms of **Susceptibility** (Figures 9a and 10a), for the top five more critical neighbourhoods (Table 1), *Housing* is the most important driving factor to increase susceptibility in these neighbourhoods, followed by the *Infrastructure* factor. Inferior quality in the construction materials and the associated high level of destruction after Hurricane Irma in these neighbourhoods can explain why these areas of the island are the most susceptible ones. These neighbourhoods are also the place of residence of a considerable portion of the undocumented immigrants. This group has been struck especially hard by

Hurricane Irma, as Irma damaged both their houses and their financial capacity. A successful plan to lower risk and vulnerability in Sint Maarten to extreme events will require a high level of compromise from the local authorities to improve and monitor the building codes in the island to accurately reflect the high potential hazard to hurricanes and floods.

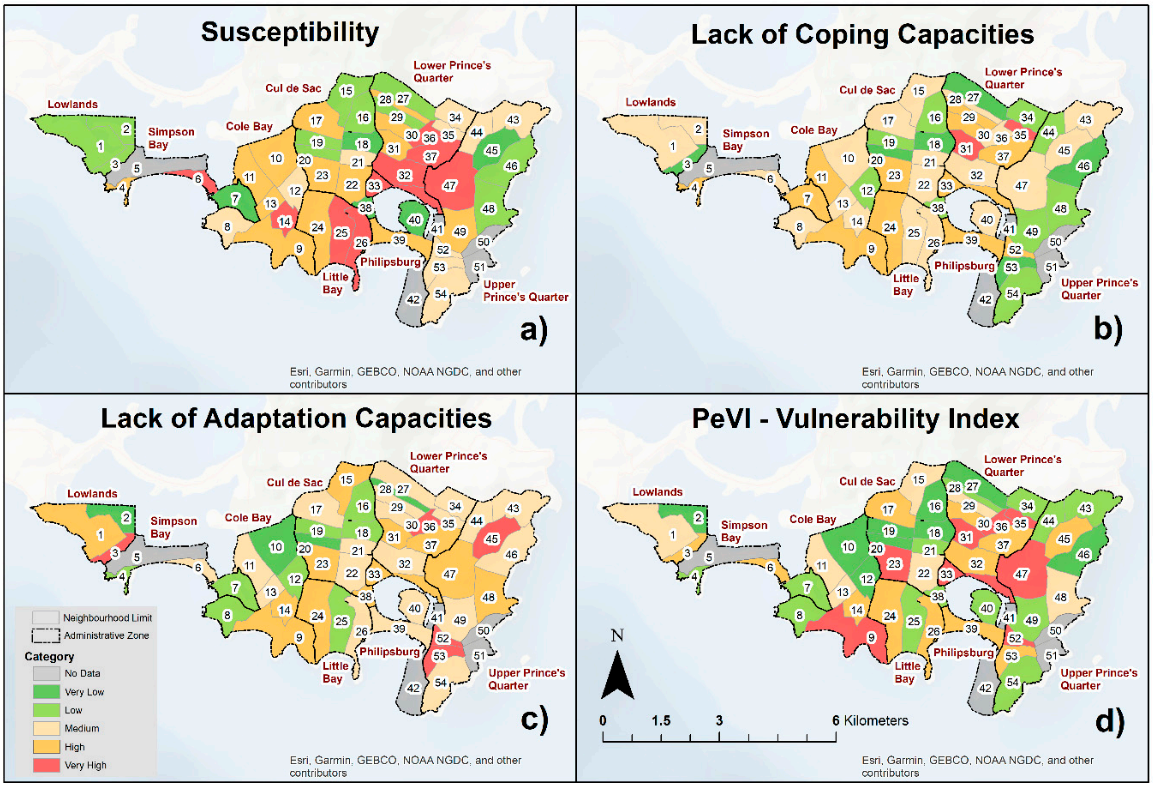

Figure 9. Susceptibility (**a**), Lack of coping capacities (**b**), Lack of adaptation capacities (**c**) and PeVI vulnerability index (**d**) for Sint Maarten at the neighbourhood scale. Numbers represent the identification (ID) of each neighbourhood, as presented in Appendix A and Table 1.

Table 1. The five most critical neighbourhoods for PeVI vulnerability index and the three components: Susceptibility, Lack of coping capacities and Lack of adaptation capacities.

