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A GIS based urban flood risk analysis model for vulnerability assessment of critical structures during flood emergencies

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Abstract

Risk analysis has become a priority for authorities and stakeholders in many European countries, with the aim of reducing flooding risk by considering the priority and benefits of possible interventions. Within this context, a flood risk analysis model was developed in this study that is based on GIS, and integrated with a model that assesses the degree of accessibility and operability of strategic emergency response structures in an urban area. The proposed model is unique in that it provides a quantitative estimation of flood risk on the basis of the operability of the strategic emergency structures in an urban area, their accessibility, and connection within the urban system of a city (i.e., connection between aid centres and buildings at risk) in the emergency phase. The results of a case study in the Puglia Region in Southern Italy are described to illustrate the practical applications of this newly proposed approach. The main advantage of the proposed approach is that it allows for the defining of a hierarchy between different infrastructures in the urban area through the identification of particular components whose operation and efficiency are critical for emergency management. This information can be used by decision makers to prioritize risk reduction interventions in flood emergencies in urban areas.

1 Introduction

Urban flooding is currently a significant problem in many cities due to the significant concentration of people and infrastructure exposed to risk. There is widespread recognition that urban disasters due to, for example, floods, are increasing, resulting in escalating human and economic losses (Johannessen et al., 2014). Between 1975 and 2002, floods due to drainage problems, flash, and river floods accounted for 9 % of all deaths from natural disasters, with about 175 000 fatalities worldwide (Jonkman, 2005), and affecting more than 2.2 billion people (Jonkman et al., 2005). From 2000 to 2006, water related disasters killed more than 290 000 people, affected more than 1.5 billion

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people, and inflicted more than US$ 422 billion in damage (United Nations World Water Assessment Programme, 2009). In light of this, there has been increased emphasis on “living with floods” (Institute of Civil Engineers 2001), “preparing for floods” (ODPM, 2002), “making space for water” (Defra, 2004) and “living with risk” (UN/ISDR, 2004). This emphasis reflects in part the perception that a risk management paradigm is more complex than a traditional standard based approach since it involves “whole systems” and “whole life” thinking. However, this is also its main strength and a prerequisite for more integrated and informed decision making in the face of flood emergencies.

It can be seen that flood forecasting, warning, planning and other non structural measures are increasingly being seen as critical for reducing flood risk. As part of this, there is a need to refine methods to estimate flood risk, with particular attention on the management of the emergency. The majority of the literature on risk analysis models (FLEMO model (Apel et al., 2009; Vorogushyn et al., 2012); HAZUM MH (FEMA, 2009; Scawthorn, 2006); DAMAGE SCANNER MODEL (Jongman et al., 2010); MULTI-COLOURED MANUAL (Penning-Rowsell et al., 2005)) placed economic values on flood risk in order to help planners in the estimation of the benefits of flood protection measures in terms of prevented flood damage. This traditional approach does not take into account the dynamic nature of the urban system with its interconnections and relationships among elements, and hence the performance of strategic structures and infrastructure in cases of emergency. Hence, residual damage assessment is not considered in these traditional risk analysis models. For example, the inaccessibility of inundated roads during emergency management activities could cause indirect damage to the operability of strategic structures such as hospitals or fire stations.

Other studies have dealt with specific aspects of emergency management, as well as identification of safest access routes (Dalziell et al., 2001), or evaluations of the number of unassisted people (Taylor et al., 2006). These studies have provided useful contributions to the analysis of road accessibility (Franchlin et al., 2006) and reliability (Lhomme et al., 2013); however, these studies did not consider emergency management of the whole system (i.e., quantification of the contributions of each structure or

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infrastructure in the maintenance of the performance of the rescue, and also its degree of vulnerability). On one hand, the above papers have not evaluated the degree of physical damage of road networks and buildings due to natural events. On the other hand, although these papers analyzed the accessibility and operability of road networks, they did not consider their typology (e.g. main roads, local roads, etc.) and the contribution of strategic structures (e.g. hospitals, civil protection centres, etc.) and hotspots (industries, resorts and hotels) in the system.

Menoni et al. (2010) attempted to evaluate the systemic vulnerability of an urban system by using a model to assess the vulnerability due to lifeline failures (i.e., road system, water system, gas system, power system, etc.) for earthquake events. They proposed a regional scale model that concentrates on the assessment of the large number of indirect damages to define where to engage in more detailed studies on vulnerability analysis (i.e. the cities and towns most affected by indirect damages evaluated through the model). This study highlighted the need to quantify, through spatial analysis, the contribution of infrastructure (e.g., road networks) and structures (e.g., hospitals, industries, schools, etc.) in a city system to support decision making regarding the type and location of the mitigation interventions.

