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Social Vulnerability Assessment for Flood Risk Analysis

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Abstract: This paper proposes a methodology for the analysis of social vulnerability to floods based on the integration and weighting of a range of exposure and resistance (coping capacity) indicators. It focuses on the selection and characteristics of each proposed indicator and the integration procedure based on the analytic hierarchy process (AHP) on a large scale. The majority of data used for the calculation of the indicators comes from open public data sources, which allows the replicability of the method in any area where the same data are available. To demonstrate the feasibility of the method, a study case is presented. The flood social vulnerability assessment focuses on the municipality of Ponferrada (Spain), a medium-sized town that has high exposure to floods due to potential breakage of the dam located upstream. A detailed mapping of the social vulnerability index is generated at the urban parcel scale, which shows an affected population of 34,941 inhabitants. The capability of working with such detailed units of analysis for an entire medium-sized town provides a valuable tool to support flood risk planning and management.

Keywords: vulnerability indicators; vulnerability cartography; flood risk; AHP; local analysis; open public data sources

1. Introduction

Floods are defined as the "temporary flooding of land that is not normally covered by water" [1]. Most river flooding is associated with the amount and distribution of precipitation in a drainage basin [2], but other reasons for flooding may include rapid snow melting in mountain ranges [3] or dam failure [4–7]. Other floods are related to coastal processes such as storm surges [8] and tsunamis [9,10]. Both river and coastal floods are mostly natural phenomena that occur with a frequency associated with a magnitude in a defined area. In general, these events are characterized by a high amount of damage, which is the result of the destructive power of water [11–13]. In addition to damage caused by the direct water impact, water's energy works as an erosive agent [14] that may undermine materials under the foundations of buildings, causing them to collapse [15]. Once the flood is over, damage may continue to increase due to electricity and water cutoffs or the spread of diseases such as cholera, leptospirosis, and typhoid fever [16–18], increasing economic and personal losses in the affected area [19]. Despite the natural origin of these floods, the main reason for damage can be identified in the human occupation of areas traditionally susceptible to flooding [20,21]. In many cases, the population is settled in flood-prone areas because no other places are available for building in the municipality. At the same time, new engineering infrastructures appear and provide a false sense of security as they do not completely prevent the land from flooding [22]. Therefore, the increased size of populations and the economic development of societies in flooding areas are the main factors in recent land-use changes and have increased society's vulnerability [23,24].

In the field of disaster risk reduction (DRR), efforts have traditionally been focused on infrastructure and technology-related measures [25]. Currently, however, there is consensus that these efforts must be accompanied by other measures related to the improvement of the resilience of people and territories in all disaster cycle phases (preparedness, response, recovery, mitigation) [26,27]. Many tasks can be applied to prevent and mitigate the effects of flooding, such as updating urban planning based on risk prevention [28], developing early warning systems [29,30] and specifically promoting people's coping capacity. Society must adapt to flooding, especially as the phenomenon becomes more common as a direct consequence of the climate change process [31,32]. This phenomenon affects the hydrological cycle, producing the following effects [33]: (i) an increase in temperature, which is reflected in an increase in evaporation and evapotranspiration and acceleration in the destruction of glaciers, (ii) drastic changes in water and snow precipitation patterns, and (iii) the ascent of sea level. Society must therefore change its way of acting, know the territory it occupies and delimit the areas most vulnerable to these phenomena. The results of these analyses will facilitate limiting the types of land use in these areas, which will minimize damage and facilitate the quick recovery of society [27].

The analysis of the components of risk is a recurring theme in the scientific literature. Various conceptual frameworks of risk have been proposed that define its main components and relationships (hazard, vulnerability, exposure, coping capacity, adaptive capacity, etc.) [25,34,35]. In all of these frameworks, there is common agreement about the two main components of flood risk: hazard (as the probability of occurrence of flood) and vulnerability (representing conditions and capacities that make a system or an individual susceptible to harm). It is relevant to highlight that the exposure is sometimes considered an independent component [36], but in this paper, exposure is included in the concept of vulnerability [15].

A review of the concept of vulnerability to floods also shows diverse conceptual frameworks that emphasize its multidimensional character [37–40], comprising physical, social, economic and environmental dimensions [41–51]. Consideration of the social dimension is one of the most common approaches in vulnerability studies. Social vulnerability includes all factors specifically related to the interactions of flood hazards with individuals, populations and communities, including the exposure of people, sociodemographic and socioeconomic profiles, employment, education, household composition, demographic structure, and the capacity of society to cope with hazards and their effects. All of these factors affect the resilience of communities to cope with flood effects, but their respective importance is not clear [25].

We perform a simplification exercise in this work and summarize the factors that affect social vulnerability into two major components: (i) the physical exposure of the individual/population/community to flooding; and (ii) resistance, which includes a set of minor components such as protection, reaction capacity and coping capacity [38].

Notably, most social vulnerability studies adopt a theoretical focus [52], although there has been an effort to perform empirical assessments in recent years [21,52–59]. These studies may present the drawbacks of using different measurement procedures, which makes it difficult to compare their results. However, the more common use of vulnerability indices as methodology better facilitates the comparison of results among different study areas [60]. Additionally, the different scale of studies is significant [56]. To date, research papers that estimate the social vulnerability of a municipality have applied a broad range of scales, with different cartographic units such as municipalities [61], municipal districts [40,62], and census blocks [57,58] or neighbourhoods [63]. Recently, new studies working with cadastral parcel data [59] have improved spatial accuracy. New public open-access databases and spatial data infrastructures provide data with high territorial precision, which opens new possibilities for more accurate analysis.

Based on the previously mentioned gaps in knowledge, the main objective of this paper is to propose a new method to assess social vulnerability to flooding by reviewing the importance of factors to map social vulnerability at a very detailed geographic scale, the cadastral parcel. This method may be applied to other areas where data are available. The proposed method is tested in the urban area of a middle-sized town, Ponferrada (Spain).

The use of indices has proved a robust method to assess social vulnerability [52,55,64–67]. Therefore, the results of the proposed method are expressed as a multicriteria index (Social Flood Vulnerability Index: FVIsocial) to show the relation between the components of social exposure (population exposure) and the resistance of people exposed to floods (protection, reaction capacity and coping capacity) for each defined geographical unit (cadastral parcel). These components are expressed as normalized quantitative indicators that are weighted based on the analytic hierarchy process (AHP). The assignment of these weights is based on work by a panel of risk experts who have conducted a pairwise comparison among indicators. The indicators are grouped into factors based on semantic meaning to simplify and improve the intelligibility of the model. The AHP process is one of the most commonly used methods when working with the integration of indicators in vulnerability studies [64,68–71].

The structure of the article is as follows. First, a description of the study area, the city of Ponferrada (Castilla y León, Spain), is presented. Ponferrada is a small town exposed to a hypothetical flood from a dam breakage. The methodology used to quantify social vulnerability is subsequently presented in a section divided into three phases: the description of the indicators used to quantify the vulnerability, the normalization to 0-1 values and the weighting of the indicators. The results map shows the application of the proposed method to the study area at the urban parcel scale. The article continues with a discussion of the advantages and limitations of the proposed methodology and ends with the main conclusions.

2. Study Site

The proposed method is applied in the urban area of the Ponferrada nucleus, a city that belongs to the municipality of the same name, which is located in the province of León (northwest of the Iberian Peninsula) (Figure 1). The municipality of Ponferrada has a total of 67,367 inhabitants distributed in 37 population nuclei. Its capital, Ponferrada, which is located on the banks of the River Sil and its affluent, the Boeza River, is the seventh-largest city of the Castilla y León region by population, with 41,858 inhabitants. It is the centre of the most important services of Bierzo County, including the district hospital, university, and regional authority. According to the population census [72], the municipality is distributed into 6 districts or demarcations. Each district is subdivided into different census sections. In total, the city is subdivided into 45 census sections, each of which averages approximately 1500 persons within the range of 625–2780 inhabitants.

The study area has been affected several times by floods. In the collected historical records [73], a total of 26 floods have been recorded in the area of Ponferrada, including not only the Sil River that runs through the city but also other streams in the area, such as Valdueza and Boeza. The flood hazard was reduced in 1960 with the construction of the Bárcena and Fuente del Azufre dams in the River Sil, located upstream of the town (Figure 1). Nevertheless, Ponferrada's river section is considered a potential flood section due to the possible downstream effect of the reservoir in a normal exploitation situation [73]. This scenario usually occurs when a large storm is expected and dam gates must be opened to be able to store the incoming water, which may lead to flood areas downstream. As a result, the floods in this area have three main triggers: (i) heavy rainfall, (ii) the exploitation of the dam, and (iii) the breakage of the dam. This research focuses on the last trigger, proposing a method to estimate social vulnerability and applying it to Ponferrada in the estimated flooded area that would be generated in the worst-case scenario in which both the Bárcena and Fuente del Azufre dams break [74] (Figure 2).

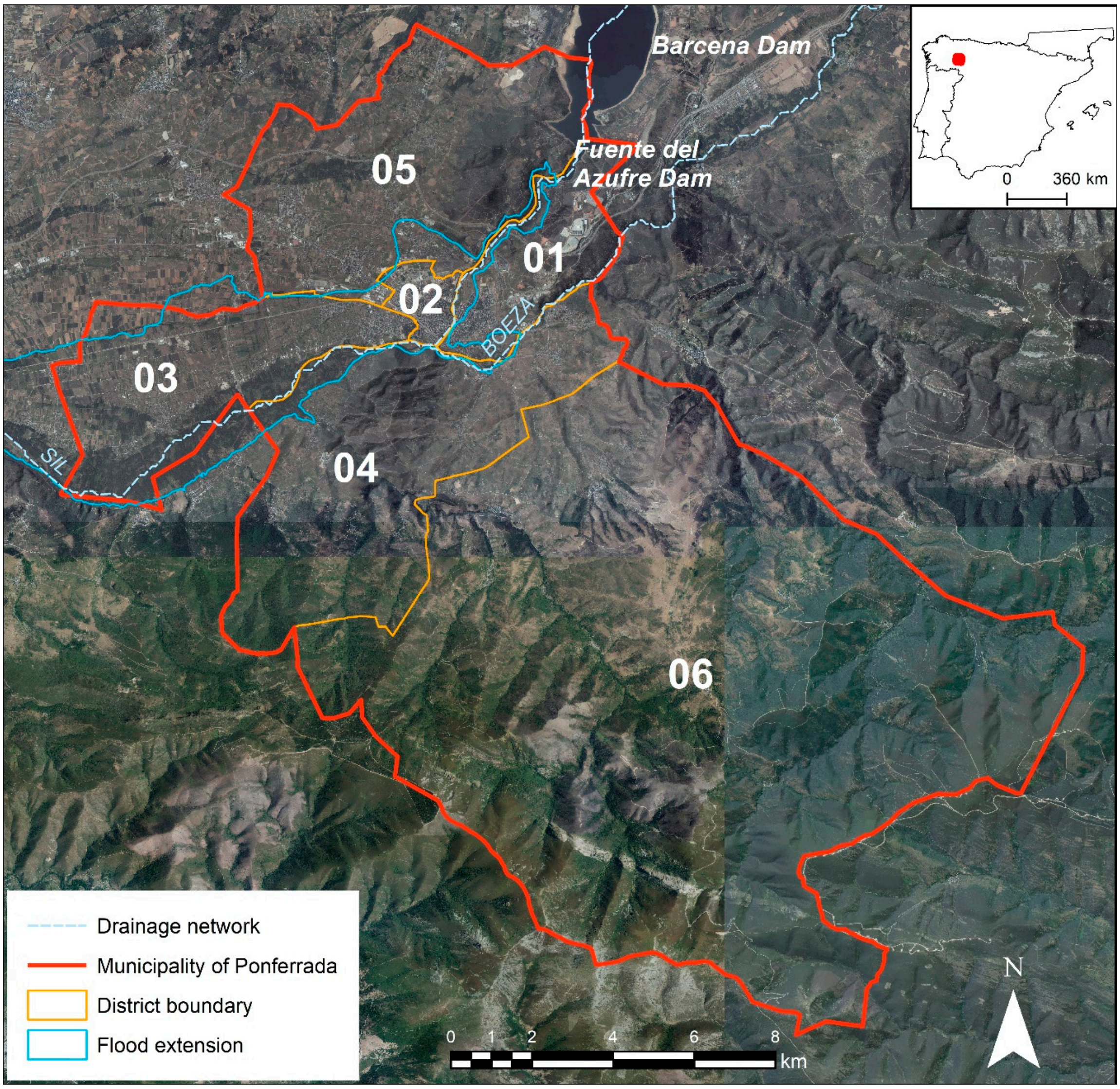

Figure 1. Location of the study area.