Component	**Top 5 Most Critical Neighbourhoods** *(ID) / Name / (Value)*				
	1	**2**	**3**	**4**	**5**
Susceptibility	(36) Dutch Quarter (41.3)	(6) Simpson Bay Village (34.5)	(14) Wind Sor (34.4)	(33) Over the Pond (34.36)	(37) Middle Region (34.0)
Lack of Coping Capacities	(35) Bishop Hill (63.5)	(31) Mount William (55.2)	(39) Philipsburg (46.7)	(33) Over the Pond (44.9)	(52) Over the Bank (44.1)
Lack of Adaptation Capacities	(36) Dutch Quarter (57.3)	(3) Maho (54.1)	(53) Vineyard (52.56)	(52) Over the Bank (51.3)	(45) Ocean Terrace (50)
PeVI—Vulnerability Index	(36) Dutch Quarter (44.9)	(52) Over the Bank (41.1)	(35) Bishop Hill (39.4)	(33) Over the Pond (38.7)	(31) Mount William (38.7)

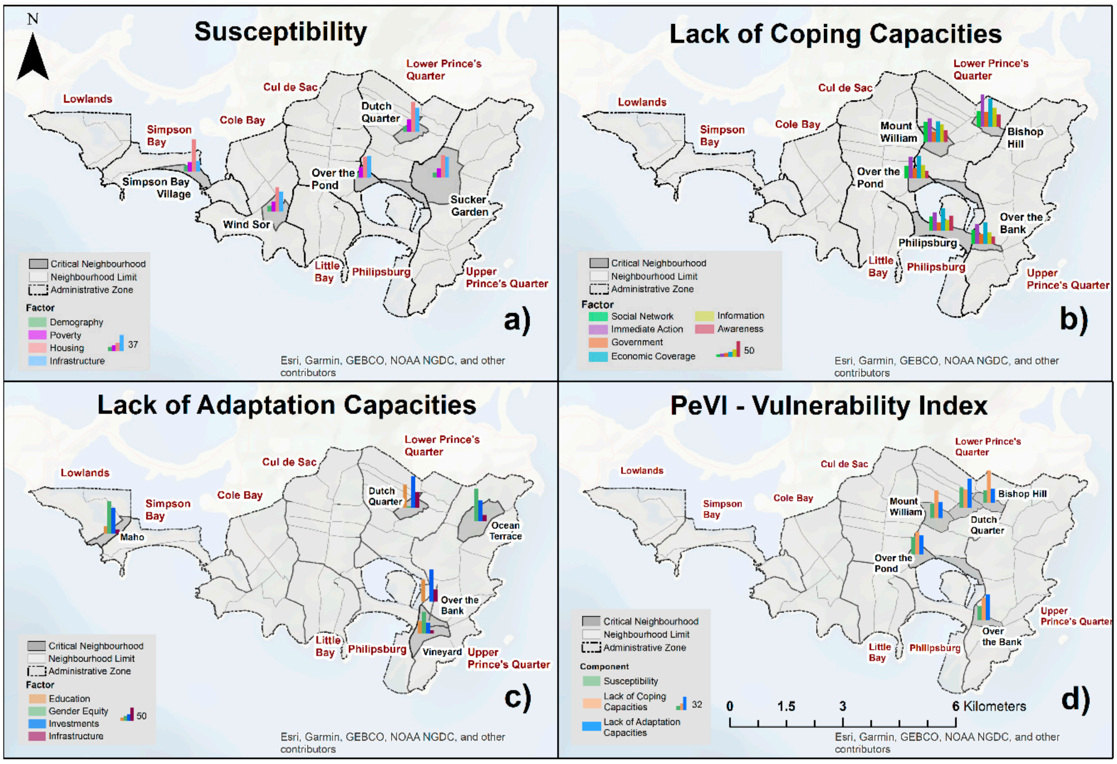

Figure 10. Top five critical neighbourhoods in Sint Maarten for each component of the vulnerability index. Susceptibility (**a**), Lack of coping capacities (**b**), Lack of adaptation capacities (**c**) and PeVI vulnerability index (**d**). The bars in the polygons represent the magnitude of each factor in the respective component or the component in the index. Labels in red represent the administrative zones and in black the neighbourhood names.

Regarding *Infrastructure* susceptibility, it is necessary to highlight that Sint Maarten is a very densely populated territory, the island is the most densely populated country in the Caribbean and the 12th in the world [93]. Population density pushes the limits of the island in terms of expansion or upgrade of the physical infrastructure such as roads and inadequately planned urban expansion in the riskiest areas such as hillsides [94]. The electricity supply in these critical neighbourhoods was very susceptible, as a considerable portion of the network remains aerial. The electricity company (or the government) cannot undertake the upgrade of the system in some of the neighbours because that requires intervention on private land and landowners may not allow it. It was observed during the fieldwork that some of the critical neighbourhoods were still in the restoration process of electricity lines.

