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Mapping Tools for Flood Risk Rescue and Assistance Management

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Abstract: The assessment of vulnerability to the danger of flooding, with a focus on the need for rescue and assistance from the population, is still in an exploratory scientific phase. The main objective of this research is to propose a methodology based on the issues of rescue and assistance in the face of the risk of floods and to provide a tool for its management. A series of maps is presented, indicating those territorial elements that require rescue and surveillance in a prioritized manner in a visual and accessible way for public administration. Four methodological cartographic proposals have been designed as follows: (1) a map of territory sectors with special rescue needs (dependent population and/or buildings without shelter); a map of the impact on transportation infrastructure and vulnerable areas of buildings (2); a map of vulnerability to possible disorder and looting caused by flooding events (3); and a map of the increase in the cost of deployment for rescue and assistance systems (4). As an experimental zone to test the effectiveness of these proposals, a peri-urban area of the municipality of Málaga (Spain) is chosen, which has an extensive history of severe floods. The results confirm the applied and preventive nature of the tool, which can be incorporated into flood risk management plans and local flood risk action plans developed by public administrations. The main finding of the research is the technical advancement that comes with a precise understanding of vulnerability and its resulting issues for better flood risk management.

Keywords: flood risk management; relief; vulnerability mapping; network analysis; local scale; GIS

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1. Introduction

Studies on floods have focused on various aspects, such as flood prediction and monitoring, risk assessment, planning and emergency management, as well as the mitigation of their impacts [1,2]. These studies have employed diverse methodologies and approaches to address the challenges associated with floods. In terms of methodology, tools and techniques such as hydrological and hydrodynamic models, geographic information systems (GIS), spatial data analysis, remote sensing, statistical analysis, and numerical simulations, among others, have been employed [3]. These methodologies enable the analysis of precipitation patterns, river and watershed behavior, soil erosion, topography, drainage capacity, and other relevant factors for understanding and predicting floods [4,5].

Regarding research objectives, studies on floods have addressed a wide range of topics. Some researchers have focused on the identification and assessment of flood-prone areas by analyzing physical [6] and socioeconomic factors [7]. Others have investigated the effects of floods on infrastructure [8], ecosystems [9], human health [10], and the social perception of natural risks [11]. Research has also been conducted on mitigation and adaptation strategies, including the construction of flood control structures, watershed management [12,13], urban planning, and public education.

For what concerns to flood management, a significant change over the past decades can be highlighted [14]. Historically, strategies implemented by public administrations to address floods have focused on controlling the phenomenon through structural measures supported by technical and technological advances. However, technological development has not corrected the trend in flood damages—on the contrary, losses are increasing [15].

Simplifying the analysis to the mere consideration of hydrological-hydraulic calculations in flood risk prevention can lead to calculation errors in zoning strategies. There has been a transition from an almost exclusive reliance on technical solutions, with the development of hydraulic infrastructure, to a more comprehensive and multimodal approach. From the current perspective, it incorporates measures for territorial planning, risk mapping, and structural actions that are appropriate and consistent with the local environment. Effective territorial flood risk management involves considering prevention measures [16]. The cartographic diagnosis of prone areas and affected elements constitutes what is known as flood risk mapping. There is a general consensus within the scientific community to consider risk as a situation susceptible to causing damage as a result of an event that occurs in a vulnerable environment [17]. Therefore, the three classic factors are considered for parameterization in the equation: hazard, exposure, and vulnerability [18]. Despite the consensus regarding risk components in analyses applied in urban planning, such as flood zoning, the most commonly used factor for risk characterization is hazard [17,19–21], focusing attention on water depth and velocity. In recent decades, theoretical reflections related to disaster risk management [22–28] are changing this trend by incorporating vulnerability as a necessary factor to effectively manage risk. Two major types of international models for flood mapping can be highlighted. On one hand, there are deterministic numerical models which can be one-dimensional, two-dimensional, or three-dimensional [29–31]. On the other hand, there are parametric or qualitative models developed in response to the complexity of applying deterministic models based on estimating a system's vulnerability through indices. These are called FVI, which stands for Flood Vulnerability Index. Vulnerability is undoubtedly what makes risk complex, due to the multitude of factors that define it, and it is considered the fundamental cause for the occurrence of a disaster [32].

The models used for delineating flood-prone areas fail in many cases. It is well known that one of the repercussions of climate change is atmospheric disturbances and an increase in the frequency of extreme events [33–35]. Therefore, there is a risk that the time series used for hydrological-hydraulic calculations may become outdated.

It could be concluded that the estimated flood-prone area, for a given return period, is at risk of becoming blurred due to factors such as climate change [36] or the mentioned inaccuracies. However, people and assets remain fixed beyond the officially declared flood zones. As a precautionary measure, it is necessary to characterize the vulnerability of the population and exposed assets to reduce the risk of disasters. All of this is done in anticipation that flood-prone areas may be underestimated. Recapitulating all the above, the study of natural (or ultimately physical) hazard would take a back seat to social vulnerability. This position may be somewhat biased since, as internationally recognized, risk management is based on knowledge of factors involving both hazard and vulnerability or exposure. However, there is no doubt that vulnerability must be taken into account when implementing effective risk management.

On the other hand, there are human factors that lead to differentiated territorial patterns, with more or less pronounced tendencies toward risk. Peri-urban areas are among the most prone [37]. Castronovo [38] defines them as areas of constant friction, with very active exchanges governed by the city, resulting in an asymmetric flow of matter and energy. The peri-urban characteristics of study areas, such as the one chosen for this work, impart a special propensity to risk. Hence, the characterization of risk deserves to be carried out not only from the perspective of hazard but also considering the vulnerability of exposed elements. Some academic works have focused their efforts on this type of analysis [39,40].

There are few works that have specifically developed models simulating the impact of a natural disaster on rescue and assistance efforts. Many of the studies analyzed so far focus on the importance of the participation of various official entities in providing relief and support during and after floods. In this regard, Paul (2003) [41] compared the performance of the state government and NGOs in providing relief assistance to flood victims in Bangladesh. Meanwhile, Carter (2017) [42] analyzed federal assistance programs and initiatives aimed at flood risk reduction and resilience in the United States.

In general, flood risk management proposals with less developed methodological approaches are presented. In this line, Raza's (2017) [43] contribution is noteworthy, presenting a spatial data model enabling the rapid assessment of populations affected by floods, facilitating timely decision-making for humanitarian responses. Another author, Huang (2021) [44], focuses on mapping the impact of floods on urban mobility, particularly the disruption of road networks, crucial for effective damage mitigation and evacuation operations. Pappalardo (2023) [45] addresses the issue of spatial equity in flood risk management, identifying areas with high exposure and vulnerability to prioritize mitigation actions benefiting the most vulnerable populations.

With a similar objective to the present research on rescue and assistance, there are studies by Sortino and Perles (2017) [46], Coles et al. (2017) [47], Yin, Yu, and Liao (2021) [48], and Zhang et al. (2022) [49]. These studies develop methods that combine flood modeling with network analysis to assess intra-urban accessibility by emergency services during flood events. As highlighted by McCallum et al. (2016) [50], other proposals introduce the novelty of analyzing massive data from social networks in designing protocols for responding to such natural disasters. This is useful for mapping the most affected areas [51] and monitoring the public's reaction to these catastrophes [52]. Rahman et al. (2021) [53] suggest an addition to hazard mapping, an Information Humanitarian Assistance System (HAIS), to enhance emergency assistance to flood victims.

Regarding the risks of public disorder and looting, previous experiences have been investigated, observing a tendency to confuse acts of survival with purely criminal acts [54]. The real risk does not necessarily increase in the directly affected areas but in neighboring areas [55,56].

In a more general sense, recent methodological and technical advances in the simulation of potential floods are of interest. Kharazi and Behzadan (2021) [57] use deep neural network algorithms to analyze street photographs, along with other algorithms for edge detection and water depth in the flood. Oliva and Olcina (2022) [58] provide emergency mapping based on the analysis of emergency calls, allowing for a deeper understanding of the functioning of the territory and the identification and typology of problems arising from these catastrophic events.

Two fundamental concepts are central to analyzing flood phenomena: the first one focused on the areas causing floods and their characterization upstream, and the second one on the areas receiving floods downstream from the receiving basins. It is at this point that the present study is developed and integrated. In light of these circumstances, Perles et al. [59] propose a cartographic catalog that covers a wide range of aspects to characterize territorial vulnerability to floods. Taking this research as a reference, this work develops one of its proposals, specifically addressing maps aimed at addressing issues related to vulnerability to danger: problem of difficulties in rescue and assistance.

The objective of this research is to propose a methodology and, consequently, a tool for flood management consisting of a cartographic series indicating the territorial elements that need rescue and surveillance as a priority within flood-prone areas. This provides a visual and accessible format for the structure of public administrations. The highlight of the research is the integration of flood simulations with network analyses and how these simulations become crucial in planning for catastrophic flood situations, as well as in intervention and the safeguarding of human lives and material assets.