Of the 45 census sections, the study focuses on only 37. The eight rejected census sections coincide with sections outside of the perimeter of the flood area or those inside the perimeter but in which no urban parcels are affected. This perimeter is estimated based on break-dam modelling of the dam [73]. From these 37 sections, the assignation of data is extrapolated from neighbouring sections in the other eight census sections. The main reason for this assignment was the coincidence of two situations: on the one hand, the affected extension of the section was small; on the other hand, the affected urban parcels were closer and had social characteristics more similar to those from the neighbouring section than to those from their own section.

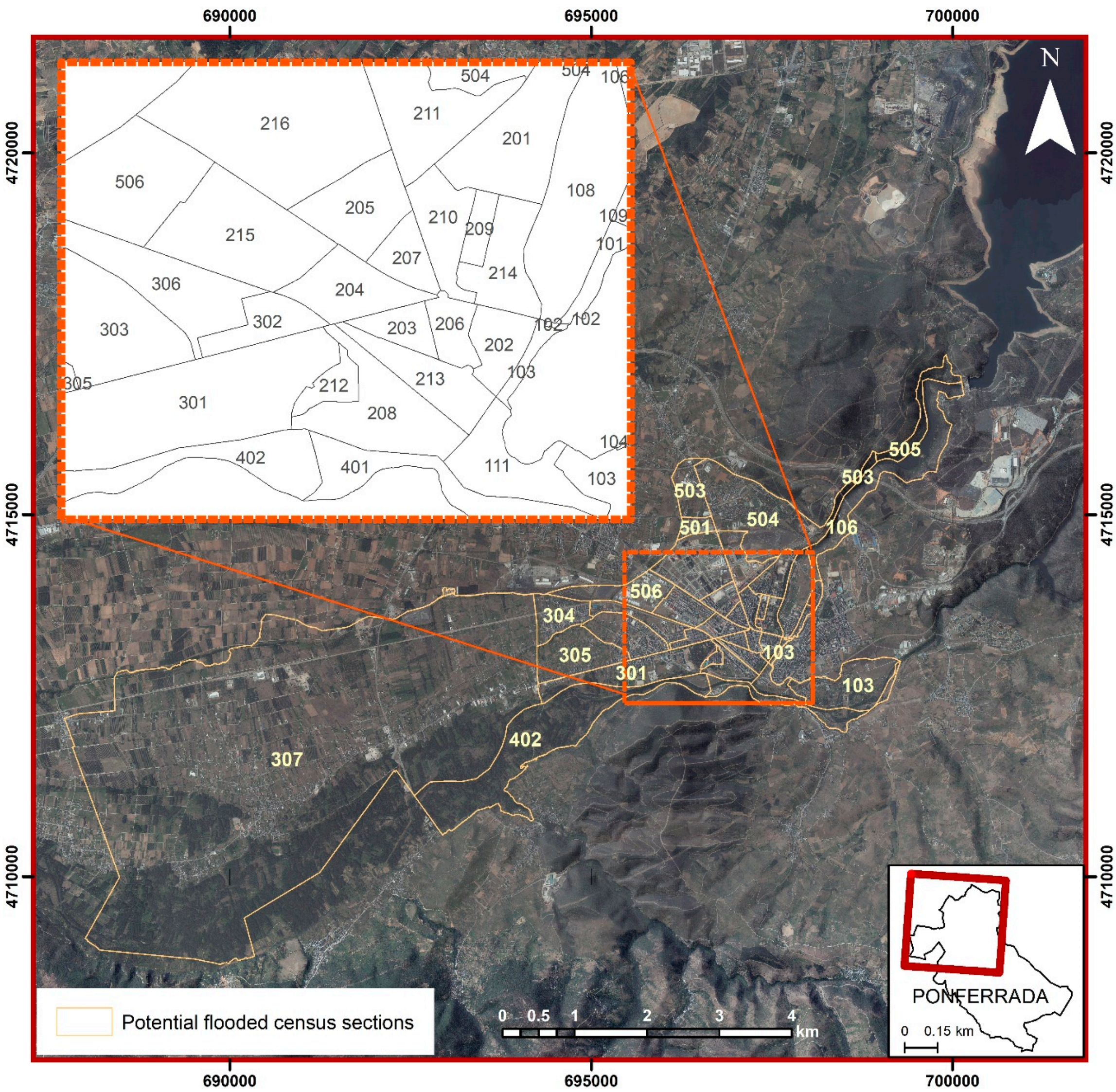

Figure 2. Census sections potentially affected by the water sheet.

3. Methodology and Data Sources

Vulnerability indices (VI) are numerical expressions that provide a statistical measure of the changes in value that vulnerability may experience. These indices are based on indicators. An indicator is a variable that reflects the state of a situation or any of its characteristics in a place at a particular time. It is expressed quantitatively as statistical information that synthesizes the data provided by the variables intended to be analysed. In the present research, all the indicators are grouped semantically into factors selected as the most representative of all the components that conform to the vulnerability. The relationships among the different elements that conform to the proposed vulnerability index are summarized in Figure 3.

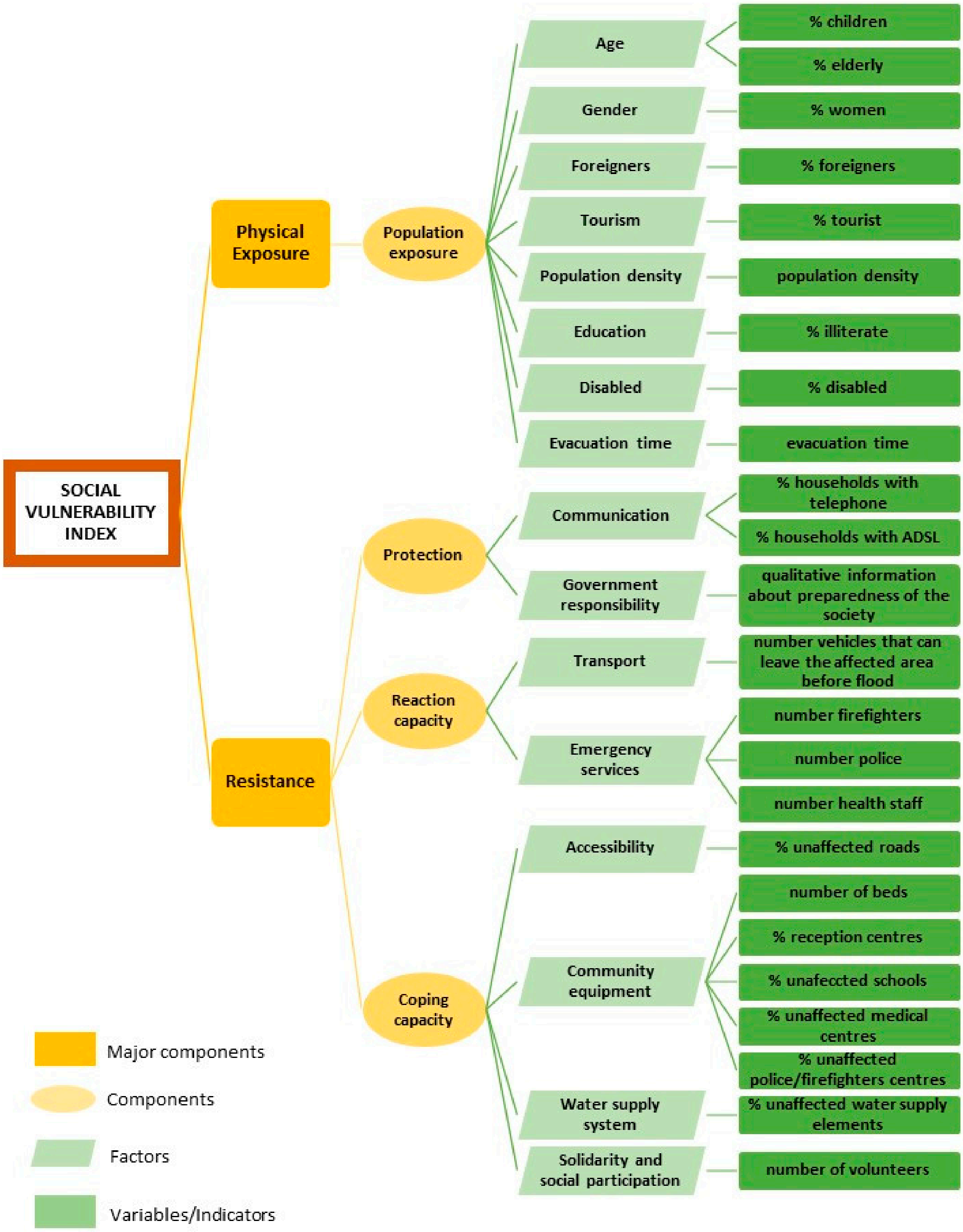

Figure 3. Relationships among the elements of the proposed vulnerability index.

Vulnerability indices are represented by equations that relate the records (weighted or not) of all the indicators (e.g., percentage of the elderly, percentage of women) with the components (e.g., exposure degree, resilience) of vulnerability. From these records, fractions are used to obtain the value of the vulnerability index, placing the indicators that increase vulnerability in the numerator and those that reduce vulnerability in the denominator [75]. In this way, the acquired results are dimensionless and allow comparison of vulnerability indices for similar indicators and for different scales in studies of different years or places.