In contrast, Ocean terrace, Betty's Estate and Dawn Beach are amongst the less susceptible neighbourhoods in Sint Maarten. These neighbourhoods have a large proportion of gated condominiums, some of which belongs to the time-sharing schemes that are abundant on the island. In Betty's state are located some of the wealthier houses we observed of permanent residents of the island; and according to findings during the fieldwork, the direction of the winds in this part of the hills favour the lesser destruction during Irma. Another factor contributing to low values of susceptibility is *Demography*; the proportion between the number of people in working age and the most vulnerable ages group indicates that there is a right number of the population to take care of the most vulnerable part of the population.

In terms of **Lack of Coping Capacities** (Figures 9b and 10b), *Immediate Action* and *Economic Coverage* are the critical factors associated with the low capacities to cope with the effects of hurricanes and floods in the most critical neighbourhoods. An explanatory variable that decreases the coping capacities is that in Sint Maarten house ownership is particularly low, with more than 53% of respondents living under rental agreements. Tenants in the island generally do not feel the responsibility to maintain and strengthen the houses they occupy, and landlords are not also active in repairing the houses.

The situation is even more complicated in those areas where the land is leased, in which usually it is forbidden (by the owner) to build a house with durable materials, which is against the construction code but a common practice in leased areas. Another explanatory variable is the low coverage of home insurance. We found that residents of Sint Maarten do not take insurance due to high rate of premiums, low trust of the insurance companies, not getting paid what the house is worth, slow claim processing, and poor client service.

On the other hand, Dawn Beach, Vineyard, St John Estate and Maho neighbourhoods have the highest coping capacities on the island. In these neighbourhoods, the driving variables of high coping capacities are related to higher *Awareness* and *Access to Information*, as well as the high capacity to react fast to the potential hazard (variable *immediate action*).

In terms of the **Lack of Adaptation Capacities** (Figures 9c and 10c), none of the factors in PeVI predominantly explains the lack of adaptation capacities across the critical neighbourhoods of Sint Maarten. An analysis location by location is needed to understand what factors are driving low adaptation capacities in the critical neighbourhoods. Maho, Vineyard and Ocean Terrace are especially critical in the *Gender Equity* factor. The ratio between male and female inhabitants with education is especially skewed in these neighbourhoods. The critical component in Dutch Quarter and Over the Bank is the variable *Investments*, measured as the speed of recovery after Hurricane Irma. This variable was valued as low during the fieldwork as we observed slow or no reconstruction of buildings in these areas. The education level also contributes largely to the lack of adaptation capacities in these neighbourhoods where the literacy rate was reported to be the most precarious in the island. In contrast, the less vulnerable neighbourhoods in terms of having the best adaptation capacities were identified to be Point Pirouette, St John Estate, Diamond and Nazareth.

In terms of overall vulnerability index (Figures 9d and 10d), we identified that the most critical neighbourhoods are Dutch Quarter, Over the Bank, Bishop Hill, Over the Pond and Mount William. Generally speaking, all these neighbourhoods present relatively high values in the three components used to compute the vulnerability index. Four of the top five most vulnerable neighbourhoods are in the top five of the lack of coping capacities, this component being the most influential driver of vulnerability in Sint Maarten.

3.3. Principal Components Analysis (PCA)

The contribution values of each factor to the PCA analysis, as presented in Table 2 shows the degree of correlation between each component in the analysis and the dimensions or principal components. To understand better which components of the index are the most influential in the PCA and the overall vulnerability of Sint Maarten Figure 11 is presented. The first principal component (PC-1), is influenced significantly by the variables C.2 (Immediate action), C.4 (Economic Coverage) and A.1 (Education). The second principal component (PC-2), is receiving more influence from S.2 (Poverty and Income), S.1 (Demography) and C.5 (Information). In the third principal component (PC-3), the most contributing factors are A.4 (Infrastructure), S.4 (Infrastructure) and A.3 Investments. For the PC-3 variables, A.1 (Education) and S.2 (Poverty and Income) also have considerable influence, but those are already accounted for in the most significant principal components. Finally, PC-4 is influenced mainly by A.2 (Gender Equity), C.3 (Government) and C.6 (Awareness) and also C.4 (Economic Coverage) that also influences PC-1. For the easiness of usability and interpretability, the dominant factors in each PC allowed us to group them in four categories, PC-1 Economic and education, PC-2 Demographic and information, PC-3 Infrastructure and investments and PC-4 Governance. These are not precise categories but dominant factors in each PC.

Table 2. Contribution of each factor to each Principal Component for the socioeconomic vulnerability in Sint Maarten. In green, the main contributing factors to each PC and in grey important contributing factors already accounted in another PC.