2. Materials and Methods

2.1. Study Area

This methodological proposal has been tested in an area with an extensive history of flooding. It is a section of District 9 in the municipality of Malaga, (Andalusia, Spain) (see Figure 1). This district, a peri-urban area of the city of Malaga, consists of four secondary cores: Campanillas, the most important one, and three under its functional influence area, Huertecilla de Mañas, Colmenarejo, and Pilar del Prado. These cores are located on the banks of the Campanillas River, a tributary of the Guadalhorce River located to the south of the Guadalhorce basin, converging with it at 8.5 km from its mouth in the Mediterranean Sea. Urban uses are interspersed with a mosaic of crops, mainly dedicated to vegetable gardens and intensive citrus cultivation under irrigation. The area has a Mediterranean climate, characterized by an annual precipitation regime ranging from 400 to 600 mm, and an average annual temperature of 17.6 °C, with mild winters and warm summers. It is regularly affected by cut off lows, causing violent episodes of precipitation. In the last 35 years, the frequency and intensity of floods in the Guadalhorce has increased. Notable floods occurred in various municipalities of Bajo Guadalhorce in 1989, during the rainy period from 1996 to 1998, or more recently, in January 2020. On 25 January 2020, 200 mm of rain were recorded in 12 h, leading to a flooding episode that exceeded the estimated return period for the area, which is 500 years. The region has a series of natural conditions that make it prone to the development of these events:

- Rugged terrain with steep slopes, drained by short-flow rivers.
- Impermeable or semi-permeable character of a large part of the surface geological materials.
- Precipitation regime typical of the Mediterranean climate, with very marked variations in a few kilometers.

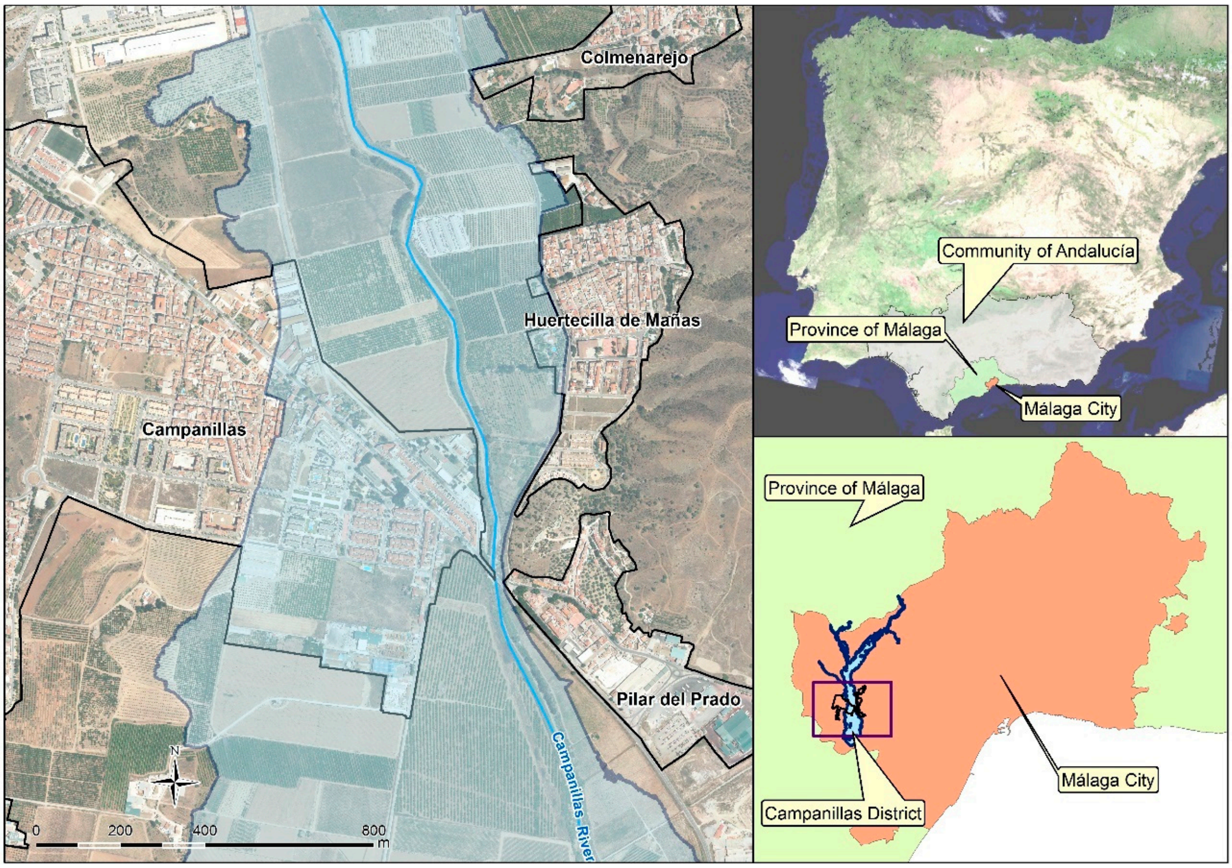

Figure 1. Situation of the study case. The map on the left shows, in blue, the potentially flooded area of the Campanillas River as it passes through the study area.

Along with these conditions are circumstances derived from human activity, including extensive deforestation in the headwaters of the basins, increasing surface runoff and higher circulation speed on slopes, as well as the encroachment of land in the riverbed and its floodplains for urban and agricultural development.

The gradual urbanization process in areas adjacent to the river has increased the risk of flooding in a section where recurrent overflows occur, causing material and personal damage. The construction of the Casasola reservoir, completed in 2007, aims primarily to regulate river flow, in addition to providing irrigation water to surrounding agricultural areas. However, successive river floods (as occurred in 2010, 2016, and more significantly in 2020, when the flooding reached levels expected for return periods of 500 years (and even exceeded them), coupled with the continuous expansion of the urbanized area, this issue has been further exacerbated. Due to these circumstances, its final stretch, prior to its confluence with the Guadalhorce, is designated as "Area with Potential Significant Flood Risk" (APSFR), along with the continuous expansion of the urbanized area, have further exacerbated this problem.

Currently, in the autonomous community of Andalusia, the region where the chosen study area for this work is located, there is an official flood risk zoning stipulated by RD 903/2010 for the assessment and management of flood risks. This regulation is the result of the transposition of Directive 2007/60/CE of the European Parliament on the assessment and management of flood risks. Under this regulation, there is a risk zoning protocol called Preliminary Flood Risk Assessment (PFRA), which starts with the designation of all areas susceptible to flooding. These areas must have a Flood Risk Management Plan (FRMP) and an internal zoning into units called APSFR.

2.2. Identification of Flood-Related Problems Related to Vulnerability

The main objective of this methodology is to address specific vulnerability issues in the face of the flood hazard. In this regard, the following advancements made in specific issues by Perles, Sortino, and Cantarero have been considered [59]:

1. Isolation of the population. This issue has already been addressed previously in the same study area [60].
2. Interruption of basic territorial services.
3. Difficulties in rescue and assistance.
4. Risky or unsafe behavior of the population.
5. Impact on goods or sectors of the territory particularly sensitive.
6. Impact on elements of the territory due to pollution and other risks associated with flooding.

In this research, the methodology for the problem of rescue and assistance to the population will be implemented and developed, as it is one of the most significant vulnerability issues in the face of the flood hazard. The choice of this problem stems from the need to reduce human casualties and material losses.

The cartographic tools offered to address all population isolation problems are as follows:

- Map of territory sectors with special rescue needs (dependent population and/or buildings without shelter)
- Map of the impact on transportation infrastructure and vulnerable areas of buildings.
- Map of vulnerability to potential disorder and looting caused by flooding phenomena.
- Map of increased travel costs for rescue and assistance systems.

2.3. Information Sources

In order to enhance the applicability of the cartographic proposal for public administration agencies and private entities, such as environmental consultancies, indicators have been carefully selected that can be generated from easily accessible published sources providing general and equivalent information. This selection has been made specifically for the autonomous community of Andalusia, located in southern Spain. To ensure the utility of the variables in applied risk management, those that, while valid in the research domain, presented significant difficulties for obtaining have been excluded. Thus, the inclusion of practical and feasible variables in the context of risk management has been prioritized. The following is a compilation of the sources used for the development of the cartographic catalog:

- DERA: Spatial Reference Data of Andalusia. Scale 1:100,000. Year: 2023.
- PNOA: National Plan for Aerial Orthophotography. Variable scale. Year: 2023.
- CartoCiudad: Continuous road network of Spain. Various working scales. Year: 2023.
- Cadastre: Virtual Cadastre General Directorate. Variable scale. Year: 2023.
- Google Earth. Variable scale. Year: 2023.
- Google Street View. Variable scale. Year: 2023.
- Hydrological Plans. Variable scale. Years: according to the Basin Authority.

2.4. Methodology Structure

The cartographic series aims to indicate those territorial elements that need rescue as a priority within flood-prone areas, providing a visual and accessible format for the structure of public administrations. It is a conception of the vulnerability of the human environment to the risk of flooding, focusing on the human lives and material possessions of individuals.

Firstly, the selection and characterization of the study area and the territorial elements to be considered are necessary. Once the strategic buildings and the population to be prioritized are identified, it is essential to estimate the degree of flooding impact and, finally, establish the level of vulnerability of the affected territorial elements.

Each of the four maps proposed in the cartographic series complements each other to address the challenges of relief and assistance in potential flood events. Below, the construction and functionality of each map are developed.

2.4.1. Map of Territory Sectors with Special Rescue Needs (Dependent Population and/or Buildings without Shelter)

The objective of this cartographic tool is to inventory within the flood-prone area those territorial elements whose nature requires the prioritized rescue of the population. This includes populations with characteristics of dependence or buildings that, due to their construction features, lack a sheltered area for seeking refuge on an upper floor.

- Step 1: Selection of Territorial Elements Involved in Map Development For the development of this methodological section, various data sources will be used to identify different elements that require special attention in terms of rescue. These elements are outlined below:
    - ➢ Buildings without Shelter Zones: This includes structures with only one floor level (I), meaning they have only a ground floor and no available rooftop. This corresponds to areas without shelter, as there is no refuge possibility for people living in these buildings during flooding.
    - ➢ Primary and preschools:

    For the identification of schools, the DERA source is used. This spatial database represents all educational establishments in Andalusia.