Following these guidelines, the proposed social flood vulnerability index (FVIsocial) is measured on a scale of 0–1 and is determined by two major components: (i) the exposure degree of social indicators; and (ii) the resistance [76], as defined by Equation (1):

$$\text{FVIsocial} = (\text{E}/\text{R})/10 \quad (1)$$

where E is the degree of social exposure (Equation (2)) and R refers to social resistance (Equation (3)).

$$E = \sum_{i=0}^{m} (\text{v}_i * \text{w}_\text{i}) \quad (2)$$

$$R = \sum_{i=0}^{\text{m}} (\text{v}_\text{i} * \text{w}_\text{i}) \quad (3)$$

where v_i is the value of each indicator (included on a scale of 0–1); w_i is the weight of each indicator (included on a scale of 0–1); and m is the number of indicators.

From Equation (1), it can be deduced that the exposure-resistance ratio will oscillate between the minimum value of 0 when the exposure degree is 0, independent of the value of the resistance, and the maximum value of 10 when the exposure degree is the maximum (1) and the resistance is the minimum (0, 1). This fraction is divided by 10 in Equation (1) to achieve a social vulnerability index with a range of 0–1. The problem of working with Equation (1) would be if resistance was 0; however, since the number of people connected via social media continues to increase [77], it is expected that every place will not reach this minimum value of 0.

Following the definition of the social vulnerability concept, the methodology developed in this research is divided into the following steps:

- Description and calculation of indicators. One added value of the proposed methodology is that the majority of these data are open access from governmental websites, although some were collected through personal enquiries.
- Indicator normalization. This process allows us to obtain dimensionless results to compare social vulnerability indices for different scales in various studies.
- Indicator weight calculation. The calculation of the weights is based on an expert panel survey following the analytical hierarchical process (AHP) methodology [78]. This method allows the evaluation of the importance of each of the indicators.

All of these phases are described in the following sections together with the data sources.

3.1. Data Sources

Most of the data required to estimate FVIsocial indicators were obtained from the open data repository of the Spanish National Statistical Database [72]. First, this database includes general social data, such as the number of inhabitants, ages, and foreign visitors, which were recorded in the last ten-yearly Spanish census in 2011. Second, this database includes spatial data at different geographic aggregation levels (municipal, districts and census sections), all of which are required in the present research. It is relevant to note that the Dirección General del Catastro in Spain has an open platform that enables the downloading of all the geographic and alphanumeric information of urban parcels [79]. To relate both attributes and geographical data, we propose the use of each indicator in its available spatial resolution and, subsequently, their disaggregation at the highest spatial resolution using geographical information system (GIS) tools. Therefore, in the last step, all the indicators should be linked to the cadastral parcel layer.

Another determining layer was the potential flood area, the perimeter of the water flood, which helped to delimit the real affected census sections and thus the study area. This map is the result of cascading dam failure modelling with a peak discharge of 2093 m^3/s according to the Boss Dambrk model [73]. It simulates one-dimensional hydrodynamic flood routing and predicts dam-break flood wave formation. Therefore, the flood area map is accompanied by a wave travel time study.

The rest of the data layers needed to estimate the indicators are as follows:

- Building doors: This is a point map containing the entrances to all the buildings, which is used to calculate the evacuation time and the population density. In general, there is only one point per urban parcel, but large buildings may show more entrances.
- Street map: This shows the communication lines inside the urban area and is an indispensable map to identify evacuation time issues; it indicates the evacuation paths.
- Road map: The access of goods during and after the emergency period is necessary to facilitate the recovery of society. This road map helps to estimate the number of access points affected by floods.
- Digital elevation model: The purpose of this map is to generate the slopes of the terrain, which are used as impedance to calculate the difficulties of evacuating people (the steeper the path, the slower the evacuation will be).

An added value of the proposed methodology is that all the information used is freely available through the Spanish government website platforms, so there is no cost to obtain updated data. The only exception is the potential flood area map of the study zone. However, many flood maps are also freely distributed.

The last data source exploited in this study comprises the different enquiries posed to (i) the population to evaluate the information on emergency response and/or (ii) public administration, consisting of the police chief, firefighter chief, dam manager chief, council tourist expert, council engineer and different NGO heads. In the first case, the idea was to randomly survey the population to evaluate how much information they have about specific protective measures in case of an emergency. In the second case, enquiries were used to obtain the following indicators:

- the level of government responsibility, whether there is an emergency plan, events to inform the population about what to do in the case of an emergency, etc.,
- percent of tourism population to obtain the internal council's data about the size of the tourism population in the town,
- the number of volunteers, to understand the size of the volunteer group that may help in the recovery period in the studied society,
- the number of emergency personnel (police, firefighters, medical workers), to identify the specialized personnel available to confront an emergency,
- the location of water supply elements to evaluate the percentage of water supply elements that will be affected by the flood and that may make the recovery process difficult.

After performing these enquiries and determining that there had been no event to inform the population, we did not implement any surveys among the population. However, if any such event is performed, it is necessary to survey the population to evaluate their level of knowledge about the procedures to follow in case of a dam failure.

3.2. Indicator Selection and Calculation

To determine the social flood vulnerability index, two tasks were carried out. First, the definitions of vulnerability factors were determined to compare different authors' approaches e.g. References [41,44,45,75,80–87]. Second, the selection of significant indicators for each factor was performed. If there was scientific consensus in the bibliographic review, the determination of the social vulnerability factor was accomplished by means of a single indicator; when there were difficulties in assigning a unique indicator to define a factor, the method works with several indicators. The state-of-the-art processes indicate that there are uniform criteria when using the following indicators: percentage of elderly, percentage of children, percentage of women, percentage of individuals with disabilities, percentage of foreigners, number of inhabitants per km^2 and percentage of illiterate population [40,80,83,86]. This is because the intersection of the circumstances of age (elderly and children), gender (women), minority status, disability status and education (without basic education) have the greatest influence on the social burdens of natural hazards since they constitute more vulnerable groups of a population that more frequently suffer major social impacts when they are exposed to a certain risk. In the case of social resistance indicators, there is also coincidence in the number of health staff per 1000 inhabitants [80,84,85,87], the number of beds per 1000 inhabitants [82,87] and the percentage of reception centres (e.g., surface area in m^2 of sports and cultural equipment) [83,87]. Based on this information, the authors propose the number of other civil protection staff per 1000 inhabitants, considering that in some countries, there is no equivalence between health and security services. The other social vulnerability indicators selected in the present study do not show international consensus, and their use varies depending on the study area and the data availability. For instance, the number of vehicles that can leave the affected area according to the type and number of accesses (roads) is supported by one study [84], while [59] suggests that the use of vehicles is dangerous and increases damage because vehicles may be swept away with shallow waters. Although this is a true scenario, driving cars may be beneficial if there is a warning period that is long enough to allow evacuation in an orderly manner. The present study selected at least one indicator for each of the most frequently mentioned vulnerability factors in the bibliographic review, considering the ease of retrieving data and their representativeness. For example, to determine the solidarity of society, the percentage of electoral votes [83,84] cannot be applied in nondemocratic countries or in countries where the population does not trust politicians. Instead, the number of volunteers may better adjust to the solidarity factor, although it may be more difficult to collect this type of data.

As a result, there are two types of indicators according to the value that they provide: quantitative and qualitative indicators. Tables 1 and 2 show the proposed vulnerability factors for exposure and resistance and the corresponding indicator deployments. As will be explained, all the indicators were merged to define the degree of exposure and the resistance of each geographical unit based on different weight values.

Table 1. Description of the proposed factors and indicators used to analyse the degree of exposure of social vulnerability for flood events.

Factors	Exposure Indicators	Normalized Values	Spatial Scale
	QUANTITATIVE INDICATORS		
Age population	% children = *(population under 16 years/total population)* × *100* % elderly = *(population over 65 years/total population)* × *100*	0%—0 100%—1	Census section
Gender population	% women = *(population of women/total population)* × *100*		Census section
Foreign population	% foreigners = *(foreign population/total population)* × *100*		Municipal level
Tourist population	% tourist = *(tourist population (national and foreign)/total population)* × *100*		Municipal level
Population density	Population density =*Total population/surface*	Min = 0 Max = 500	Parcel level
Evacuation time	Evacuation time	Min = 0 Max = arrival time of the water sheet	Parcel level
Education	% illiterate population = *(population without studies/total population)* × *100*	0%—0 100%—1	Census section
Disabled population	% disabled = *(population with disabilities/total population)* × *100*	0%—0 100%—1	District level

Table 2. Description of the proposed social vulnerability factors and indicators of resistance to flood events.

Factors	Resistance Indicators	Normalized Values	Spatial Scale
	Quantitative Indicators		
Communications	% of households with a telephone = *(households with telephone lines/total number of cores)* × 100 % of households with ADSL = *(households with Internet access/total number of households)* × *100*	0%—0 100%—1	Census section
Emergency services	Number of firefighters per 1000 inhabitants = *(firefighter number/total population)* × *1000*	Min = 0 Max = 1	County level
	Number of local police per 1000 inhabitants = *(local police number/total population)* × *1000*	Min = 0 Max = 1.5	Municipal level
	Number of national police per 1000 inhabitants = *(n° of national police/total population)* × *1000*	Min = 0 Max = 2	County level
	Number of health staff per 1000 inhabitants = *(n° of doctors and nurses/total population)* × *1000*	Min = 0 Max = 2.3	Municipal level
Transport	Number of vehicles that can leave the affected area according to the type and number of accesses (roads)	Min = 0 Ma x= 3015	Water sheet level
Accessibility	% of accesses not affected by the water sheet= *(n° of unaffected accesses/total)* × *100*	0%—0 100%—1	Water sheet level
Community equipment	Number of beds per 1000 inhabitants = *(n° of beds/total population)* × *1000*	Min = 0 Max = 3.1	County level
	% of reception centres (surface area in m^2) (sports, cultural equipment, etc.)	0%—0 100%—1	Municipal level
	% of unaffected schools = *(n° of schools not affected/total)* × *100* % of unaffected medical centres = *(n° of unaffected medical centres/total)* × *100* % of unaffected police centres and firefighters = *(n° of unaffected centres/total)* × *100*	0%—0 100%—1	Municipal level
Water supply system	% of unaffected water supply elements = *(n° of water supply elements not affected/total)* × *100*	0%—0 100%—1	Municipal level
Solidarity and social participation	Number of volunteers	Min = 0 Max = 1.5	Municipal level
	QUALITATIVE INDICATORS		
Government responsibility	Historical record of disasters (Yes/No) Alert system (Yes/No) Emergency plan (Yes/No) Emergency drill (Yes/No) Evacuation routes (Yes/No) Courses or brochures (Yes/No)	Yes—1 No—0	Municipal level

The spatial distributions of all these indicators were mostly determined by a GIS reclassification of an administrative boundary map. Only the population density and evacuation time required more detailed spatial analyses.

3.2.1. Population Density

The areas of higher population density represent areas of higher exposure to a hazard and areas where evacuation may be more difficult, so they are very vulnerable. Although this is a relevant indicator, the personal protection data law remains the main impediment when estimating its value. For this reason, population data are only available at the census section level in open sources. To spatially disaggregate these data, it is necessary to estimate the number of dwellings in each urban parcel. This calculation is possible through the attribute database linked to the cadastral parcel layer, where it is possible to estimate the amount of properties targeted to residential use based on a unique reference cadastral identifier. The population registered in a census section is distributed homogeneously among all dwellings belonging to the same census section.