Factor	PC-1	PC-2	PC-3	PC-4
C.2 Immediate Action	0.79	0.18	0.02	0.32
C.4 Economic Coverage	0.78	0.18	−0.08	0.40
A.1 Education	0.64	0.13	0.48	0.09
S.2 Poverty and Income	−0.20	0.63	0.56	0.34
S.1 Demography	−0.46	0.57	0.02	−0.16
C.5 Information	0.33	0.49	−0.06	−0.14
A.4 Infrastructure	0.31	−0.28	0.50	−0.37
S.4 Infrastructure	0.56	−0.25	0.45	−0.25
A.3 Investments	0.40	−0.54	0.27	−0.01
A.2 Gender Equity	−0.32	−0.53	0.13	0.55
C.3 Government	0.22	−0.40	−0.38	0.43
C.6 Awareness	0.54	0.37	−0.34	0.20
C.1 Social Network	0.57	−0.12	−0.54	−0.45
S.3 Housing	0.52	0.17	−0.03	−0.19
Eigenvalue	3.61	2.09	1.64	1.41
Variance (%)	25.77	14.93	11.72	10.09
Cumulative variance (%)	25.77	40.69	52.41	62.51

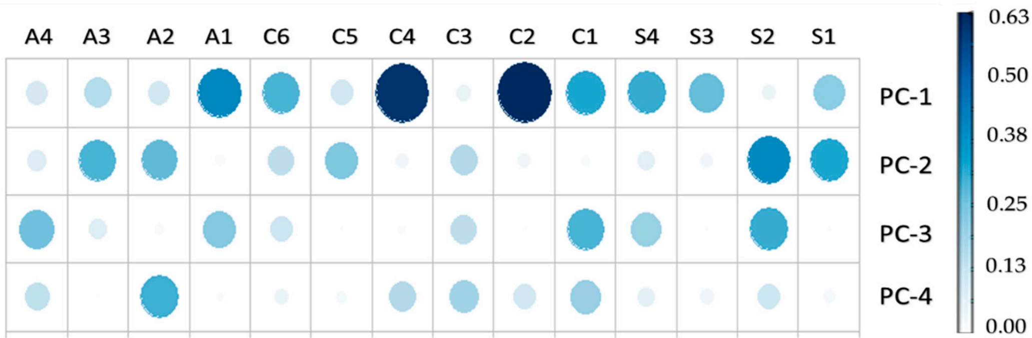

Figure 11. Contributing components to the first Principal Components in the PCA run for Sint Maarten vulnerability. The biggest and darkest the circle the most influential the component to the dimension and overall in the dataset. C2 (Immediate action) and C4 (Economic Coverage) are the most influential components for dimension one and the whole vulnerability index as well.

A coefficient closer to either 1 or −1 means that it has a stronger correlation to that component, positively and negatively affecting the component respectively [91]. The more significant the contribution of a variable to a principal component, the more influential towards increasing vulnerability. This result is not only consistent with the PeVI but supports the conclusions that coping capacities and especially the variables C.2 and C.4 are the key factors to have an effective vulnerability and disaster risk reduction plan on the Island. Given the fact that in a small island state as Sint Maarten most of the population can be exposed during an extreme weather event, it makes sense that immediate action plays a vital role in the vulnerability assessment. It is essential that residents can move fast to a secure zone or even to have the possibility to fly out of the island and to have the means to protect their houses in case of an imminent disaster, but also the ability to bounce back faster from the effects of it. A wealthier economy can help to mitigate the impacts by increasing house ownership and more households that can acquire home insurance to protect their assets. Education can help to close the economic gap on the island as a mid or long-term solution.

The spatial distribution of the Principal Components Analysis at the neighbourhood level is shown in Figure 12. The spatial distribution reveals that there is a geographic distribution of the different factor composing the vulnerability of Sint Maarten. PC-1, Economic and education category, is especially critical in the lower prince's quarter zone, in this category the neighbourhoods Bishop Hill, Mount William, Over the Bank, Dutch Quarter and Over the Pond are the most critical ones. PC-2, referring to the demographic and information category does not aggregate in a particular zone, instead is distributed along the island. Neighbourhoods St. John State, Union Farm, Nazaret, Defiance and Point Pirouette are the critical ones in terms of PC-2. The category Infrastructure and investments (PC-3), is more critical in two zones: Lower and Upper Prince's Quarter and in distributed among Dutch Quarter, Over the Pond, Defiance and Over the Bank neighbourhoods. Finally, PC-4 distribution shows that governance category is also distributed on the island with not a clear critical zone. Four neighbourhoods are critical regarding governance, Ocean Terrace, Bishop Hill, Maho and Beacon Hill.