    1. All educational centers located in the affected population nucleus and those in nearby population nuclei that are functionally and spatially linked are selected.
    2. Only those schools whose attributes meet the characteristics of primary education or preschools are classified and separated.

    - ➢ Other social facilities with dependent populations:

    For cases like nursing homes, special education centers, and centers for diversity functional support, there are no structured geographic information sources in the study case, such as DERA, or databases from which information can be extracted, as is the case with the Cadastre headquarters. Therefore, a photointerpretation investigation through using Google Earth and conducting fieldwork has been conducted for the identified territorial elements to be georeferenced and mapped.
- Step 2: Determination of the degree of isolation due to flooding In the case of buildings without shelter, it is not necessary to measure their degree of isolation since they

are completely flooded and affected. Therefore, they are cataloged with the highest possible vulnerability level. For both primary and preschools and centers for the elderly, special education, or disability assistance, the degree of isolation to which these centers are subjected has been taken into account. Isolation levels are established as follows:

- ➢ Flooded: located within the flood-affected area.
- ➢ Totally isolated: all access points to the centers are flooded, creating a situation of temporary isolation and complete territorial dysfunction during the flood.
- ➢ Partially isolated: some accesses are flooded, resulting in partial isolation and less intense territorial dysfunction.

- Step 3: Establishment of the degree of vulnerability of the affected territorial elements
  - ➢ Very vulnerable: all buildings within the flood-prone area that also lack shelter, as well as all primary or preschools, nursing homes, special education, and centers for diversity functional support within the flood-prone area.
  - ➢ Vulnerable: in this category, centers with total isolation of their accesses due to flooding, located outside the flood-prone area, are categorized.
  - ➢ Moderate vulnerability: centers outside the directly affected flood area, but with some access points cut off, resulting in partial isolation, are considered.

  The complete procedure is summarized in the flowchart in Figure 2.

2.4.2. Map of the Impact on Transport Infrastructure and Vulnerable Areas of Buildings

The main objective of this cartography is to identify and map all buildings with basements within the flood-prone area and also all roadways with underpasses that may be flooded, trapping people and cars inside them. Both conditions are characterized as areas with a special need for assistance in pumping or draining the flooded area during and immediately after the phenomenon.

- Step 1: Selection of territorial elements involved in the map development.

  Basements

  1. All data from the Cadastre in the study area located within the flood-prone area are collected, considering both rural and urban cartography.
  2. Next, all building elements with a basement are selected, i.e., all building elements with subgrade elements, with codes -I, -II, or -III in the Cadastre. In any case, any building containing a subgrade level should be included, as there are buildings with underground parking or other subgrade elements with multiple subgrade levels.
  3. All elements are unified according to their cadastral reference, so that they are unified and displayed on the map.

  Underpasses

  1. Select the sections of the road network affected by the flood-prone area. The road layer from DERA is used. This georeferenced information is geometrically intersected with the flood spots in the flood-prone area.
  2. Once all the roads in the study area have been separated, they must be subjected to fieldwork and photointerpretation through Google Street View tools to detect all underpasses that may exist within the road network. It is important to note that underpasses only exist when the roads are significant and there is a junction of different arcs of the road, which facilitates or narrows down the work. The goal is to detect underpasses prone to flooding, as exemplified in the following image (Figure 3).

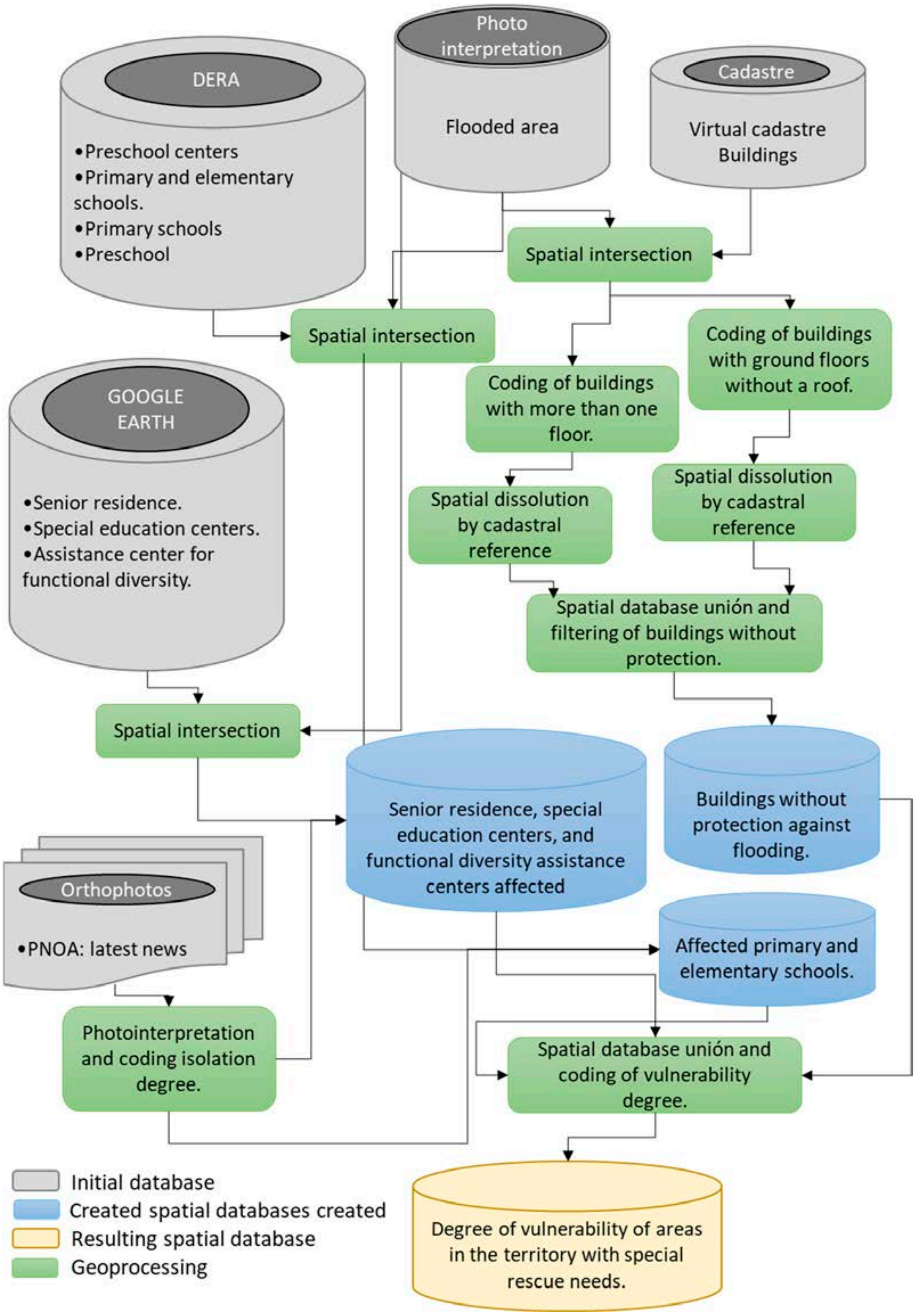

Figure 2. Conceptual diagram of the methodology for the "Territorial Sectors with Special Rescue Needs (dependent population, buildings without shelter)" map.

- Step 2: Selected territorial elements and their degree of impact from flooding.

Basement drainage needs

Basements are classified based on the surface area they occupy. In this case, as a basement's surface area increases, it has a greater water storage capacity. Therefore, with the same amount of water received, a larger basement will have a lower water level, covering less height compared to a smaller basement. A larger basement will fill up more slowly, so its drainage needs are greater. As the flood level reached becomes higher, the damage it causes is more significant. Therefore, it has been decided to classify the importance of basements inversely proportional to their size. The final classification is as follows (Table 1).

Figure 3. Flooded underpasses, fieldwork photos on the left and Google Street View photo on the right (road intersections).

Table 1. Thresholds for classification of drainage needs according to the type of basement.

Basement Size	Drainage Needs:
0 to 100 m^2 (Small basements)	High
100 to 500 m^2 (Medium basements)	Medium
>500 m^2 (Big basements)	Low

However, not all basements have a single level; there may be underground parking lots with a greater number of below-grade levels. In these cases, the difficulties of drainage and assistance to potential affected individuals increase for technical reasons. To address this scenario, a correction factor is applied, as reflected in the following Table 2.

Table 2. Classification of vulnerability based on drainage needs applying the correct factor for below-ground levels.

Drainage Needs				
Low	**Medium**	**High**		
Moderate vulnerability	Vulnerable	Very vulnerable	−1	Below ground levels
Vulnerable	Vulnerable	Very vulnerable	−2	
Vulnerable	Very vulnerable	Very vulnerable	≤3	

Need for drainage of underpasses

The importance of underpasses is closely related to the hierarchy of the road to which the underpass belongs; for a highway or expressway, its importance is vital, while for an isolated road, its importance is much lower. According to this criterion, it has been decided to classify underpasses according to the different hierarchies of roads and paths that may exist, as shown in Table 3 as follows.

- Step 3: Establishment of the degree of vulnerability of the affected territorial elements. Three categories are established: very vulnerable, vulnerable, and moderate vulnerability. The complete procedure is summarized in the flowchart in Figure 4.