The final step to calculate the population density is to distribute the total population of each building among the number of building doors. As can be inferred, this process is impossible to perform without GIS capabilities.

3.2.2. Evacuation Time

The evacuation time is an indicator that measures the relationship between citizens' velocity of displacement and the time of arrival of the flood water. Until now, this indicator has only been used for emergency management, and very few studies have included it to define vulnerability [88]. Its importance is that it establishes a very clear threshold between those areas where there is a possibility of social recovery and those in which such recovery is impossible. The latter correspond to areas in which the evacuation time is greater than the time of arrival of the water wave.

To estimate evacuation time, calculations may be performed assuming that people evacuate on foot or by vehicle. In the case of Ponferrada, there are very few escape routes, which produces a funnel effect. For this reason, this paper focuses only on the evacuation time of pedestrians. Some studies have identified walking and driving in flood waters as the main danger for people during floods [89]. Consequently, Ref. [59] suggests moving upstairs in high buildings. This option was not considered in the present study, because without an emergency plan or information advice, people's main reaction will be to run away from the river.

The calculation of the evacuation time indicator starts with the generation of a slope map. According to this resulting topography, the time that a person requires to walk a distance is estimated. As an example, on flat terrain, it was considered that the average speed was 3.8 km/h [54]. This is a value slightly more conservative than previous estimates [90,91], but it is considered to better fit with an old population such as Ponferrada. Next, the resultant slope map is reclassified based on the inverse velocity (minutes/metres). This new map together with the street and the flood water sheet maps are the inputs to generate a cost-distance map that allows the estimation of the evacuation time for each urban parcel. Other methods that can be used to estimate the evacuation time are linked to flood evacuation simulators [92].

3.3. Indicator Normalization

In this work, normalization is used to compare and combine indicators of different natures. For this purpose, the final normalized value must be between 0 and 1. Two different methods of normalization follow. The first is applied to indicators whose values are percentages. In this case, the normalization process is immediate and involves dividing the value by 100. The second method is based on linear transformation functions [93] (Equation (4)), although this method does not limit the use of other types of functions if new indicators are incorporated in the future.

$$y = ((x - \mathrm{Min}))/((\mathrm{Max} - \mathrm{Min})) \quad (4)$$

where x is the real value of the indicator, Min is the minimum established for the indicator, and Max is the maximum established for the indicator.

All transformation functions used the value 0 as a minimum value. To define the maximum value of the transformation function, we searched for generic values endorsed mostly by institutions of recognized prestige and international scope. Therefore, this value is different for each indicator, as described below and shown in Tables 2 and 3:

- Population density: The maximum value corresponds to the maximum number of people who can occupy a residential building based on the number of evacuation exits. For the example of the Ponferrada municipality, the Spanish government sets 500 as the maximum value for buildings with a single outlet, corresponding in this case with the portal of the building [94].
- Evacuation time: The minimum and maximum values are functions of the time required to reach the perimeter of the water sheet and the time that the population has available from the start of the alert until the water reaches the city. These values may vary if an emergency plan is implemented in the municipality that includes an estimated time of alert. In this indicator, the normalization values are not continuous but take a value of 0 when the evacuation times are less than the arrival times of the water sheet or a value of 1 when the time required is greater than the available time before reaching a maximum degree of exposure.
- Number of firefighters per inhabitant: The maximum value is 1 firefighter per 1000 inhabitants, which is a value defined from the recommendations of different institutions [95].
- Number of local police per 1000 inhabitants: The maximum value is established according to the local regulations of each study area. For instance, in the study case of Ponferrada, the value corresponds to 1.5 local police per 1000 inhabitants.
- Number of national police per 1000 inhabitants: In this case, the maximum value is 2, and it is determined according to the national recommendations of the study area.
- Number of health staff per 1000 inhabitants: The maximum value for the application of the transformation function is 2.3. This value is set [96] as the minimum recommended number of health personnel necessary to cover the needs of primary health care.
- Number of vehicles that can leave the affected area according to the type and number of accesses: The maximum value of this transformation function is calculated by the multiplication of the peak hour intensity value (i.e., the maximum number of vehicles per hour in a road section) by the number of available accesses that allow adequate evacuation. If the number of vehicles in the study area is higher than the previous product, the resistance will be minimal (0). In our case study, the estimation of the peak hour intensity value is derived from the average daily index. According to regional regulations, the peak hour intensity value is 12% of the achieved average daily index [97].
- Number of beds per 1000 inhabitants: The maximum value of the transformation function of this indicator corresponds to the average number of beds in each country since there is currently no optimum level of beds recommended for adequate care of the population. The reason for this lack is that these values vary according to the structure of the health system of each country [98]. For example, in Spain in 2011 and therefore in Ponferrada, the average was established as 3.1 beds per 1000 inhabitants according to data from Spanish regulations [99].
- Number of volunteers: Currently, no recommended ratio of volunteers has been established by any international organization, possibly due to the variety of the social mass that constitutes the different volunteer organizations and the lack of training standards in the field of volunteering that unifies this sector. Given this situation, this study proposes that the maximum value is 1.5, which is the same value established for the local police, who would be responsible for the organization and the direction of volunteers in the case of a disaster.
- Qualitative indicators that measure the known information according to the population affected by the natural phenomenon plus the security and warning measures: These indicators involve a questionnaire mostly aimed at analysing the perception and resistance of a society with closed answers ("yes or no") (Table 2).

Table 3. Weights of indicators that indicate the exposure degree of social vulnerability.

Indicators	Weight (w_i)
Population density	0.264
Evacuation time	0.264
% disabled	0.121
% children	0.105
% elderly	0.104
% foreign tourism	0.042
% foreigners	0.032
% national tourism	0.024
% illiterate population	0.025
% women	0.018

In the case of qualitative indicators, the proposed normalization method considers that the questions to which the answer is *yes* are equivalent to a resistance of 1, while the questions with a response of *no* equal a resistance of 0. The results from each of the questions were added and divided by the total number of answered questions.

3.4. Estimation of Indicator Weight Values (w_i)

Our hypothesis is that not all indicators will have the same importance in relation to social vulnerability, so we must assign different weights to the indicators and deploy a hierarchy. In this study, the assignment of weights to the indicators was performed by applying a qualitative method comparing pairs, known as the AHP [68–71]. This method is based on the responses of an expert panel, which, in our case, involved 15 experts including geologists, engineers, geographers, and civil workers. The panel participants answered a survey for the assessment of the weight of each indicator. Each expert independently compared all the resistance indicators and eight of the ten indicators of exposure. To assure the consistency of their answers, the consistency ratio, CR [78], was estimated. The 15 surveys showed a CR lower than 0.1, which indicates a high level of consistency. According to the results of these 15 surveys, different weights were assigned to each indicator (Tables 3 and 4). It is important to highlight that the surveys were sent together with a list of the indicators, which the experts were asked to order by importance. This information allowed for the elimination of inconsistencies.

Table 4. Weights of indicators that indicate the resistance of social vulnerability.

Indicators	Weight (w_i)
Qualitative indicators: Historical record of disasters, alert system, emergency plan, emergency drill, evacuation routes and courses or brochures	0.186
Number of firefighters, local and national police per 1000 inhabitants	0.133
% of unaffected police centres and firefighters	0.098
Number of volunteers	0.084
Number of health staff per 1000 inhabitants	0.078
% of accesses not affected by the water sheet	0.077
% of unaffected water supply elements	0.068
% of unaffected medical centres	0.058
% of reception centres (surface area (m^2) of sports centres, cultural centres, etc.)	0.049
% of schools not affected	0.048
Number of beds per 1000 inhabitants	0.044
% of households with telephone	0.035
% of households with ADSL	0.024
Number of vehicles that can leave the affected area according to the type and number of accesses (roads)	0.019

The two exposure indicators not analysed by the panel were the population density and evacuation time. For both of these indicators, the maximum weight value was assigned. There are two main reasons for this high score. First, if there is no population (density) in the affected area, the condition of social vulnerability will be minimal. In this case, it is considered that the value does not have to be equal to 0 since in certain unbuilt parcels (e.g., parks), a population may exist. Second, if the evacuation time exceeds the time of arrival of the water sheet (plus the alert time, if this information is available), the population, regardless of age, sex, nationality, education or physical capacity, will not have sufficient time to reach a safe area, so the rest of the indicators will be of secondary importance.

4. Results

The application of the proposed methodology for the assessment of the social vulnerability to floods in the study zone of Ponferrada (Spain) shows that the social vulnerability for 3330 parcels of the 6441 analysed parcels is very high, reaching the maximum value of 1 (Figure 4). This means that approximately 77% of the inhabitants affected by the water sheet will experience heavy damage from the dam break.

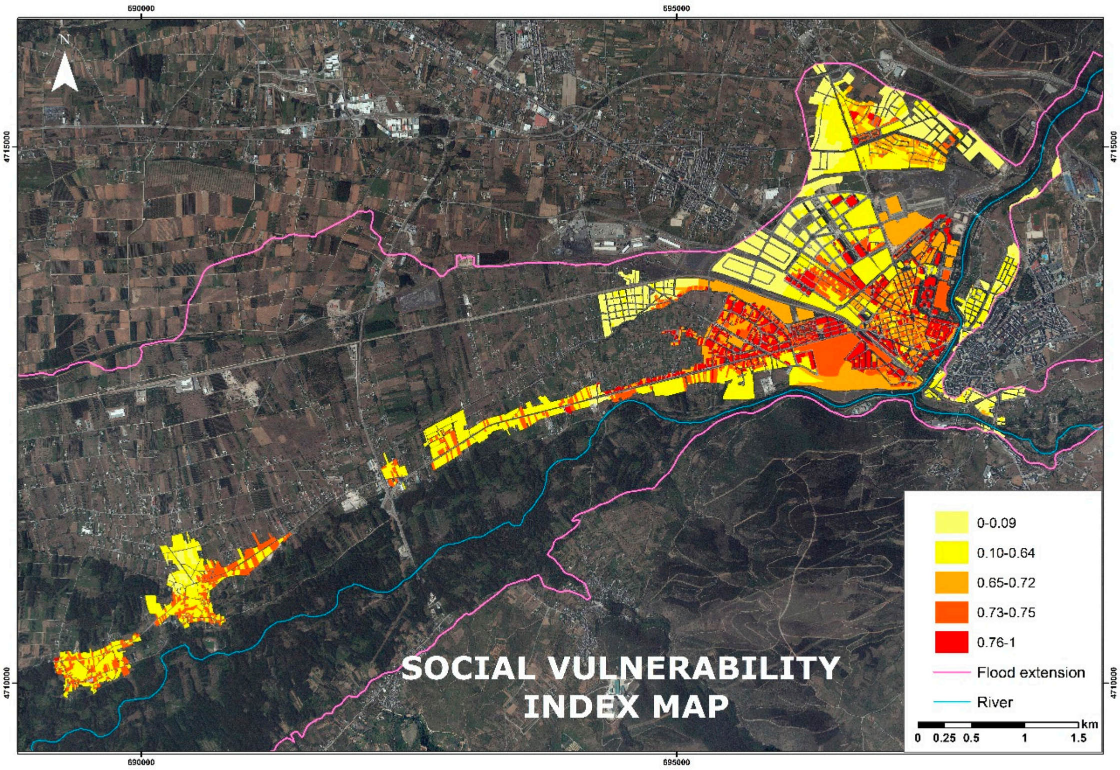

Figure 4. Map of the social vulnerability in Ponferrada due to a potential dam break. Break values of the legend correspond to the quantile distribution to better visualize the spatial distribution of index values.