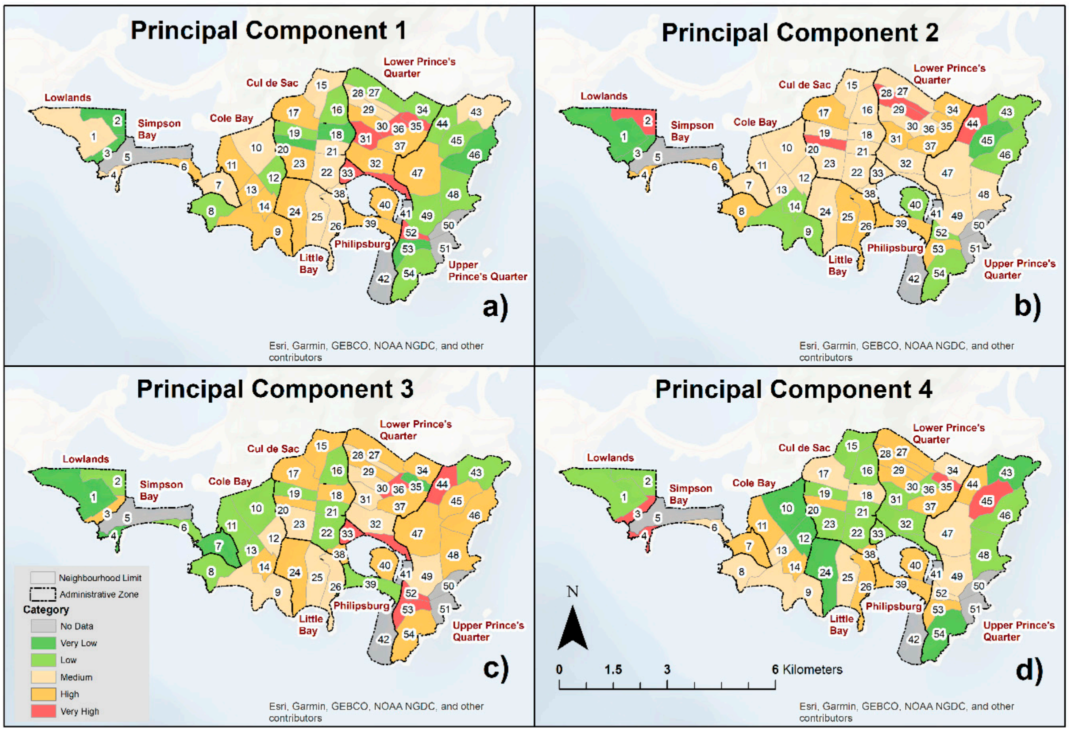

Figure 12. Principal Component 1 (**a**), Principal Component 2 (**b**), Principal Component 3 (**c**), Principal Component 4 (**d**) for Sint Maarten Vulnerability at the neighbourhood scale. Numbers represent the identification (ID) of each neighbourhood, as presented in Appendix A and Table 1.

3.4. Clustering Analysis

Furthermore, PCA allows clustering analysis of neighbourhoods to be performed. This clustering can help decision-makers to see common drivers of vulnerability across the island. This analysis can be used to evaluate where the potential impact of a specific measure to reduce vulnerability will have the most positive impacts. We run a classification method for clustering the neighbourhoods using the first two components.

The clustering analysis revealed five clusters of neighbourhoods in Sint Maarten (Figure 13). Cluster 1 is made up of two neighbourhoods, Maho and Ocean Terrace. This group is characterised by high values for the factor Gender Equity (A.2) and low values for the factors Information (C.5), Social Network (C.1) and Housing (S.3). Cluster 2 is composed of seven neighbourhoods: Defiance, Nazareth, Point Pirouette, St John Estate, Union Farm and Vineyard. This group is characterised by high values for the factors Poverty and Income (S.2) and Demography (S.1) and low values for the factors Investments (A.3), Social Network (C.1), and Infrastructure (A.4). Cluster 3 is made up of neighbourhoods such as Betty's Estate, Dawn Beach, Low Lands and Oyster Pond. This group is characterised by low values for the factors Immediate Action (C.2), Economic Coverage (C.4), Housing (S.2), Education (A.1) and Awareness (C.6). Regarding cluster 4, this group has neighbourhoods such as Philipsburg and Simpsons Bay Village. This group is characterised by high values for the factor Housing (S.3) and low values for the factor Information (C.5). Finally, cluster 5 is made up of the most critical neighbourhoods in terms of socioeconomic vulnerability on the island such as Bishop Hill, Cay Bay, Dutch Quarter, Mount William, Over the Bank, Over the Pond and Sentry Hill. Neighbourhoods in this cluster are characterised by having high values for the factors Infrastructure (S.4), Education (A.1), Immediate Action (C.2), Information (C.5), and Economic Coverage (C.4).