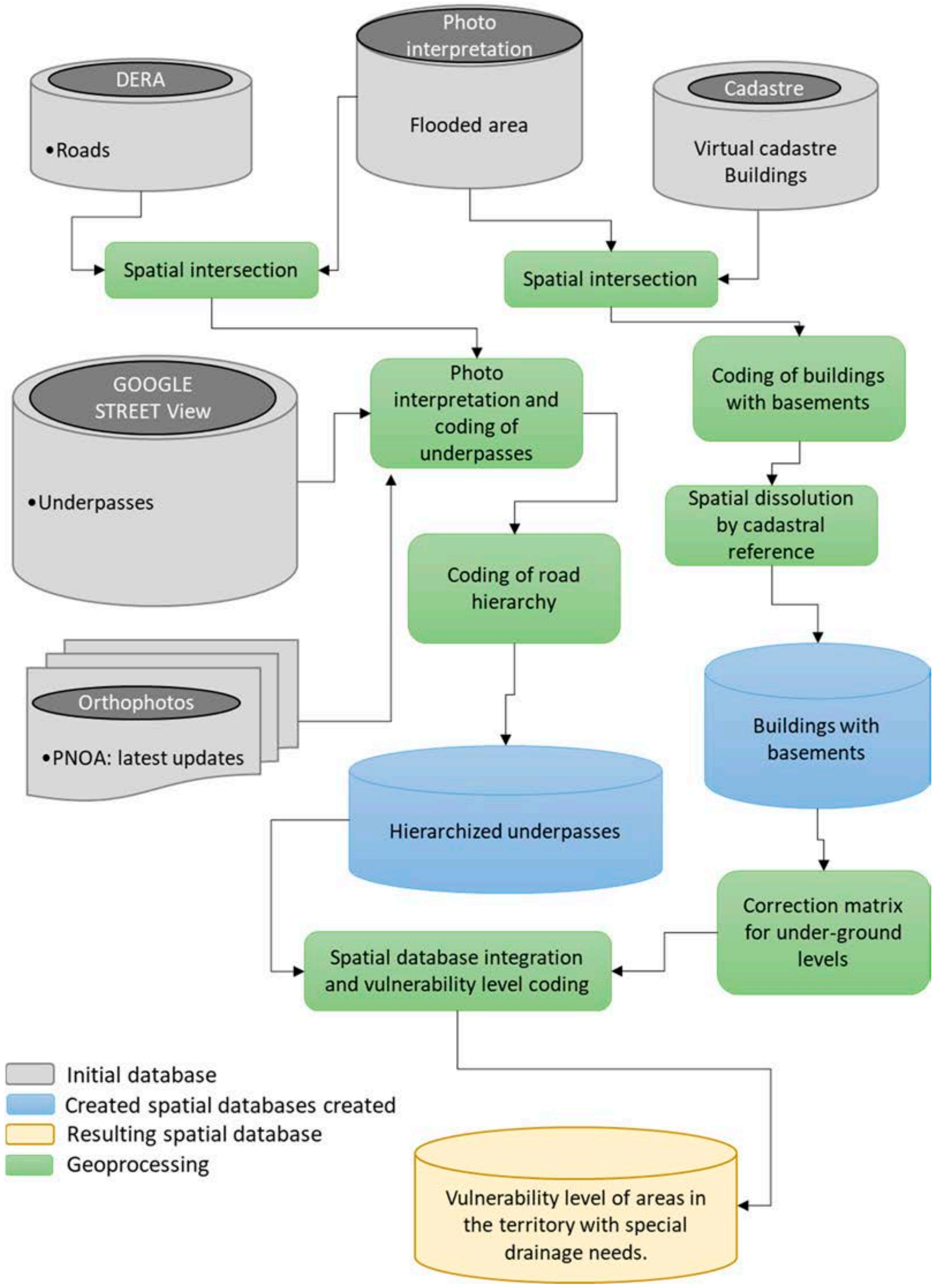

Figure 4. Conceptual diagrams of the methodology for the map "Territorial sectors with special assistance needs (water pumping from basements, underpasses with special drainage needs)".

Table 3. Classification thresholds for drainage needs, according to road hierarchy.

Road Hierarchy	Underpass Drainage Need
Main road	Very high
First order	High
Second order	Medium
Third order	Low

2.4.3. Map of Vulnerability to Possible Disorder and Looting Caused by Flood Phenomena

The main objective of this mapping is to detect commercial establishments, including shopping centers, supermarkets, and retail stores which may be susceptible to looting by the population during a flood event. The mapping aims to identify areas of potential conflict from both the perspective of flood risk and public safety.

- Step 1: Selection of territorial elements involved in the development of the map.

All commercial establishments are selected. Shopping centers are obtained from the DERA source, distinguishing between open and closed shopping centers. Regarding supermarkets and retail businesses, alphanumeric data from the Cadastre and the exploitation of the "Type 14: Construction Registry" through its initial position field No. 71, "Destination Code," corresponding to Commerce (C) and Supermarkets (CSP) are exploited and extracted, according to the coding established by the Cadastre. It should be clarified that in the supermarket category.

On the other hand, stream depths with a return period of 500 years are used to define the degree of danger affecting the different selected territorial elements.

- Step 2: Selected territorial elements and their degree of impact by flooding.

To determine the degree of impact on territorial elements, the following criteria have been established:

Shopping centers (open and closed) or Supermarkets: They are classified based on the square meters of the affected territorial elements. The assumption is that a larger surface area exposes more valuable items inside, making them more attractive to looters due to a greater variety and quantity of merchandise.

To classify them, the surfaces of the centers in the municipality of Malaga have been calculated and subjected to basic statistical measures of mean and dispersion, after removing outliers, obtaining an average of 1500 square meters and a similar standard deviation. This leads to the following classification in Table 4.

Number of retail stores per building: Through the Cadastre, the number of retail stores per building has been obtained. Based on the quantity of businesses within the buildings, they have been categorized, taking into account that the average value for the study area is two stores per building. After subjecting the data to the removal of outliers, the buildings are proposed to be classified as follows in Table 5.

Classification of the depths: The territorial elements affected by flooding are classified according to the depth of the stream that affects them (Table 6), considering that the same building, due to its dimensions, can be affected by different levels of depth. To address this situation, the building is assigned the depth of the greatest depth it is affected by and, therefore, the highest danger condition it is affected by.

Table 4. Classification thresholds for supermarkets and shopping centers.

Type	Surface (m^2)	Classification
Shopping centers and supermarkets	0–1500	Small
	>1500–3000	Medium
	>3000	Big

Table 5. Classification thresholds for retail stores per building.

Number of Businesses Per Building	Classification
≤2	Medium
3–4	Considerable
≥5	High

Table 6. Categorization of water depth.

Draft (m)	Category
0–0.2	Medium
>0.2–0.5	High
>0.5	Very high

- Step 3: Establishment of the degree of vulnerability of the affected territorial elements.

For the final establishment of the degree of vulnerability, the following correlation matrix (Table 7) is generated, where the depths (stream depth) by which the territorial elements (shopping center or supermarket and retail stores per building) are affected are related.

Table 7. Flood vulnerability degrees in shopping centers or supermarkets.

Surfaces of Shopping Centers and Supermarkets				
Small	**Medium**	**Big**		
Vulnerable	Very high vulnerability	Very high vulnerability	Very high	Draft of the affected buildings
Moderate vulnerability	Vulnerable	Very high vulnerability	High	
Moderate vulnerability	Moderate vulnerability	Vulnerable	Medium	

In addition, the relationship between the number of retail stores per building and the depth of buildings is considered (Table 8).

Table 8. Vulnerability degree.

Number of Retail Businesses Per Building				
Medium	**High**	**Very High**		
Vulnerable	Very high vulnerability	Very high vulnerability	Very high	Draft of the affected buildings
Moderate vulnerability	Vulnerable	Very high vulnerability	High	
Moderate vulnerability	Moderate vulnerability	Vulnerable	Medium	

The complete procedure is summarized in the flowchart in Figure 5.

2.4.4. Map of Increased Travel Cost for Rescue and Assistance Systems

The main objective of this cartography is to obtain a simulation of response times (isochrone or arrival time maps) for rescue and assistance systems (firefighters) in areas affected by flooding. Additionally, it addresses how the depths of the flooded areas (water depths) should be simulated so that network analysis models incorporate the segments that emergency services can no longer access, creating barrier zones in the model and, therefore, being the most vulnerable in a rescue situation.

- Step 1: Selection of territorial elements involved in the map's development.
  Firefighters: All fire stations within the municipality of the study area, as well as those in nearby municipalities that can provide coverage to the area, are located. For this, equipment located within a radius of 30 km from the flooded area has been considered. The databases used are those found in DERA. It is crucial, when selecting rescue services, to verify that they are not rendered unusable by the flood itself so that they can provide assistance. In the case study addressed in the research, all services are located outside the flood zone and, therefore, are operational.
  Road network: It is necessary to obtain a road network containing the structure of arcs and nodes to establish correct connectivity and simulate network analysis. The necessary information is available in the Digital Street Map of Andalusia (2023). Cost of

travel calculations (impedance) within the network are performed to simulate network analysis. In this case, it is necessary to consider that what is sought is response times, i.e., how much time each agent spends traveling through the road network to access the flooded area. Therefore, travel costs are expressed in seconds or minutes, and the following formula is used for this:

$$\text{Impedance min} = \text{Length (m)} \times 60\ \text{speed (km/h)} \times 1000 = \text{Length} \times 0.06/\text{speed (km/h)}$$

This formula allows obtaining the time it takes for an agent to travel through each arc of the road network, so that when simulating network analysis, the optimal route in time is obtained, accumulating the total cost of reaching the flooded area.

Water depth (drafts): In this case, and after conducting personal interviews with the firefighters of the "Pirámides de Málaga" to establish the maximum height at which rescue trucks can access without resorting to inflatable boats, it is determined to be 0.8 m of draft. Beyond this threshold, it is not safe due to the loss of stability and the possible buoyancy of the trucks, establishing the threshold or barrier zones for network analysis simulation. Therefore, the spatial database of drafts in the flooded area is used and incorporated into the network analysis simulation.