In the studied case, the highest values are derived from the maximum exposure values assigned to the evacuation time indicator. In these parcels, the analysis shows that the time needed to reach an area outside the flood area is larger than the time needed by the water wave to reach the parcels (Figure 5). In addition, the value of the resistance cannot decrease this vulnerability as the resistance indicators do not have enough value to decrease the high population exposure due to the short time available to evacuate. In the rest of the parcels for which the evacuation time is low enough to reach a safe place before the water wave arrives, the social vulnerability values are very low, at less than 0.074.

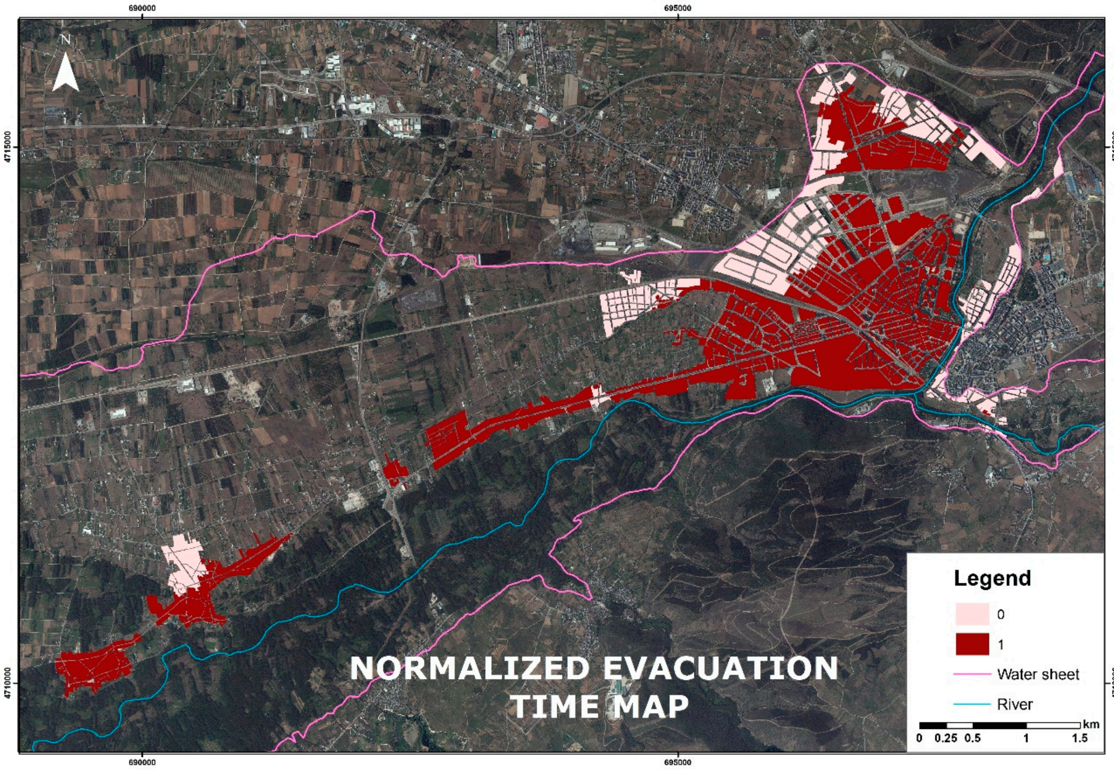

Figure 5. Normalized evacuation time map in Ponferrada.

The two other indicators that increase the vulnerability of Ponferrada are the age of the people and the population density. The impact on the vulnerability of the first indicator is due to the predominance of the elderly population compared to the number of young people in the studied society (Table 5). Therefore, the elderly indicator shows high values due to the high percentage that this ageing sector represents compared to the overall population.

Concerning the characteristics of the population, the census sectors that show the highest vulnerability values according to age data (children and elders) are in six sectors: sector 11 in district 1, sector 14 in district 2, sectors 2, 3 and 7 in district 3 and sector 4 in district 5. Except for sectors 3 and 7 of district 3, the rest of the sectors are located along the river. The distribution of women is more or less equal everywhere, and the only census sector that highlights this indicator is number 14 in district 2, which coincides with a large percentage of elderly persons. The next indicator, the foreign population, shows very low values except in sections 2 and 12 of district 2 and section 5 in district 3. All of these sections are on the riverside. With regard to the illiterate population, this indicator shows high values in section 11 in district 1, sections 1, 9 and 11 in district 2 and sections 4 and 5 in district 3. Again, all of these sections are on the riverside. Finally, the indicators related to the municipal data concerning tourism and the district data on people with disabilities present very low values. Once normalized, both indicators show values lower than 0.1.

Similar to the evacuation time, the population density indicator is analysed for the cadastral parcels (Figure 6). Upon normalizing the values, there are only two parcels in which the indicator reaches the highest possible value of 1. The rest of the parcels show very low values, at less than 0.25.

Table 5. Indicators related to age, gender, foreigners and education in Ponferrada. The highest values appear in bold font.

Census Section	% Children	% Elders	% Women	% Foreigners	% Illiterate Population
			DISTRICT 1		
1	14.2	16.6	51.6	4.2	15.1
3	9.5	18	50.9	3.2	14.5
8	18.8	18.5	49.1	6.6	15.9
9	19.1	12.8	49.4	0	15.7
11	14.7	25.7	55.1	0	40.4
Average	*15.26*	*18.32*	*51.22*	*2.8*	*20.32*
			DISTRICT 2		
1	3.1	32.6	49.6	1.34	37.9
2	24	12.4	47.6	20.22	13.5
3	9.1	19	52.3	3.13	11.9
4	10.1	12.5	50.4	8.12	9.3
5	15.9	13.4	52	8.94	25.2
6	7.3	28.2	50.5	9.22	21.8
7	8.1	20.8	50.2	10.1	10.4
8	9.1	12	57.7	7.57	26.2
9	8	30	50.2	8.92	34.7
10	10.5	20.1	48.9	11.71	19.2
11	3.2	29.1	46.8	0	39.9
12	18.1	17.6	48.6	22.25	21.7
13	12.9	17.1	58.8	0.4	17.7
14	12	31.2	64.8	0	16.8
15	20.8	6.9	53.8	0	7.6
16	20.3	3.7	52.5	0.8	6.4
Average	*12.03*	*19.16*	*52.17*	*7.05*	*20.01*
			DISTRICT 3		
1	21	11.8	49	10.8	11.8
2	11.9	30.5	58.8	2.5	31.7
3	16.2	22.7	51.6	6.5	32.7
4	9.1	20.7	50.9	0	34.1
5	8.7	10.9	50.5	25.5	41.8
6	15.6	16.9	47.5	6.5	21.3
7	15	22.8	46.4	0	30.3
Average	*13.93*	*19.47*	*50.67*	*7.40*	*29.10*
			DISTRICT 5		
4	16.8	21.9	51.8	0.5	15.1
			OVERALL STUDY AREA		
Average	*13.21*	*19.19*	*51.63*	*6.17*	*22.09*

In relation to resistance, the indicator related to the scarcity of information among the population decreases resistance considerably and imposes an increase of social vulnerability [75,83,85]. The main reason for this low information level is the inadequate effort of the government and local authorities to encourage training actions to reduce vulnerability. In the case of Ponferrada, these actions must focus not only on the breakage of the dam but also on other flood phenomena caused by the overflowing of rivers, which have much higher frequency. This type of action would cause a state of alert in the population that should not be confused with a state of alarm. The population will not reach this second state once they know how to act.

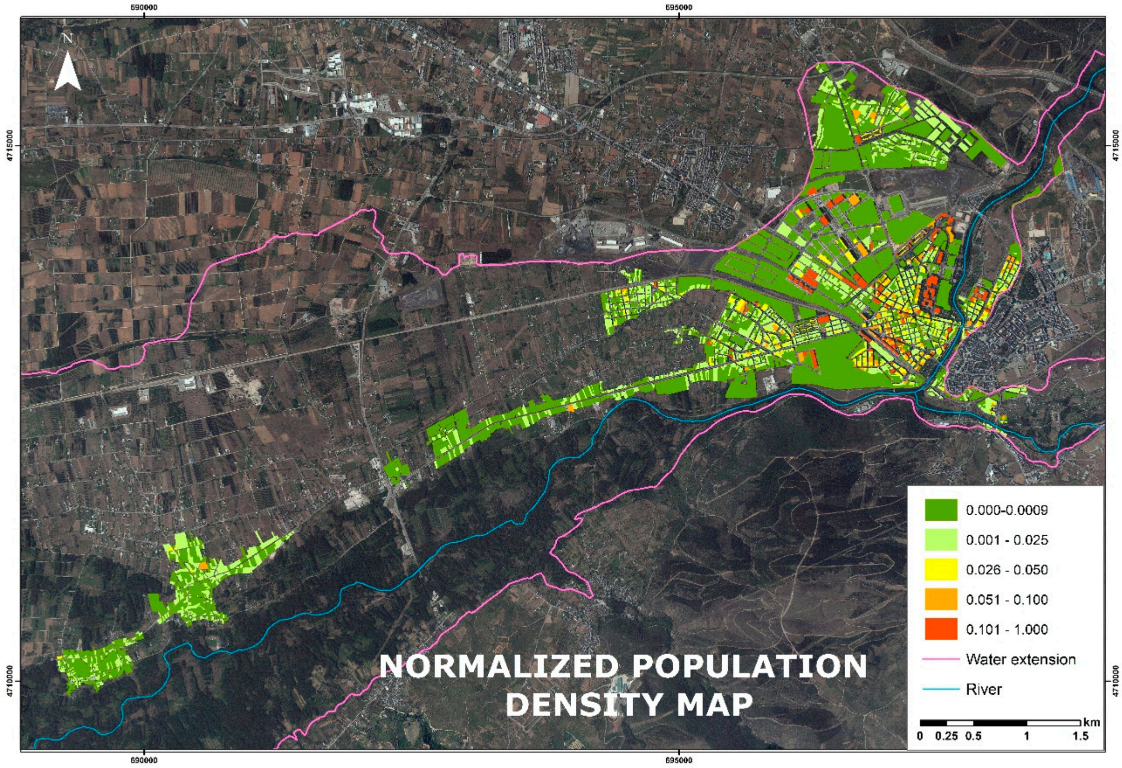

Figure 6. Normalized population density indicator in Ponferrada. Break values of the legend are adjusted to better visualize the spatial distribution of index values.

On the other hand, the indicators that increase resistance, and therefore reduce social vulnerability, are those related to communications, including those with reference to telephone and Internet access, indicators of emergency and health personnel and indicators concerning community equipment related to the number of beds. Ponferrada presents high values of these indicators since it is an area with a certain level of development and good standards of living due to the solidity of the institutions and the guarantee of services and basic rights (Tables 6 and 7).