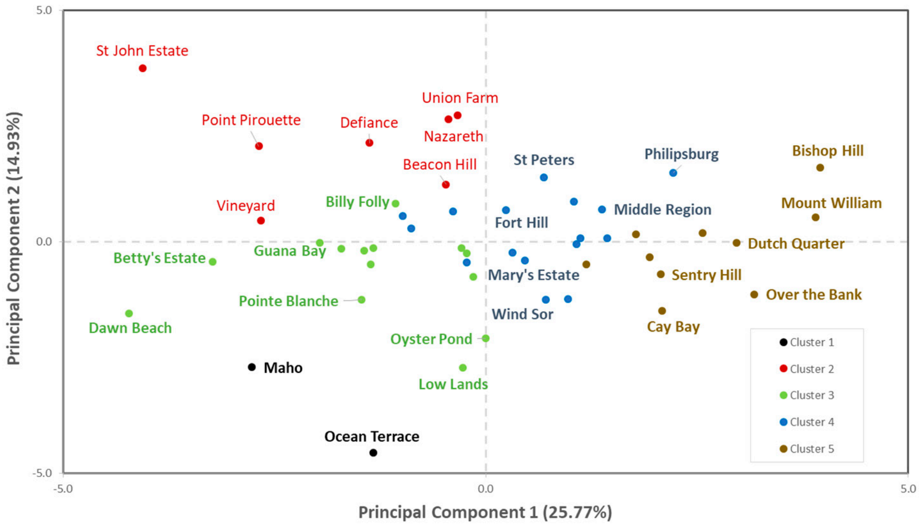

Figure 13. Clustering classification of neighbourhoods based on PC-1 and PC-2. The classification reveals five clusters in Sint Maarten. In parenthesis, the percentage of variance explained by the principal component.

Practical applications of this clustering analysis will be that if the government of Sint Maarten invest in campaigns to increase awareness of natural hazards, the effect of such campaigns will be reflected more significantly in neighbourhoods within cluster 3. In contrast, if efforts to reduce socioeconomic vulnerability in Sint Maarten are put into improving the economic status of the residents of the island (improving factor C.4 Economic coverage), such effort will benefit the most those neighbourhoods that belong to the critical cluster 5.

3.5. Recommendations for Vulnerability Reduction in Sint Maarten and Policy Implementation

The research revealed the specific needs of each neighbourhood which are necessary to lower its vulnerability (see Sections 3.2–3.4). The government of Sint Maarten can use outputs from this research for disaster risk management activities on the island to address specific variables of vulnerability based on individual neighbourhood needs and to further develop existing policies and introduce new ones. The results also point to the most critical neighbourhoods which require additional focus, efforts and resources to lower risk and vulnerability, areas such as Dutch Quarter, Over the Bank, Bishop Hill, Over the Pond and Mount William. Within these areas, special attention needs to be placed on the economic and in the educational factors. In the above mentioned critical neighbourhoods, it is needed to improve the quality of housing, increase their ability to protect their assets, the ability to evacuate to safer zones or dedicated shelters and to increase the insurance coverage.

Our work identified that areas with higher number of undocumented immigrants are among the most critical ones in terms of socio-economic vulnerability. Undocumented immigrants in Sint Maarten have extra levels of vulnerability as they build their houses in the marginal lands of the hillsides using weak construction materials (wood walls and zinc roofs), they also have limited access to water and sanitation and less formal jobs or contracts. To address this issue, the government of the island should not only improve the outdated building codes and increase inspections but also assist in rebuilding both financially and technically across the island. The government should also review the land leasing model to implement more strict control over the quality of constructions in those areas identified as the most vulnerable during the household survey [31].

We also detect that given the multiracial and multicultural environment of immigrants in Sint Maarten (undocumented or not) the fact that warning information is mainly disseminated in English and Dutch it is excluding large sectors of the population with little or no knowledge of these languages, especially the Hispanic and French-speaking communities. Hence, we suggest that an effective measure to reduce vulnerability is through improving the communication of the warning messages, by including more languages and by simplifying the content of the message so it can be easily understood for non-educated inhabitants.

To minimise the impacts of a disaster such as the one caused by Hurricane Irma, the government of Sint Maarten needs to promote policies and strategies to diversify the economy of the island to not only depends on tourism which could potentially decrease the level of vulnerability since the economic coverage was the predominant factor driving socio-economic vulnerability on the island.

In addition, the observed slow recovery pace after Hurricane Irma was directly related to economic issues of the island economy. As reported in [31], the government can address this situation among others with the implementation of a hurricane fund which can be implemented using a percentage of the taxes on the touristic sector in a yearly basis. Such fund will allow Sint Maarten to finance the reconstruction with less dependency on the Dutch government or other external financial organisations or donors and improving resident wellbeing.