- Step 2: Selected territorial elements and their degree of flooding impact. To establish the different degrees of territorial impact, it is necessary to first generate a simulation of network analysis. To simulate network analysis and obtain isochrone maps, it is necessary to program the GIS with the following parameters:
  - FACILITIES: These are the starting points from which the network analysis is executed, in this case, the different fire department agents providing rescue and assistance.
  - NETWORK: This is the vital geometric support through which the program establishes calculations and weights; these can be done based on distances or by some specified cost.
  - IMPEDANCE OR TRAVEL COST: The system calculates what the operator programs, meaning it can calculate different types of costs. For this work, travel or displacement time is used, which has already been explained earlier in terms of how it is calculated and is based on the average speeds listed in the following Table 9.
  - BARRIERS OR COST INCREMENTS: Anything that hinders the movement of vehicles on the road network or increases their travel cost for some reason. In this work, impedance within the flooded area has been considered, so as the water depth increases, it is incrementally factored in, using the following Table 10:

Table 9. Average maximum speeds by road type.

Road Type	Maximum Speed
Urban road network	40 km/h
Roads and bypasses	80 km/h
Expressways and highways	100 km/h

Table 10. Thresholds of stream depth and employed multiplier cost.

Depth of the Current (Draft)	Multiplier Factor for Normal Displacement Cost
0–80 cm	2
>80 cm	1000 [1]

[1] Oversized displacement cost to ensure the blockage of access for emergency and relief transportation means.

Multiplied by an exaggerated number to delimit the inaccessible area for rescue and assistance vehicles on land.

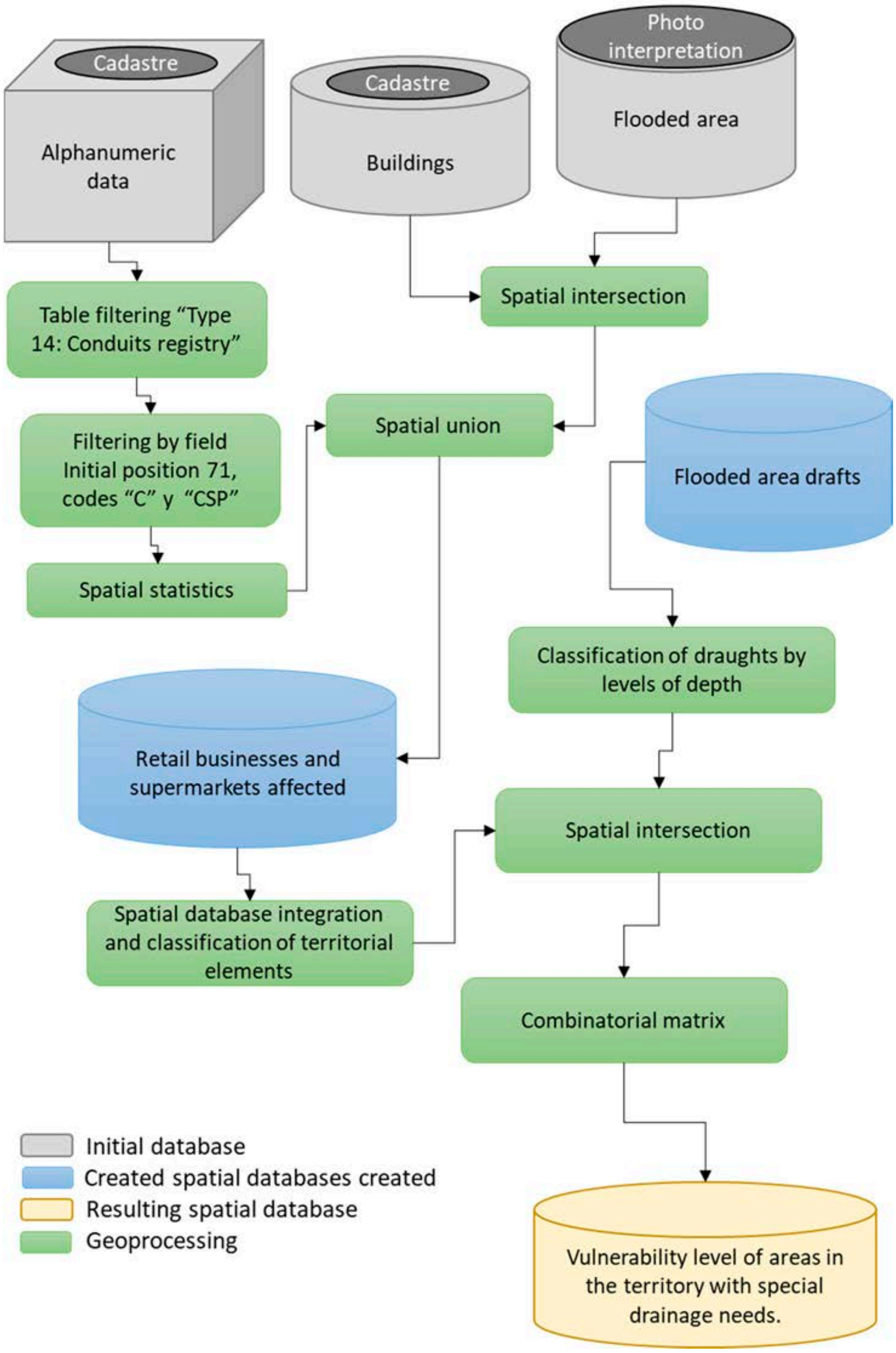

Figure 5. Conceptual diagram of the methodology for the map "Territorial Sectors with Special Surveillance Needs During the Crisis (Disorder, Looting)".

- Step 3: Establishment of the degree of vulnerability of the affected territorial elements.

To determine the degree of vulnerability, two network analysis simulations were conducted and compared, following these steps:

A network analysis model without the flooding phenomenon, obtaining a simulation of normal response times.

Subsequently, a network analysis was conducted with the flooded areas included and the additional costs that entails, resulting in another network analysis, in this case with different results from the previous one and with higher travel costs.

The difference between the network analysis with the flooded areas and the normal network analysis was calculated, generating a zone of differences in response time, i.e., increases in costs due to flooding. These time increments are used to determine the degree of vulnerability. For the classification of the results and the assignment of vulnerability degrees, tangible and recognizable time values have been established, which in this case are those corresponding to 60 s (1 min). Intervals based on these values are shown in Table 11.

The complete procedure is summarized in the flowchart shown in Figure 6.

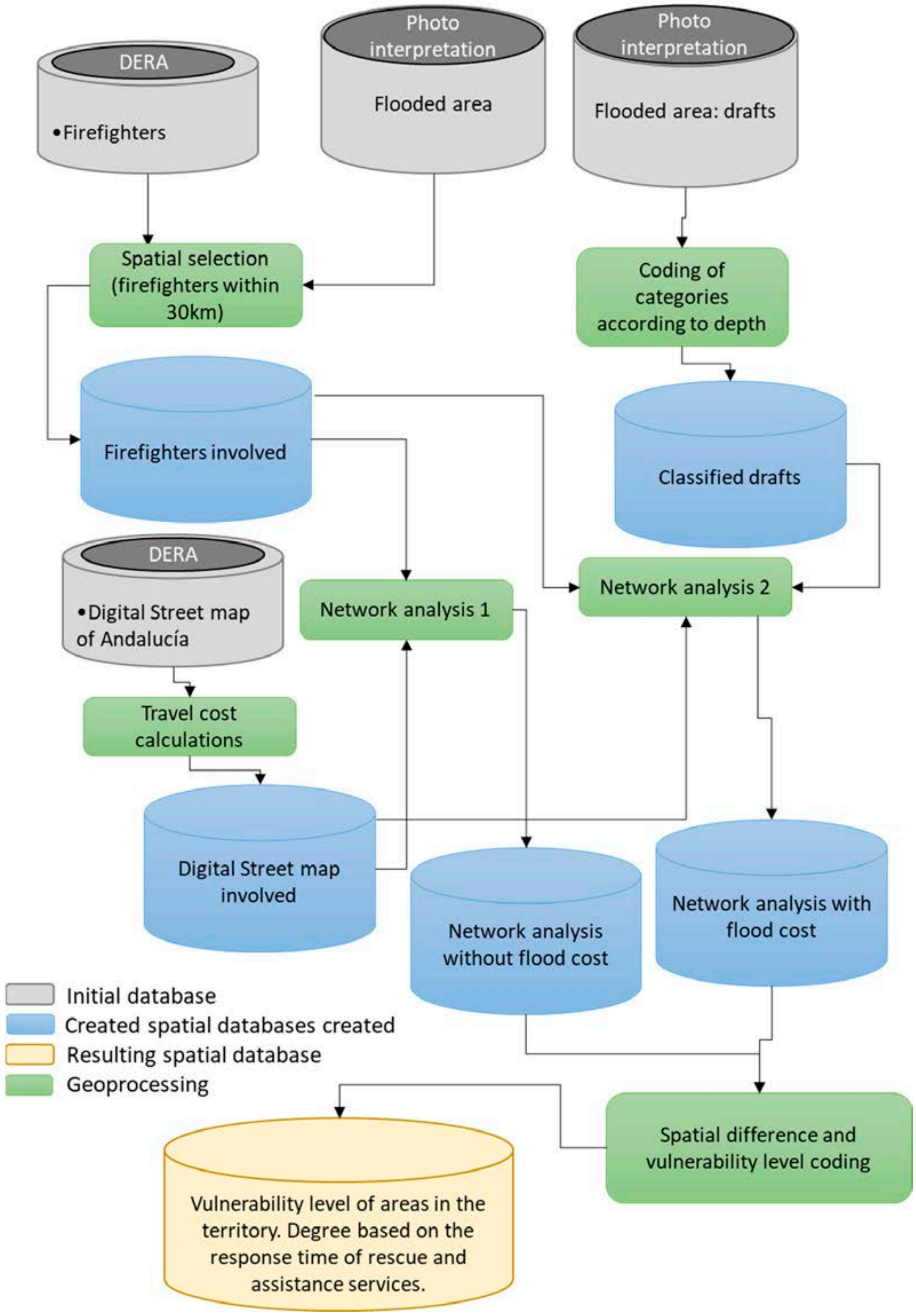

Figure 6. Conceptual scheme of the methodology for the map "Accessibility of emergency and assistance services to sectors of the territory with the highest potential needs".