Table 6. Values of indicators of health, security and community equipment in Ponferrada.

Indicators	Values
Number of health staff per 1000 inhabitants	1
Number of beds per 1000 inhabitants	0.788
Number of firefighters, local and national police per 1000 inhabitants	0.614
Number of volunteers	0.485
Reception centres (surface area (m^2) of sports centres, cultural centres, etc.)	0.809
% of unaffected medical centres	0.5
% of unaffected water supply elements	0.485
% of schools not affected	0.406
% of unaffected police centres and firefighters	0
Information on the population	0
% of accesses not affected by the water sheet	0.8
Number of vehicles that can leave the affected area according to the type and number of accesses (roads)	0

Table 7. Values of communication indicators calculated at the census section level but presented in this table at the district level because their values are quite homogeneous in the study area.

Indicators	District Level	
	Values	Number
% of households with a telephone	0.943	1
	0.945	2
	1	3
	1	5
% of households with ADSL	0.621	1
	0.616	2
	0.485	3
	0.744	5

5. Discussion

It is necessary to promote a culture of prevention that favours the study of the different types of vulnerability in a certain area to save millions of euros, avoid the loss of accumulated wealth and, above all, save human lives in the face of disasters [40,64,100]. The present research focuses on the social aspect and proposes a method for quantifying it based on the integration of exposure level and resistance components. With this purpose, the developed method is based on vulnerability indices as they allow dimensionless results to be obtained at the social level that can be objectively compared with vulnerability in different areas, during different periods of time and at different scales.

According to the results, the indicator that shows greater relevance concerning the increase of a society's vulnerability is the evacuation time, which is a novel indicator in this type of study; very few studies have included it to define vulnerability [88]. Its importance is that it establishes a very clear threshold between areas where there is a possibility of social recovery and those in which such recovery is truly difficult. The latter correspond to areas in which the evacuation time is greater than the time of arrival of the water sheet, so they represent locations where there is not sufficient time to reach a comfort zone. Evacuation times may increase considerably depending on two factors: the time of day and the characteristics of the population. If the disaster occurs at night, when most people are sleeping, the population's reaction time will be longer, and they will need more time to reach a safe place. At the same time, the displacement velocity will vary according to whether the evacuated population includes old people, children and individuals with disabilities, for instance. The main way to reduce these indicator values would be to increase the alarm time and developing early warning systems. Specifically, the alarm time refers to warnings carried in emergency messages through loudspeakers, lights or sounds [101]. If this time is added to the time of the water wave arrival, a person has more time to assimilate the alarm information and initiate movement for a correct evacuation. The resistance of society thus increases, and social vulnerability decreases. At the time this study was performed, Ponferrada did not have an alarm system or emergency plan to broadcast emergency messages if a dam failure occurred. Since the time for the water wave to reach the town is approximately 15 min, if messages are spread when the dam breaks, there is not enough time to save all the people in the town. This is why the values of the evacuation time indicator are so high. Nevertheless, the latest studies suggest remaining at home [89] or converting the upper floor of buildings at meeting points [59]. However, these alternatives will only be safer if they are included in emergency planning and citizens know before the event how to react.

Another indicator relevant to vulnerability studies is the population density indicator [84,86]. As expected, it is a basic indicator since if there is no population, the social vulnerability will be minimal. This is the main reason for the high weight value with respect to the rest of the indicators. In contrast to other studies, in the case of Ponferrada, the importance of this indicator lies in its weight and not in the overpopulation condition or high number of people living on each unit of the surface [75,82,84,86]. Although the calculation of its real value does not present difficulties, its normalization is complex and requires working at the building portal level to establish the evacuation capacity of people in buildings. For this reason, GIS is the only tool that can be applied in this process.

Ponferrada is an old society, which implies high vulnerability, but it has a low number of immigrants, foreigners and people with disabilities. This means that indicators related to these three groups will show lower values than in towns where there is an important economic development that functions as an immigrant call [80] or where there is an important tourism inversion [83].

The normalization of each of the indicators allows dimensionless values [75] to be obtained to enable the comparison of results not only in different periods but also in different study areas. However, not all normalization processes allow this multi-area analysis [64,102]. To achieve this goal, normalization must avoid the use of the maximum value obtained in the specific study area and work with generic concepts that can be assigned as minimum and maximum values. These generic values may be ratios, recommendations or already established standards at both national and international levels without forgetting the context of the study area. In the case of non-existent indicators, this generic value may be associated with the generic value of a similar indicator. For instance, in the case of Ponferrada, the maximum value applied to normalize the indicator of the number of volunteers was the same maximum value established for the local police. Nevertheless, this process is not always easy. The need to search for a generic value for each of the indicators in the transformation function is the step that presents the greatest difficulty when normalizing indicators.

Concerning the weights, the AHP method has shown its fitness for some of the indicators. This method has several characteristics, including the incorporation of both qualitative and quantitative indicators, the hierarchical decomposition of the problem, the organization and structure of the criteria, the mathematical sustenance of the method and the analysis of inconsistencies of the judgements issued, that contribute to the quality of the drawup of the decision process [103]. Nevertheless, this method also has some drawbacks. In this study, two problems were found in its application. The first is that the interviewed experts had some difficulties in establishing judgements about the weights of the indicators because of the large number of indicators, which hindered comparative analyses between them. For this reason, certain inconsistencies were found in the values of the weights assigned by the interviewed experts. To avoid these inconsistencies, it is recommended that in addition to the weight values, the experts establish a hierarchy of the indicators that define the exposure degree of social vulnerability and another hierarchy for the indicators that define resistance to social vulnerability. In this way, if inconsistencies are detected, possible failures in the paired comparison of the indicators can be solved, as has been done in this work. In turn, to facilitate the generation of matrices containing the weights of the indicators, a document with a brief definition of each of the indicators to be analysed should be added to the surveys to achieve homogeneity in the language and identical interpretations. The second problem that the AHP method presents is its rigor; it is not flexible in the face of future changes. This means that new indicators cannot be incorporated to define different vulnerabilities. The surveys should be repeated, incorporating the new indicators to assign the new weights.

Finally, the distribution of social vulnerability data by means of a map has been shown to be a useful tool for delimiting the areas most vulnerable to floods and to allow their diagnosis. For instance, the evacuation time map together with a map of the characteristics of buildings may help to define meeting points in high buildings spread within the flood water sheet to save people who otherwise would not reach a safe area. Therefore, working at a detailed scale proves worthwhile not only for emergency response but also for better prevention planning, improving the resilience of society. The new open-access data appear to be a perfect source to perform this type of study, although these data have limits in the scale of analysis due to the personal protection data law requirements.

6. Conclusions

Natural disasters are an increasingly popular topic at the social and economic levels since there has been a significant increase in their impact in recent decades. Therefore, it is necessary to promote a strategic and systematic prevention approach that allows the reduction of vulnerability in the face of threats, dangers and risks associated with disasters and emphasizes the need to use adequate means to increase the resilience of nations and communities in the face of disasters. The analysis of vulnerability from a social perspective has proven a valuable tool to support flood risk planning and management, when comparing the results of social vulnerability at multi-temporal and multi-spatial levels.

In the present study, the proposed method makes these comparisons possible through the use of several indicators whose normalization is based on generic values. The definition of these values has been shown to be the most difficult step of the method due to the lack of data on some of the treated indicators, so the method is open to some adjustments adapted to different study areas and types of risks. Regardless, the practicality of the proposed method has been proven by applying it in the urban area of the Ponferrada nucleus (León) in the case of a flood due to the rupture of the Bárcena dam and, in a concatenated way, to the breakage of the Fuentes del Azufre dam. The results of this application showed high social vulnerability as a consequence of the lack of time to evacuate. This indicator showed that the 15 min required for the water wave to reach the town are not enough to evacuate the inhabitants in the affected area. Almost 77% of the affected population of Ponferrada will not be able to reach a safe place.

Finally, the proposed method presents the results with high spatial variability by means of a map. This cartography allows the delimitation of the most vulnerable areas facing floods at the smallest possible scale to allow their diagnosis. This entails, among other tasks, the design of prevention, emergency and evacuation plans and decision-making with respect to the locations of new constructions.

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References

1. Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks. *Off. J. Eur. Union Eur. Commun.* **2007**, *288*, 27–34.
2. Bennett, B.; Leonard, M.; Deng, Y.; Westra, S. An empirical investigation into the effect of antecedent precipitation on flood volume. *J. Hydrol.* **2018**, *567*, 435–445. [CrossRef]
3. Beniston, M.; Stoffel, M. Rain-on-snow events, floods and climate change in the Alps: Events may increase with warming up to 4 °C and decrease thereafter. *Sci. Total Environ.* **2016**, *571*, 228–236. [CrossRef] [PubMed]
4. Scholz, M. Predicting Dam Failure Risk for Sustainable Flood Retention Basins. *Sustain. Water Treat.* **2019**, 301–321. [CrossRef]
5. Prakash, M.; Rothauge, K.; Cleary, P.W. Modelling the impact of dam failure scenarios on flood inundation using SPH. *Appl. Math. Model.* **2014**, *38*, 5515–5534. [CrossRef]
6. Rico, M.; Benito, G.; Díez-Herrero, A. Floods from tailings dam failures. *J. Hazard. Mater.* **2008**, *154*, 79–87. [CrossRef]
7. Hollins, L.; Eisenberg, D.; Seager, T. Risk and resilience at the Oroville Dam. *Infrastructures* **2018**, *3*, 49. [CrossRef]
8. Ye, F.; Zhang, Y.J.; Yu, H.; Sun, W.; Moghimi, S.; Myers, E.; Liu, Z. Simulating storm surge and compound flooding events with a creek-to-ocean model: Importance of baroclinic effects. *Ocean Model.* **2020**, *145*, 101526. [CrossRef]