Finally, we see the use of PeVI in combination with the PCA analysis as a tool that can be easily used by the government to perform traceability and evolution of vulnerability in Sint Maarten once the authorities undertake policies and strategies to lower some of the drivers of the vulnerability identified in this paper. Alternatively, PeVI can also be used to evaluate what will be the possible impacts of a specific measure before its implementation.

4. Conclusions

We present in this research a methodology to assess and map the socioeconomic vulnerability of SIDS at a neighbourhood scale. We assess vulnerability using a vulnerability index with three major components, susceptibility, lack of coping capacities and lack of adaptation. The resulting index (PeVI) was then applied to the case study of Sint Maarten after the disaster caused by Hurricane Irma in 2017. To compute the index, we use census data in combination with data coming from a survey we performed in the aftermath of Hurricane Irma. Using the survey allowed us to expand the index to be able to capture elements that can particularly change vulnerability after a disaster, such as elements of risk awareness and perception and access to information in combination with information associated to the direct impact of the hurricane and the recovery in the island.

Vulnerability indexes, such as the PeVI and the associated maps, are a robust decision-making and communication tool. The index can be used to identify those areas more vulnerable to natural hazards (such as floods and hurricanes), and guide policymakers on where to focus the limited resources available to mitigate (or eliminate) the impact of a potential hazard. However, the representation of vulnerability and its components in a single number reduces the richness of the information that each variable used to produce such components and index can provide. Using PCA analysis as a complementary method can compensate for this trade-off between information richness (in the variables) and the robustness of communication of an aggregated index.

Vulnerability assessments based on the computation of indexes and vulnerability assessments based on Principal Components can be seen as complementary methods. The way we propose to use the methodology exposed in this paper is to compute first the vulnerability index to identify the most critical areas in terms of absolute vulnerability. Once hotspots have been highlighted, by using PCA, it is possible to determine which are the root causes or the most influential variables that contribute towards vulnerability in a specific area. PCA in this research allows us to increase the understanding of how multiple and often interdependent indicators of vulnerability vary in relation to each other and to understand the common drivers of vulnerability across different neighbourhoods.

Hurricane Irma was very catastrophic for Sint Maarten but offered an excellent opportunity to perform an in-depth analysis of some of the root causes of vulnerability and to incorporate new variables into the computation of vulnerability indexes that are only possible to observe and detect after the disaster has unfolded. To our knowledge, this is the most integrative study of this type and offer a framework to assess vulnerability in other similar areas with similar potential hazards and geographic characteristics.

The indexes and associated maps produced in this paper are the first of this kind for Sint Maarten despite the potential hazards they encounter each year during the hurricane season. Overall, we can state that we have offered a comprehensive and valuable static image of the vulnerability to hurricanes and floods in Sint Maarten. It is important to mention that we face limitations in data acquisition, access to the full extent of the census data was restricted, and we could not gain access to some areas on the island, especially gated condominiums.

Another limitation of the PeVI is the lower number of factors used to measure the lack of adaptation component when compared with the other two vulnerability components. We could not include as many elements as desire due to the complexity of the component and the limitations to data access on the island. Future vulnerability analysis in Sint Maarten should include more elements of adaptation capacities to have a more balanced index. Examples of variables that could be included can be: climate change perception, adoption of green infrastructure and nature-based solutions, income parity ratio, air quality data, enhancements of early warning systems and the implementation of a hurricane (or disaster) fund.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/12/4/1452/s1, C S-1: Vulnerable age groups formula; Equation S-2: Dependency ratio formula; Equation S-3: Unemployment ratio formula; Equation S-4: Road infrastructure formula; Equation S-5: Household size indicator formula; Equation S-6: Multi-storey building formula; Equation S-7: Ratio car ownership formula; Equation S-8: Trust in institutions formula; Equation S-9: Emergency infrastructure formula; Equation S-10: Level of education formula; Equation S-11: Education ratio formula; Equation S-12: Gender parity ratio for values < 1.0 formula; Equation S-13: Gender parity ratio for values ≥ 1.0 formula; Table S1: Building wall and roof materials and their standardised values; Table S2: Decade of construction and their standardised values; Table S3: Type, material and average slope of roads and their standardised values; Table S4: Type of energy supply and their standardised values; Table S5: Buildings damage assessment and their standardised values; Table S6 Number of years living in Sint Maarten and their standardised values; Table S7: Ratio car ownership and their standardised values; Table S8: Degree of trust in institutions based on the question (i) and their standardised values; Table S9: Degree of performance perception based on the question (ii) and their standardised values; Table S10: Degree of trust in institutions based on the question (iii) and their standardised values; Table S11: Adequacy of emergency infrastructure based on the question (iv) and their standardised values; Table S12: House insurance based on the question (v) and their standardised values; Table S13: House ownership based on the question (vi) and their standardised values; Table S14: Access to early warning information based on the question (vii) and their standardised values; Table S15: Influence of not knowing where to evacuate on evacuation behaviour based on the question (viii) and their standardised values; Table S16: Number of days the respondent received warning information based on the question (ix) and their standardised values; Table S17: Risk perception based on the question (x) and their standardised values; Table S18: Risk knowledge based on the question (xi) and their standardised values; Table S19: Frequency of warning information based on the question (xii) and their standardised values; Table S20: Speed of recovery after Hurricane Irma and their standardised values; Table S21: Vulnerability of critical infrastructure and their standardised values.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Susceptibility, Lack of coping capacities, Lack of adaptation capacities and PeVI vulnerability index for each neighbourhood in Sint Maarten. The five most critical neighbourhoods in each category are highlighted in bold and underline.