Table 11. Degree of vulnerability.

Increases in Response Times Due to Flooding Phenomenon (s)	Classification
0–60	Moderate vulnerability
60–120	Vulnerable
>120	Very vulnerable

3. Results

All the results presented in this research refer to a catastrophic event that occurred on 25 January 2020. The flood extent depicted in the maps is the result of a fusion of the mapping of the flooded area, through photointerpretation processes, and fieldwork for this catastrophic event, with the hypothetical 500-year return period mapped through existing hydrological-hydraulic study.

3.1. Mapa de los Sectores del Territorio con Especiales Necesidades de Rescate

The cartography (Figure 7) allows detecting the buildings that would require priority attention.

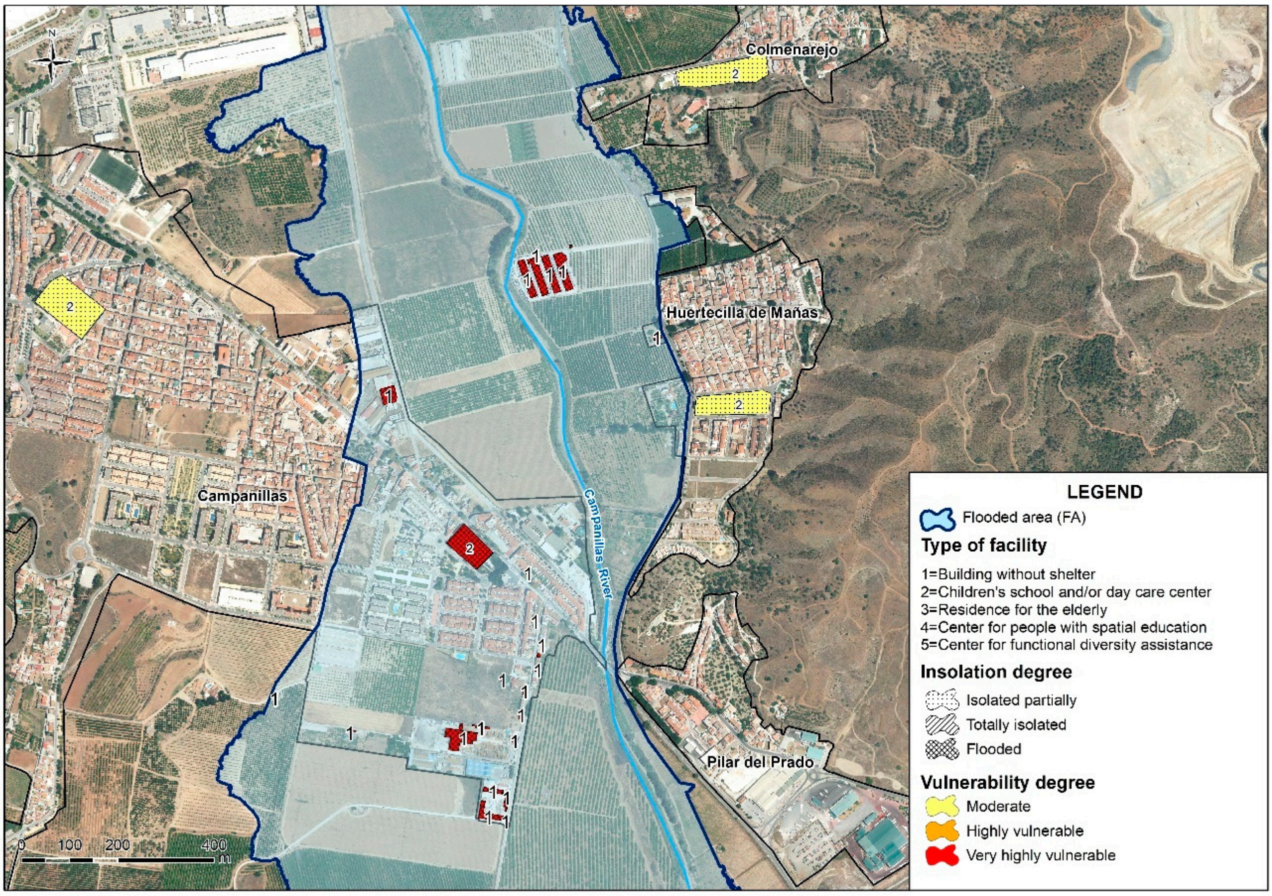

Figure 7. Comprehensive map of the sectors of the territory with special rescue needs.

The highest degree of vulnerability is confined to the flooded area of the Campanillas River, affecting the right bank of the Campanillas nucleus and, on its left bank, a series of industrial hangars in the secondary nucleus of Huertecilla de Mañas. There is a prevalence of areas without shelters, associated with scattered peri-urban residential environments, consisting of old constructions, to the south of the urban center. Notably, there is an impact on an educational center with very high vulnerability, located in the city center itself. Outside the flooded area, three educational centers are in a state of moderate vulnerability, affected by the partial loss of their accessibility and, consequently, the speed of response to their user population.

3.2. Map of the Territory Sectors with Special Assistance Needs Based on Transport and Storage Infrastructure and Buildings

To analyze urbanized areas most vulnerable to the flood hazard concerning their impact on strategic infrastructure, a zoom focused on the Campanillas nucleus is presented (Figure 8).

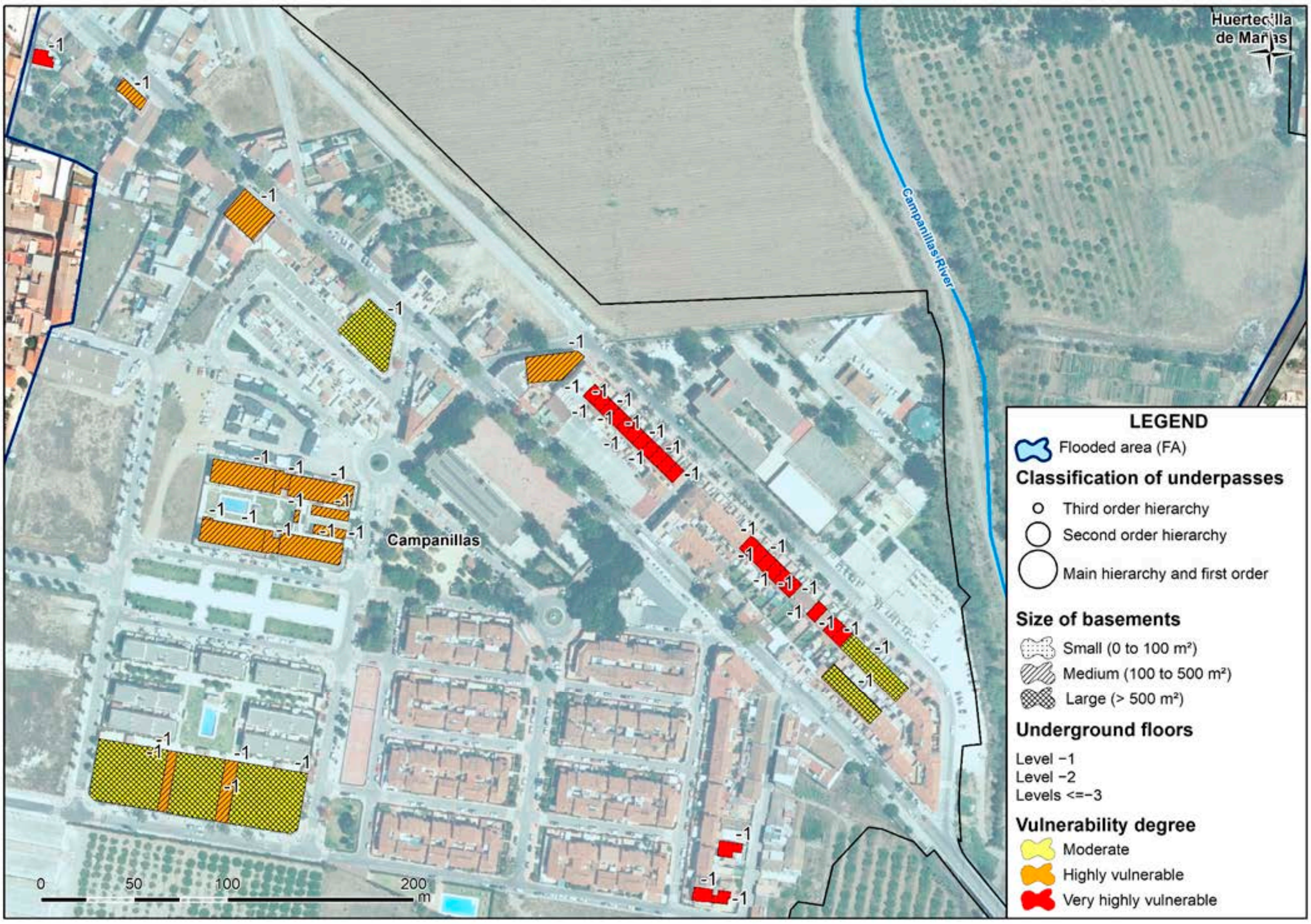

Figure 8. Example of territory sectors with special assistance needs based on transport and storage infrastructure and buildings.