9. Pignatelli, C.; Sansò, P.; Mastronuzzi, G. Evaluation of tsunami flooding using geomorphologic evidence. *Mar. Geol.* **2009**, *260*, 6–18. [CrossRef]
10. Van Veen, B.A.D.; Vatvani, D.; Zijl, F. Tsunami flood modelling for Aceh & west Sumatra and its application for an early warning system. *Cont. Shelf Res.* **2014**, *79*, 46–53. [CrossRef]
11. Ahmadalipour, A.; Moradkhani, H. A data-driven analysis of flash flood hazard, fatalities, and damages over the CONUS during 1996–2017. *J. Hydrol.* **2019**, *578*, 124106. [CrossRef]
12. Rojas, R.; Feyen, L.; Watkiss, P. Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation. *Glob. Environ. Chang.* **2013**, *23*, 1737–1751. [CrossRef]
13. Tanoue, M.; Hirabayashi, Y.; Ikeuchi, H. Global-scale river flood vulnerability in the last 50 years. *Sci. Rep.* **2016**, *6*, 36021. [CrossRef] [PubMed]
14. Wicherski, W.; Dethier, D.P.; Ouimet, W.B. Erosion and channel changes due to extreme flooding in the Fourmile Creek catchment, Colorado. *Geomorphology* **2017**, *294*, 87–98. [CrossRef]
15. Oubennaceur, K.; Chokmani, K.; Nastev, M.; Lhissou, R.; El Alem, A. Flood risk mapping for direct damage to residential buildings in Quebec, Canada. *Int. J. Disaster Risk Res.* **2019**, *33*, 44–54. [CrossRef]
16. Liu, Z.; Lao, J.; Zhang, Y.; Liu, Y.; Zhang, J.; Wang, H.; Jiang, B. Association between floods and typhoid fever in Yongzhou, China: Effects and vulnerable groups. *Environ. Res.* **2018**, *167*, 718–724. [CrossRef]
17. Wijerathne, K.B.P.C.A.; Senevirathna, E.M.T.K. Identify the risk for leptospirosis disease during flooding periods (Special reference to Medirigiriya Divisional Secretariat Division in Polonnaruwa district). *Procedia Eng.* **2018**, *212*, 101–108. [CrossRef]
18. Songsore, J. The Complex Interplay between Everyday Risks and Disaster Risks: The Case of the 2014 Cholera Pandemic and 2015 Flood Disaster in Accra, Ghana. *Int. J. Disaster Risk Res.* **2017**, *26*, 43–50. [CrossRef]
19. Dewan, T.H. Societal impacts and vulnerability to floods in Bangladesh and Nepal. *Weather Clim. Extrem.* **2015**, *7*, 36–42. [CrossRef]
20. Mustafa, A.; Bruwier, M.; Archambeau, P.; Erpicum, S.; Pirotton, M.; Dewals, B.; Teller, J. Effects of spatial planning on future flood risks in urban environments. *J. Environ. Manag.* **2018**, *225*, 193–204. [CrossRef]
21. Nga, P.H.; Takara, K.; Cam Van, N. Integrated approach to analyze the total flood risk for agriculture: The significance of intangible damages—A case study in Central Vietnam. *Int. J. Disaster Risk Res.* **2018**, *31*, 862–872. [CrossRef]
22. Kron, W. Changing flood risk-A re-insurer's viewpoint. In *Changes in Flood Risk in Europe*; Kundzewicz, Z.W., Ed.; CRC Press, IAHS Special Publication: Boca Raton, FL, USA, 2012; Volume 10, pp. 459–490.
23. Hirabayashi, Y.; Mahendran, R.; Koirala, S.; Konoshima, L.; Yamazaki, D.; Watanabe, S.; Kanae, S. Global flood risk under climate change. *Nat. Clim. Chang.* **2013**, *3*, 816–821. [CrossRef]
24. Kapucu, N. Emergency and crisis management in the United Kingdom: Disasters experienced, lessons learned, and recommendations for the future. In *Comparative Emergency Management*; McEntire, D., Ed.; FEMA: Washington, DC, USA, 2009; Chapter 4. Available online: https://training.fema.gov/hiedu/aemrc/booksdownload/compemmgmtbookproject/ (accessed on 23 January 2020).
25. Flanagan, B.E.; Gregory, E.W.; Hallisey, E.J.; Heitgerd, J.L.; Lewis, B. A Social Vulnerability Index for Disaster Management. *J. Homel. Secur. Emerg. Manag.* **2011**, 8. [CrossRef]
26. Driessen, P.P.; Hegger, D.L.; Kundzewicz, Z.W.; Van Rijswick, H.F.; Crabbé, A.; Larrue, C.; Matczak, P.; Pettersson, M.; Priest, S.; Suykens, C.; et al. Governance strategies for improving flood resilience in the face of climate change. *Water* **2018**, *10*, 1595. [CrossRef]
27. Barredo, J.I.; Engelen, G. Land use scenario modeling for flood risk mitigation. *Sustainability* **2010**, *2*, 1327–1344. [CrossRef]
28. Muller, M. Adapting to climate change: Water management for urban resilience. *Environ. Urban.* **2007**, *19*, 99–113. [CrossRef]
29. Durga, B.K.; Moulika, M.B.; Kumar, K.P.; Varma, L.K. Design of early warning flood detection systems. *IJETSR* **2018**, *5*, 794–799.
30. Thielen, J.; Bartholmes, J.; Ramos, M.H.; De Roo, A. The European flood alert system ĝ€" part 1: Concept and development. *Hydrol. Earth Syst. Sci.* **2009**, *13*, 125–140. [CrossRef]
31. Milly, P.C.D.; Wetherald, R.T.; Dunne, K.A.; Delworth, T.L. Increasing risk of great floods in a changing climate. *Nature* **2002**, *415*, 514–517. [CrossRef]

32. Oppenheimer, M.; Campos, M.; Warren, R.; Birkmann, J.; Luber, G.; O'Neill, B.; Takahashi, K. Emergent risks and key vulnerabilities. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., White, L.L., Eds.; Cambridge University Press: Cambridge, UK, 2014; pp. 1039–1099. Available online: https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-Chap19_FINAL.pdf (accessed on 23 January 2020).
33. EEA-European Environment Agency. *Climate Change, Impacts and Vulnerability in Europe 2016*; EEA: Luxembourg, 2017; p. 421.
34. Richard Eiser, J.; Bostrom, A.; Burton, I.; Johnston, D.M.; McClure, J.; Paton, D.; White, M.P. Risk interpretation and action: A conceptual framework for responses to natural hazards. *Int. J. Disaster Risk Res.* **2012**, *1*, 5–16. [CrossRef]
35. Hufschmidt, G.; Crozier, M.; Glade, T. Evolution of natural risk: Research framework and perspectives. *Nat. Hazards Earth Syst. Sci.* **2005**, *5*, 375–387. [CrossRef]
36. Mishra, K.; Sinha, R. Flood risk assessment in the Kosi megafan using multi-criteria decision analysis: A hydro-geomorphic approach. *Geomorphology* **2020**, *350*, 106861. [CrossRef]
37. UNDRO. *Natural Disasters and Vulnerability Analysis*; Office of the United Nations Disaster Relief Coordinator: Geneva, Switzerland, 1980; p. 53.
38. Vargas, J. *Políticas Públicas Para la Reducción de la Vulnerabilidad Frente a los Desastres Naturalesy Socio-Naturales*; Naciones Unidas, CEPAL: Santiago, Chile, 2002; Volume 50, p. 79.
39. Kumpulainen, S. Vulnerability concepts in hazard and risk assessment. In *Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions*; Special Paper 42; Schmidt-Thome, P., Ed.; Geological Survey of Finland: Espoo, Finland, 2006; pp. 65–74.
40. Aroca-Jiménez, E.; Bodoque, J.M.; García, J.A.; Díez-Herrero, A. Construction of an integrated social vulnerability index in urban areas prone to flash flooding. *Nat. Hazards Earth Syst. Sci.* **2017**, *17*, 1541–1557. [CrossRef]
41. Dwyer, A.; Zoppou, C.; Nielsen, O.; Day, S.; Roberts, S. *Quantifying Social Vulnerability: A Methodology for Identifying Those at Risk to Natural Hazards*; Geoscience Australia Record; Geoscience Australia: Canberra, Australia, 2004; p. 92.
42. Karmakar, S.; Slobodan, P.S.; Peck, A.; Black, J. An information system for risk-vulnerability. Assessment to flood. *Int. J. Geogr. Inf. Syst.* **2010**, *2*, 129–146. [CrossRef]
43. Kappes, M.S.; Papathoma-Köhle, M.; Keiler, M. Assessing physical vulnerability for multihazards using an indicator-based methodology. *Appl. Geogr.* **2012**, *32*, 577–590. [CrossRef]
44. Birkmann, J. (Ed.) *Measuring Vulnerability to Natural Hazards: Towards Disaster Resilient Societies*; United Nations University Press: Tokyo, Japan, 2013; p. 720.
45. Dunning, C.M.; Durden, S. *Social Vulnerability Analysis: A Comparison of Tools*; U.S. Army Corps of Engineers Institute for Water Resources: Alexandria, VA, USA, 2013; p. 34.
46. Hummell, B.M.D.; Cutter, S.L.; Emrich, C.T. Social vulnerability to natural hazards in Brazil. *Int. J. Disaster Risk Sci.* **2016**, *7*, 111–122. [CrossRef]
47. Creach, A.; Chevillot-Miot, E.; Mercier, D.; Pourinet, L. Vulnerability to coastal flood hazard of residential buildings on Noirmoutier Island (France). *J. Maps* **2016**, *12*, 371–381. [CrossRef]
48. Noradika, Y.; Lee, S. Assessment of social vulnerability to natural hazards in South Korea: Case study for typhoon hazard. *Spat. Inf. Res.* **2017**, *25*, 99–116. [CrossRef]
49. Hardy, R.D.; Hauer, M. Social vulnerability projections improve sea-level rise risk assessments. *Appl. Geogr.* **2018**, *91*, 10–20. [CrossRef]
50. Aksha, S.; Juran, L.; Resler, L.M.; Zhang, Y. An analysis of social vulnerability to natural hazards in Nepal using a modified social vulnerability index. *Disaster Risk Sci.* **2019**, *10*, 103–116. [CrossRef]
51. Apotsos, A. Mapping relative social vulnerability in six mostly urban municipalities in South Africa. *Appl. Geogr.* **2019**, *105*, 86–101. [CrossRef]
52. Armaș, I.; Gavriș, A. Social vulnerability assessment using spatial multi-criteria analysis (SEVI model) and the Social Vulnerability Index (SoVI model)—A case study for Bucharest, Romania. *Nat. Hazards Earth Syst. Sci.* **2013**, *13*, 1481–1499. [CrossRef]