ID	Neighbourhood	Susceptibility	Lack of Coping Capacities	Lack of Adaptation Capacities	PeVI—Vulnerability Index
1	Low Lands	25.16	32.51	32.25	29.97
2	Point Pirouette	24.83	34.13	2.19	20.38
3	Maho	23.82	21.60	**<u>54.06</u>**	33.16
4	Beacon Hill	29.56	41.68	13.48	28.24
5	The Airport	No Data	No Data	No Data	No Data
6	Simpson Bay Village	**<u>34.46</u>**	39.06	24.41	32.64
7	Cole Bay Lagoon	20.39	40.44	17.00	25.95
8	Billy Folly	27.39	35.65	14.95	26.00
9	Cay Bay	29.69	40.93	43.02	37.88
10	Diamond	30.18	34.71	6.36	23.75
11	Cockpit	31.58	40.42	22.91	31.64
12	Cole Bay Village	27.85	27.51	15.11	23.49
13	Orange Grove	29.31	38.14	25.66	31.04
14	Wind Sor	**<u>34.42</u>**	33.70	32.49	33.54
15	Reward	24.50	36.68	32.65	31.28
16	Ebenezer	22.95	29.43	16.00	22.79
17	St Peters	31.81	38.31	28.67	32.93
18	Betty's Estate	19.89	21.98	18.41	20.09
19	Retreat Estate	22.97	27.64	17.17	22.60
20	St John Estate	24.89	19.75	4.43	16.36
21	Saunders	25.93	36.92	22.25	28.37
22	Mary's Estate	31.74	37.35	24.45	31.18
23	Sentry Hill	30.82	42.13	41.15	38.03
24	Cay Hill	30.59	42.00	32.23	34.94
25	Belair	32.64	36.00	15.66	28.10
26	Fort Hill	32.88	38.24	26.94	32.69
27	Bethlehem	24.81	23.21	24.16	24.06
28	Nazareth	30.65	36.63	8.44	25.24
29	Union Farm	25.27	39.43	25.10	29.93
30	Zorg En Rust	29.83	43.21	24.33	32.46
31	Mount William	29.45	**<u>55.17</u>**	31.60	**<u>38.74</u>**
32	Madame's Estate	32.56	38.02	27.76	32.78
33	Over the Pond	**<u>34.36</u>**	**<u>44.94</u>**	37.73	**<u>39.01</u>**
34	Belvedere	26.23	29.68	29.08	28.33
35	Bishop Hill	26.97	**<u>63.55</u>**	27.54	**<u>39.35</u>**
36	Dutch Quarter	**<u>41.27</u>**	36.22	**<u>57.34</u>**	**<u>44.94</u>**
37	Middle Region	**<u>34.01</u>**	41.06	31.54	35.54
38	Easter Fresh Pond	20.00	30.45	36.29	28.91
39	Philipsburg	30.09	**<u>46.68</u>**	27.36	34.71
40	Pond Island	21.25	33.33	28.81	27.80
41	Salt Pans	No Data	No Data	No Data	No Data
42	The Harbour	No Data	No Data	No Data	No Data
43	Oyster Pond	26.20	34.90	24.18	28.43
44	Defiance	26.71	29.22	26.02	27.32
45	Ocean Terrace	17.19	35.03	**<u>50.00</u>**	34.08
46	Dawn Beach	22.13	15.17	22.85	20.05
47	Sucker Garden	33.52	38.53	41.38	37.81
48	Guana Bay	23.87	27.75	37.92	29.85
49	Hope State	30.46	25.50	30.54	28.84
50	Geneva Bay	No Data	No Data	No Data	No Data
51	Back Bay	No Data	No Data	No Data	No Data
52	Over the Bank	27.74	**<u>44.09</u>**	**<u>51.32</u>**	**<u>41.05</u>**
53	Vineyard	25.81	19.23	**<u>52.56</u>**	32.54
54	Pointe Blanche	27.36	24.38	26.39	26.04

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