The impact on a significant portion of the buildings in the flooded area is recognized due to the presence of basements. These are primarily residential buildings, with an intercalated and random distribution of their vulnerability level based on the size of the basements, which depends on the construction model, ranging from individual basements for each property to parking areas that occupy the equivalent surface of entire cadastral plots. The most vulnerable situations are identified in attached single-family homes.

In the study area, there are no underpasses, so it does not affect the interpretation of the vulnerability of road infrastructure.

3.3. Map of Territory Sectors with Special Surveillance Needs during the Crisis (Disorder, Looting)

The result of identifying areas with special surveillance needs is shown in Figure 9.

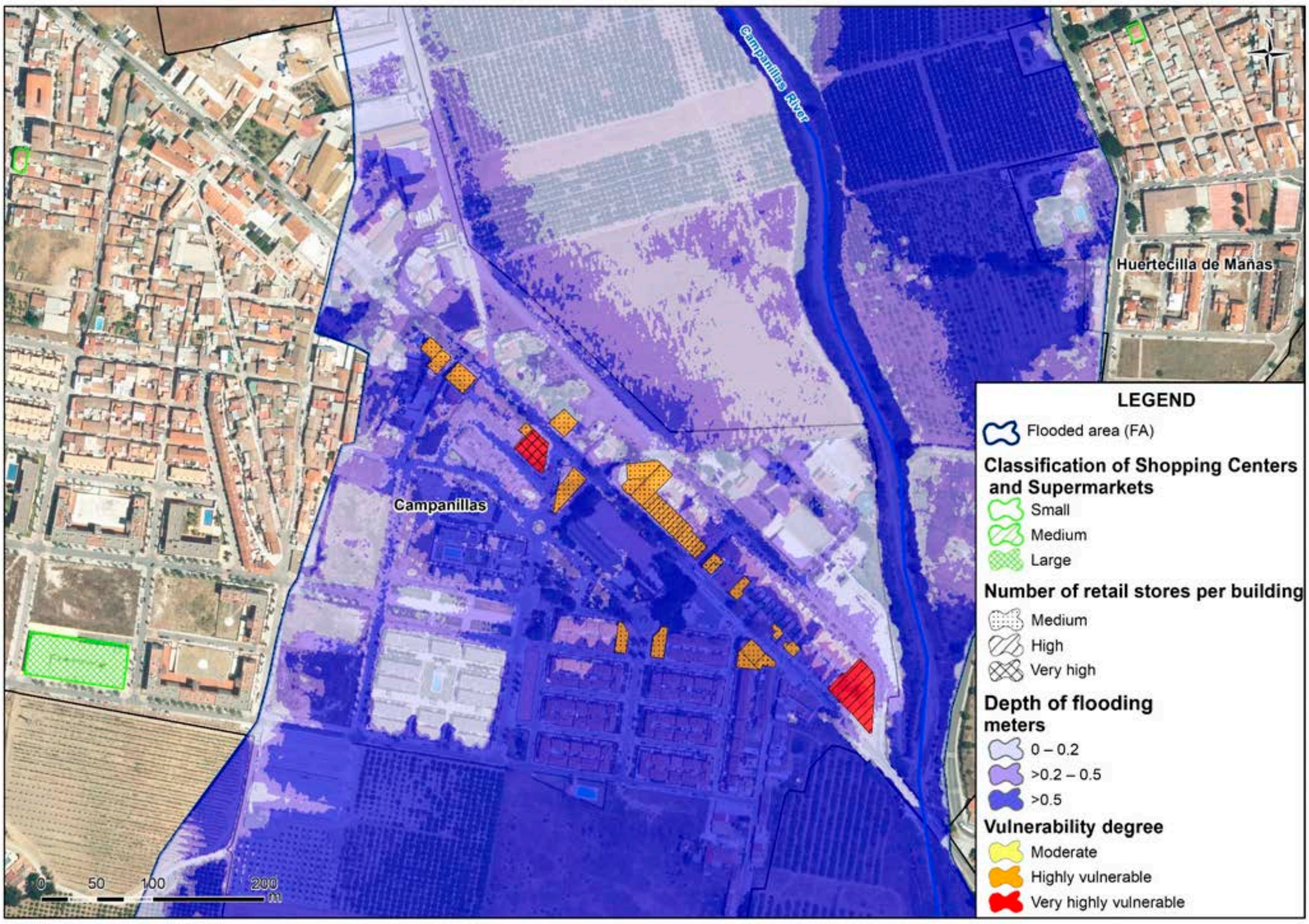

Figure 9. Sample of the map of territory sectors with special surveillance needs during the crisis (disorder, looting).

In the case study, large commercial areas are outside the flooded area caused by the overflow of the Campanillas River, so they do not represent an affected territorial element in our study areas. However, a series of commercial premises in the Campanillas area are affected, with their vulnerability mainly based on the number of businesses per building. The impact of commercial activity is consistently found at "high" and "very high" depth levels. The linear pattern of commercial activity, closely related to the main avenue of the city, is particularly noteworthy.

3.4. Map of Increased Travel Cost for Rescue and Assistance Systems

As observed in Figure 10, the flooded area extends over a partially orthogonal road network, converging onto a main road that serves as a connecting axis with the core of Málaga.

Precisely, this road is affected by a higher water depth level on the right bank of the Campanillas River, along with some of the surrounding roads, resulting in its classification as an area with a very high vulnerability level, with an increase in response time of more than two minutes compared to a normal situation. The vulnerability gradient follows a southeast-northwest axis, parallel to the river's trajectory, and is only interrupted where the urbanized space ends. Another area where a higher water depth of the current is estimated is on the left bank of the river, in the area between the secondary core of Huertecilla de Mañanas and the river, although with minimal impact on urbanized areas.

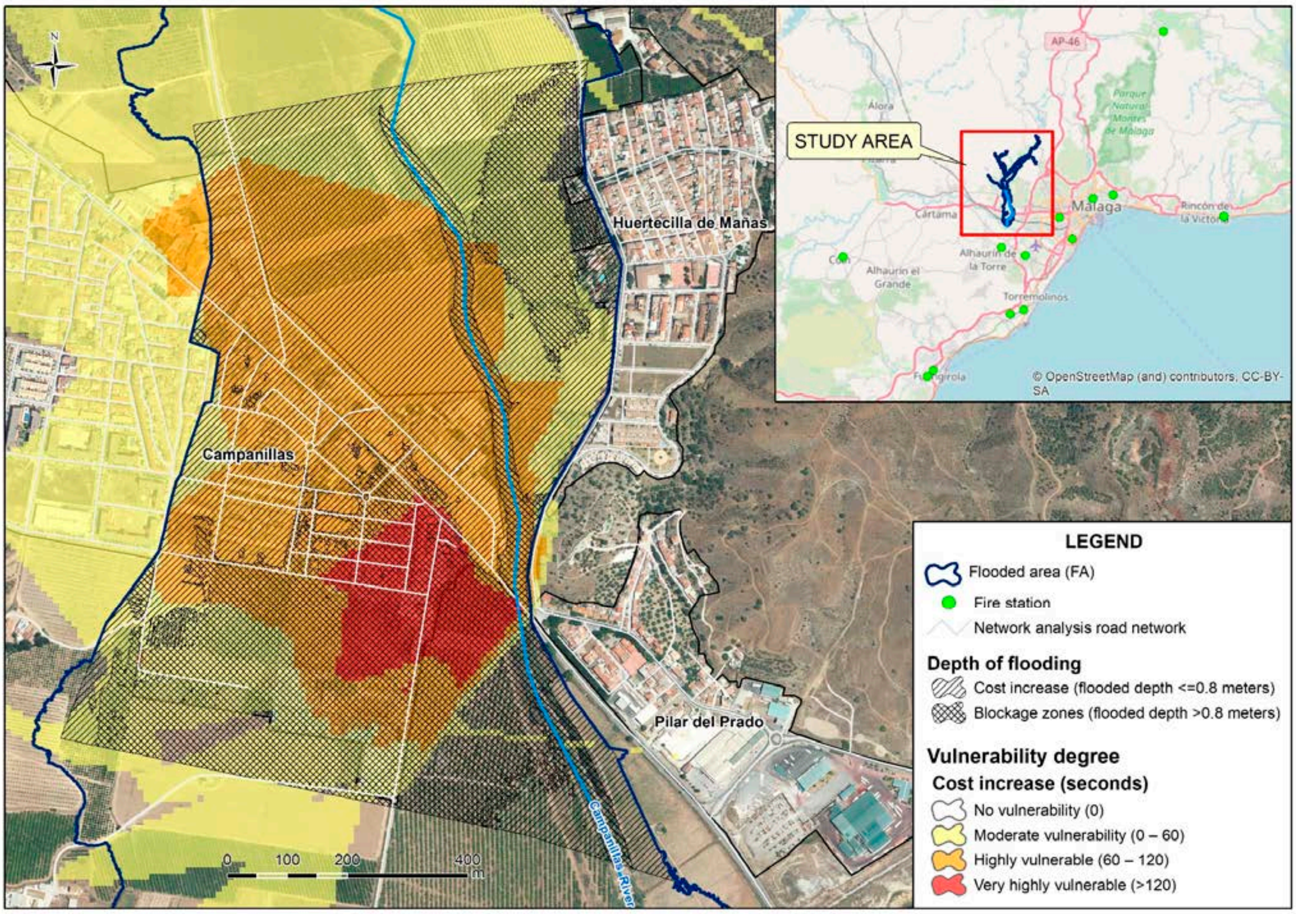

Figure 10. Comprehensive Map of Increased Travel Cost for Rescue and Assistance Systems.