53. Pérez-Morales, A.; Navarro-Hervas, F.; Álvarez Rogel, Y. Propuesta metodológica para la evaluación de la vulnerabilidad social en poblaciones afectadas por el peligro de inundación: El caso de Águilas (Murcia, sureste ibérico). *Doc. D'anàlisi Geogràfica* **2016**, *62*, 133–159. [CrossRef]
54. Cano, V. Aplicación de los SIG para la generación de rutas de evacuación en caso de desastres, como ayuda para la planificación urbana: "caso costa oriental del lago de Maracaibo". *Rev. de la Fac. de Ing. UCV* **2011**, *26*, 17–26.
55. Willis, I.; Fitton, J. A review of multivariate social vulnerability methodologies: A case study of the River Parrett catchment, UK. *Nat. Hazards Earth Syst. Sci.* **2016**, *16*, 1387–1399. [CrossRef]
56. Debbage, N. Multiscalar spatial analysis of urban flood risk and environmental justice in the Charlanta megaregion, USA. *Anthropocene* **2019**, 28. [CrossRef]
57. Cutter, S.L.; Mitchell, J.T.; Scott, M.S. Revealing the vulnerability of people and places: A case study of Georgetown County, South Carolina. *Ann. Am. Assoc. Geogr.* **2000**, *90*, 713–737. [CrossRef]
58. Prudent, N.; Houghton, A.; Luber, G. Assessing climate change and health vulnerability at the local level: Travis County, Texas. *Disasters* **2016**, 40. [CrossRef]
59. Arrighi, C.; Pregnolato, M.; Dawson, R.J.; Castelli, F. Preparedness against mobility disruption by floods. *Sci. Total Environ.* **2019**, *654*, 1010–1022. [CrossRef]
60. Tate, E.; Cutter, S.; Berry, M. Integrated multihazard mapping. *Environ. Plan. B Plan. Des.* **2010**, *37*, 646–663. [CrossRef]
61. Bjarnadottir, S.; Li, Y.; Stewart, M. Social vulnerability index for coastal communities at risk to hurricane hazard and a changing climate. *Nat. Hazards* **2011**, *59*, 1055–1075. [CrossRef]
62. Gautam, D. Assessment of social vulnerability to natural hazards in Nepal. *Nat. Hazards Earth Syst. Sci.* **2017**, *17*, 2313–2320. [CrossRef]
63. Ebert, A.; Kerle, N.; Stein, A. Urban social vulnerability assessment with physical proxies and spatial metrics derived from air- and spaceborne imagery and GIS data. *Nat. Hazards* **2009**, *48*, 275. [CrossRef]
64. Sebald, C. Towards an integrated Flood Vulnerability Index—A Flood Vulnerability Assessment. MSc Thesis, Faculty of Geo-Information Science and Earth Observation, University of Twente, Enschede, The Netherlands, 2010.
65. Westen, C.V.; Kingma, N. Vulnerability assessment. In *Multi-Hazard Risk Assessment*; Guide Book; Westen, C.V., Alkema, D., Dam, M., Kerle, N., Kingma, N., Eds.; United Nations, University-ITC School on Disaster Geoinformation Management (UNU-ITC DGIM): Enschede, The Netherlands, 2011; pp. 255–287.
66. Papathoma-Köhle, M. Vulnerability curves vs. vulnerability indicators: Application of an indicator-based methodology for debris-flow hazards. *Nat. Hazards Earth Syst. Sci.* **2016**, *16*, 1771–1790. [CrossRef]
67. De Ruiter, M.C.; Ward, P.H.; Daniell, J.E.; AERTS, J.C.J.H. A comparison of flood and earthquake vulnerability assessment indicators. *Nat. Hazards Earth Syst. Sci.* **2017**, *17*, 1231–1251. [CrossRef]
68. Gao, J.; Nickum, J.; Pan, Y. An assessment of flood hazard vulnerability in the Dongting Lake Region of China. *Lakes Reserv. Res. Manag.* **2007**, *12*, 27–34. [CrossRef]
69. Generino, P.; Sony, E.; Proceso, L. Analytic Hierarchy Process (AHP) in spatial modeling for floodplain risk assessment. *Int. J. Mach. Learn. Comput.* **2014**, *4*, 450–457.
70. Ouma, Y.O.; Tateishi, R. Urban flood vulnerability and risk mapping using integrated multi-parametric AHP and GIS: Methodological overview and case study assessment. *Water* **2014**, *6*, 1515–1545. [CrossRef]
71. Danumah, J.H.; Odai, S.N.; Saley, B.M.; Szarzynski, J.; Thiel, M.; Kwaku, A.; Koffi, F.; Akpa, L. Flood risk assessment and mapping in Abidjan district using multi-criteria analysis (AHP) model and geoinformation techniques, (Cote d´Ivoire). *Geoenviron. Disasters* **2016**, *3*, 1–13. [CrossRef]
72. INE-Instituto Nacional de Estadística. Available online: https://www.ine.es/ (accessed on 22 April 2019).
73. CHMiño-Sil- Confederación Hidrográfica del Miño-Sil. *Evaluación Preliminar del Riesgo de Inundación (EPRI) e Identificación de las Áreas con Riesgo Potencial Significativo de Inundación (ARPSIs) del Territorio Español de la Demarcación Hidrográfica del Miño-Sil*; Ministerio de Medio Ambiente y Medio Rural y Marino: Madrid, Spain, 2011; p. 39.
74. CHMiño-Sil-Confederación Hidrográfica del Miño-Sil. *Plan de Emergencia de la Presa de Bárcena*, Unpublished material. 2012.
75. Balica, S.F. Applying the Flood Vulnerability Index as a Knowledge Base for Flood Risk Assessment. Ph.D. Thesis, Delft University of Technology and the Academic Board of the UNESCO-IHE, Institute for Water Education, Enschede, The Netherlands, 6 June 2012.

76. Tascón-González, L. Análisis metodológico para la estimación de la vulnerabilidad por inundaciones. Ejemplo de aplicación en el municipio de Ponferrada (León, España). Ph.D. Thesis, Universidad de León, León, Spain, 30 September 2017.
77. Poushter, J.; Bishop, C.; Chwe, H. *Social Media Use Continues to Rise in Developing Countries but Plateaus Across Developed Ones*; Pew Research Center: Washington, DC, USA, 2018. Available online: https://www.pewresearch.org/global/wp-content/uploads/sites/2/2018/06/Pew-Research-Center-Global-Tech-Social-Media-Use-2018.06.19.pdf (accessed on 23 January 2020).
78. Saaty, T.L. Decision making with the analytic hierarchy process. *Int. J. Serv. Sci.* **2008**, *1*, 83–98. [CrossRef]
79. Dirección General del Catastro. Available online: http://www1.sedecatastro.gob.es/ (accessed on 19 December 2019).
80. Cutter, L.S.; Boruff, B.J.; Shirley, W.L. Social vulnerability to environmental hazards. *Soc. Sci. Q.* **2003**, *84*, 242–261. [CrossRef]
81. Hearn, B.; Laska, S.; Willinger, B.; Mock, N. Gender and disasters: Theoretical Considerations. In *Katrina and the Women of New Orleans*; Willinger, B., Ed.; Tulane University: New Orleans, LA, USA, 2008; pp. 11–21.
82. Fekete, A. Validation of a social vulnerability index in context to river-floods in Germany. *Nat. Hazards Earth Syst. Sci.* **2009**, *9*, 393–403. [CrossRef]
83. Ruiz, M. Vulnerabilidad Territorial y Evaluación de Daños Postcatástrofe: Una Aproximación Desde la Geografía del Riesgo. Ph.D. Thesis, Universidad Complutense de Madrid, Madrid, Spain, 24 May 2011.
84. Holand, I.; Lujala, P.; Ketil, J. Social vulnerability assessment for Norway: A quantitative approach. *Norsk Geogr. Tidsskr. Nor. J. Geogr.* **2011**, *65*, 1–17. [CrossRef]
85. Popovici, E.-A.; Costache, A.; Dan, B.; Dogaru, D.; Sima, S. Vulnerability assessment of rural communities to floods in the western part of Romania (Banat plain). 13th International Multidisciplinary Scientific GeoConference SGEM. *J. Environ. Prot. Ecol.* **2013**, *1*, 1161–1168. [CrossRef]
86. Koks, E.E.; Jongman, B.; Husby, T.G.; Botzen, W.J.W. Combining hazard, exposure and social vulnerability to provide lessons for flood risk management. *Environ. Sci. Policy* **2014**, *47*, 42–52. [CrossRef]
87. Aroca, E.; Bodoque, J.M.; García, J.A.; Díez, A. Análisis de la vulnerabilidad social ante avenidas súbitas en zonas urbanas de Castilla y León (España). In Proceedings of the XIV Reunión Nacional de Geomorfología, Málaga, Spain, 22–25 June 2016; pp. 283–290.
88. Quezada-Hofflinger, A.; Somos-Valenzuela, M.A.; Vallejos-Romero, A. Response time to flood events using a Social Vulnerability Index (ReTSVI). *Nat. Hazards Earth Syst. Sci.* **2019**, *19*, 254–267. [CrossRef]
89. Salvati, P.; Petrucci, O.; Rossi, M.; Bianchi, C.; Pasqua, A.A.; Guzzetti, F.G. Gender, age and circumstances analysis of flood and landslide fatalities in Italy. *Sci. Total Environ.* **2018**, *610–611*, 867–879. [CrossRef]
90. Laghi, M.; Cavalletti, A.; Polo, P. *Coastal Risk Analysis of Tsunamis and Environmental Remediation*; Asian Disaster Preparedness Center: Klong Luang, Thailand, 2006; p. 98.
91. Jones, J.M.; Peter, N.G.; Natah, W.J. *The Pedestrian Evacuation Analyst—Geographic Information Systems Software for Modeling Hazard Evacuation Potential*; U.S. Geological Survey: Reston, VA, USA, 2014; p. 25.
92. Bernardini, G.; Postacchini, M.; Quagliarini, E.; Brocchini, M.; Cianca, C.; D'Orazio, M. A preliminary combined simulation tool for the risk assessment of pedestrians' flood-induced evacuation. *Environ. Model. Softw.* **2017**, *96*, 14–29. [CrossRef]
93. Garmendia, A. Valoración de impactos ambientales. In *Evaluación de Impacto Ambiental*; Garmendia, A., Salvador, A., Crespo, C., Garmendia, L., Eds.; Pearson-Prentice Hall: Upper Saddle River, NJ, USA, 2005; pp. 225–284.
94. Ministerio de Empleo y Seguridad Social. *Evaluación y Diagnóstico de las Condiciones de Evacuación en Edificios de Elevada Ocupación*, 3rd ed.; Centro Nacional de Medios de Protección: Sevilla, Spain, 2012; p. 18.
95. Hauke, A.; Georgiadou, P.; Malmelin, J.; Punakallio, A.; Päkkönen, R.; Meyer, S.; Nicolescu, G. *Emergency Services: A Literature Review on Occupational Safety and Health Risks*; European Agency for Safety and Health at Work (EU-OSHA): Luxembourg, 2011; p. 80.
96. World Health Organization. *World Health Statistics-2009*; WHO: Geneva, Switzerland, 2009; p. 149.
97. Junta de Castilla y León. *Plan Regional Sectorial de Carreteras 2008–2020*; Junta de Castilla y León: Valladolid, Spain, 2008; p. 278.
98. World Health Organization. *World Health Statistics-2017*; WHO: Geneva, Switzerland, 2017; p. 116.
99. Ministerio de Sanidad, Servicios Sociales e Igualdad. *Los Sistemas Sanitarios en los Países de la UE: Características e Indicadores de Salud 2013*; Ministerio de Sanidad, Servicios Sociales e Igualdad: Madrid, Spain, 2014; p. 99.

100. Connor, R.F.; Hiroki, K. Development of a method for assessing flood vulnerability. *Water Sci. Technol.* **2005**, *51*, 61–67. [CrossRef]
101. INSHT. *NTP 436: Cálculo Estimativo de Vías y Tiempos de Evacuación. GUÍAS de buenas prácticas*; Instituto Nacional de Seguridad e Higiene en el trabajo - Ministerio de Trabajo y Asuntos Sociales de España: Madrid, Spain, 1997; p. 6.
102. Lee, J.S.; Choi, H.I. Comparison of flood vulnerability assessments to climate change by construction frameworks for a composite indicator. *Sustainability* **2018**, *10*, 768. [CrossRef]
103. Klaus, D. Implementing the Analytic Hierarchy Process as a standard method for multi-criteria decision making in corporate enterprises—A new AHP excel template with multiple inputs. In Proceedings of the International Symposium on the Analytic Hierarchy Process, Kuala Lumpur, Malaysia, 23–26 June 2013.