4. Discussion

The map series allows simulating the impact of floods on rescue and assistance operations, serving as a tool for designing technical documents such as flood risk management plans. The scale is highly detailed, enabling the identification of vulnerable points that require improvement, recommended routes, and means for carrying out assistance and evacuation tasks at the scale of individual constructions. The four-map series is organized for complementary interpretation, identifying the vulnerability of the population, buildings, facilities, and infrastructure.

The map of sectors of the territory with special rescue needs (1) allows locating where the most dependent population is or where highly vulnerable public facilities are to flood events. Distinguishing refuge areas refines the degree of vulnerability in flooded areas.

The map of transport infrastructure and vulnerable areas of buildings (2) makes it possible to identify buildings and infrastructure with spaces in which people, animals and vehicles can become trapped, such as basements and roads with subways within the flood zone. Its detection allows the zoning of those areas with a special need for assistance in pumping or draining the flooded area.

The vulnerability map in the face of potential disorder and looting caused by flooding phenomena (3) allows us to identify commercial establishments, including shopping centers, supermarkets, and retail stores that, in the event of a flood, may be subject to looting by the population. The depth of the current allows for a deeper understanding of the severity of the flood's impact, which can affect how looting can occur and the level of damage it can cause to the resources stored in commercial establishments.

The last map, showing the increase in the cost of deployment for rescue and assistance systems (4), serves a dual purpose. On one hand, it estimates the response times of rescue and assistance systems (firefighters) to areas affected by the flood, allowing the detection of possible delays of up to more than two minutes compared to the usual intervention time. On the other hand, it also provides a simulation of the depths of the more realistically flooded areas so that network analysis models incorporate segments that emergency services can no longer access, creating barriers to the model.

From a methodological standpoint, choosing an appropriate number of intervals can influence the interpretation of data and the communication of the intended information. Thus, the proposal to create a series of maps has required specifying how the measured phenomena are graphically represented. The results of the variables, expressed in interval scales, are presented in groups ranging from two to four categories to optimize result interpretation, providing clear legibility that highlights territorial patterns and allows for comparisons between case studies.

The map of the impact on transport infrastructure and vulnerable areas of buildings (2) identifies buildings and infrastructure with spaces where people, animals, and vehicles can become trapped, such as basements and roadways with underpasses within the flood zone. Detecting these areas allows zoning those with special needs for pumping or drainage in the flooded area.

There are few works that specifically develop models simulating the impact of a natural disaster on rescue and assistance tasks. In this case, it aligns with Febrina [61], who, after conducting a systematic literature review, identified deficiencies in the current emergency operations system in the event of floods, such as the lack of an integrated information system and insufficient collaboration among stakeholders.

There are some previous experiences with a similar objective to the present research. For example, the research by Sortino and Perles (2017) [46], Coles et al. (2017) [47], Yin, Yu, and Liao (2021) [48], and Zhang et al. (2022) [49] pursues a similar objective to the present investigation, developing methods that combine flood modeling with network analysis to assess intra-urban accessibility by emergency services during flood events. In contrast to previous proposals that focus on modeling the accessibility of emergency services during the disaster to the affected territory as a whole, selecting some facilities as in the case of Coles et al. (2017) [47], the present research identifies the location of the most vulnerable population, buildings, and infrastructure that require priority attention.

Unlike the proposals of Godoy and González (2019) [51], which consider the use of Big Data from social media information in the design of protocols for responding to this type of natural disaster, such information has not been utilized, although it could generate added value. It can enhance the identification of the most vulnerable areas based on population concentration and flood impact. However, these datasets may not cover regions with data scarcity, where few people use social media, or in areas with limited mobile signals where people cannot use their smart devices to report infrastructure failures. Additionally, there is a user privacy issue, as the accuracy of such information allows for exact location identification without implicit consent.

In the present study, qualitative methods such as expert interviews in managing the effects of natural disasters, as included in the proposal by Hassanzadeh and Nedovic-Budic (2016) [62], were not introduced. Interviews and surveys provide nuances in understanding the impact of natural disasters but slow down the methodology development process and limit its applicability to other study areas, besides potentially generating contradictory interpretations.

Rahman et al. (2021) [53] propose, as an addition to hazard mapping, a Humanitarian Aid Information System (HAIS) to enhance emergency assistance to flood victims. In the same vein, the cartographic methodologies presented here go a step further, providing accurate information about the most vulnerable areas in need of rescue and assistance. This type of mapping allows for better organization and prevention in flood risk management and integrating these cartographic tools into Humanitarian Aid Information System (HAIS) models would significantly enhance the method and improve decision-making.

Regarding the risks of public disorder and looting, research has been conducted on the apparent trend of increased crime and looting in areas affected by natural disasters, with varying conclusions [54–56]. Regardless of whether this risk increases or not, it is an existing risk that must be addressed. This study provides a novel diagnosis of specific vulnerable areas that require priority surveillance, taking into account factors such as the size and number of businesses, as well as the depth of the current.

Finally, it is essential for these cartographic methodologies to transcend the realm of flood risks. In the current conditions of climate change, it is urgent to apply these methodologies to all areas that could potentially be susceptible to flooding events, allowing for a more comprehensive and preventive risk management approach, thereby preventing the loss of human lives and material goods. The methodologies designed in this research can be of great interest when combined with other studies, such as the simulation of potential floods. In this line, Kharazi and Behzadan (2021) [57] employ deep neural network algorithms to analyze street photographs in flooded areas, along with other algorithms for edge detection and water depth detection. On the other hand, Oliva and Olcina (2022) [58] provide emergency mapping based on the analysis of emergency calls, allowing for a deeper understanding of the functioning of the territory and the identification and typology of problems arising from these catastrophic episodes.

The methodology adds value by proposing an original and innovative method based on the development of detailed mapping to address specific vulnerability issues arising from the flood risk. It provides a differential and widely applicable approach for both risk management and prevention through planning processes. Specifically, this methodology facilitates the planning and intervention of relief and assistance actions against the flood risk.

The main limitations of the proposed methodology are based on the continuous dependence on extreme rainfall data that lead to flooding, conditioning the territorial elements that must be studied and intervened. In the current conditions of climate change, the increase in storms and their intensity requires the continuous revision of flood-prone areas in hydrological-hydraulic studies, including pre-existing maps. A proposed improvement is to generate broader territorial zones susceptible to flooding and apply the proposed methodology across the entire territory. This enhances safety but poses a limitation as it requires an increase in the study area, entailing implications in terms of human and economic resources for public administrations.

One aspect that is challenging to incorporate into this type of cartography is the duration of a flood episode, which in reality is a crucial factor in aspects such as the need to expand emergency operation procedures or estimate shortages of essential services and supplies. To address such problems, future research directions suggest experimenting with different scenarios based on the intensity of the flooding. This would involve creating multiple versions of maps, such as the one depicting areas of the territory with special rescue needs, allowing for the identification of where the population is located (Figure 7), and the one showing the increase in the cost of deployment for rescue and assistance systems (Figure 10).

5. Conclusions

Vulnerability assessments have always played a secondary role within flood risk studies, with a considerable emphasis on hazard analysis. The research presented here addresses a specific vulnerability issue related to rescue and assistance actions. It emphasizes one of the most critical issues that should be the focus of many studies on flood risk: the preservation of human life. This research prioritizes the creation of cartographic tools that support decision-making and intervention to safeguard human lives by simulating the response times of rescue and assistance systems. It also focuses on the protection of people's property.

The study introduces a model that simulates the impact of floods on rescue and assistance efforts, serving as a tool for designing technical documents such as flood risk management plans and specific local action plans. The research is detailed, allowing for the proactive identification of vulnerable points that need improvement, recommended routes, and means for carrying out assistance and evacuation tasks at the scale of individual building units.

The first map (Figure 7) is a crucial tool for prioritizing areas of the territory that require intervention. It highlights areas without safeguards for the general population and vulnerable groups in particular (such as children and dependents). The second map (Figure 8) distinguishes buildings and infrastructure with special drainage needs due to their underground levels, where the risk of loss of human lives and property is particularly high. The vulnerability map in the face of possible disorder and looting caused by flooding events (Figure 9) identifies commercial establishments that may be vulnerable to looting by the population during a flood. Developing this cartography could be of interest in formulating protocols for preserving essential consumer products during a flood episode. In the last map (Figure 10), the increase in the cost of deployment for rescue and assistance systems is considered to establish the best alternative supply routes. The proposed cartographic approach can also be developed to include the analysis of shelters and accommodations for the evacuated population.

The cartographic tools proposed in this research are considered timely and necessary for their integration into flood risk management plans deployed by the government of Spain, as transposed into Spanish legislation through Royal Decree 903/2010 in relation to Directive 2007/60 on the assessment and management of floods. Specifically, these methodologies aim to improve vulnerability control in areas classified as APSFR.

Looking ahead, in the current context of climate change, floods are a potential threat to any territory, not confined to areas classified as flood-prone. Future research directions involve extending the proposed cartography to any territory, focusing on local territorial and urban planning. The incorporation of these evaluated instruments at the highest level of detail significantly enhances the improvement of flood risk emergency plans in Andalusia. These plans, crucial for all local administrations, must be continuously developed and updated for implementation when a flood event occurs.

Author Contributions: J.F.S.B. designed the conceptual approach; designed and developed the methodology; prepared the database and revised and approved the final version of the manuscript. J.F.S.B. and H.C.N. analyzed the data, interpreted the results and were involved in writing the manuscript. H.C.N. was involved in the compilation of previous and current research. M.F.M.R. revised and approved the final version of the manuscript. All authors have read and agreed to the published version of the manuscript.

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