Pascale et al. (2010) and Sdao et al. (2013) focused on the evaluation of dependences and interdependences in an urban system in the case of floods and/or landslide events by studying the vulnerability, in terms of physical damage and functional relationship between operative centres and industries at risk or roads and private buildings at risk, etc., due to landslide or flood events. However, they did not analyze the spatial accessibility and operability relationships within the urban system based on the path connections and analysis, which is very important during the emergency phase of a flood event (i.e. during and immediately after a flood).

The proposed study overcomes the limitations of the approaches and models discussed above by integrating the concepts and methods of the previously mentioned studies, based on an accessibility and reliability analysis of the road network, within a systemic flood vulnerability analysis. The proposed model couples the flow approach

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(Dalziell et al., 2001; Franchlin et al., 2006), based on flow and functionality of paths (i.e. comparison between the flow during normal working conditions and under disruption), with an approach based on topology (Lhomme et al., 2013) that considers structural analysis (i.e. it considers the number of alternative paths to the disruptions of one or several paths). In addition, the dependences and interdependences (Sdao et al., 2013) between buildings at risk (e.g. schools, private building, industries, etc.) and rescue centres (e.g. hospitals, fire stations, etc.) are evaluated with a spatial analysis approach based on flows and topologies in order to assess in an efficient way the vulnerability of the system during the emergency phase. Finally, the accessibility and operability model for vulnerability assessment of strategic elements in the emergency phase of a flood, is also integrated in a flood risk analysis model for urban areas, based on quantitative methods of previous and commonly used literature studies (USACE, 2008; Department of Homeland Security, 2011; Escuder-Bueno at al., 2012).

The proposed model for flood risk assessment in urban areas provides a comprehensive and quantitative evaluation of direct damage to inform decision-making in terms of loss of life and structural and economic damage. Secondly, an innovative model was developed for investigating the relationships of spatial accessibility and functional/operability failure (i.e. the performance to guarantee victim assistance and rescue activities) in a complex urban system during the emergency phase. Concurrently with the occurrence of physical and functional damage to urban areas, the operability of the strategic emergency structures, their accessibility and connection within the city, or in general the urban area, is an important priority in emergency management. The integration of the two models within GIS aims to assess the direct and indirect damage of a flood event in order to understand the strengths and fragilities of a particular urban area. The proposed approach defines a hierarchy between the various structures (e.g., hospitals, fire stations, town halls, schools, industries, etc.) and infrastructure (e.g., main roads, secondary and local roads, bridges, etc.) through the identification of those structures/infrastructure whose operation and efficiency are critical in emergency

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management. In this manner, the proposed model can aid in prioritizing the decisions on the type and site of flood mitigation strategies that should be planned.

In Sect. 2, the overall GIS framework is outlined, in Sect. 3 the validation and results on a real flood event are described, in Sect. 4 the results are provided, and the overall discussion and conclusions are provided in Sect. 5.

2 Overall framework

This section describes the integration of a model that assesses the degree of accessibility and operability of strategic emergency response structures within quantitative flood risk analysis in urban areas with the aim of prioritizing actions for flood risk reduction (Fig. 1). Section 2.1 summarizes the proposed GIS methodology for the rapid appraisal of the consequences for an urban population, which can also be used to assess the direct structural and economic damages for residential, commercial, and industrial buildings. Section 2.2 describes the proposed approach to explore the dependencies and interdependencies among the structures and infrastructure of a city during the emergency phase of a flood event (i.e. during or immediately after a flood).

Both parts of the proposed approach require the characterization of the system during the preliminary phases of the scheme in Fig. 1, i.e., phase I: input data acquisition and harmonization (data collection, site visits, etc.), and phase II: hydrological analysis and flood scenario evaluation. This evaluation should preferably be conducted using a 2-D flood model (e.g., MIKE Flood developed by the Danish Hydraulic Institute, Telemac2D developed by the National Hydraulics and Environment Laboratory of the Research and Development Directorate of the French Electricity Board, CCHE2D developed by the National Center for Computational Hydroscience and Engineering of the University of Mississippi) that is likely to be data intensive but provides more detailed results in terms of velocity and water depth distribution.

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2.1 GIS direct impact assessment

This phase of the model, i.e. phase III in Fig. 1, is composed of two parts and it provides two principal results: the assessment of the loss of life and of the direct economic damages due the flood event.

2.1.1 Population at Risk and Loss of Life estimation

During incidents of urban flooding, consequences in terms of loss of life can be estimated as the combination of population exposed to the flood, i.e. population at risk, as in phase III of Fig. 1, and fatality rates (Escuder-Bueno at al., 2012) related to the characteristics of the flood, i.e. flood severity, evaluated in phase II. Indeed, the results of flood modelling and the data from the population census are used. Geographic analyses were carried out using Map Algebra techniques implemented in a set of scripts tested and developed using the Python scripting language (http://www.python.org/), the Open Sources GDAL libraries (http://www.gdal.org/), as well as the NumPy Python module (http://www.numpy.org/). To combine multiple maps in Map Algebra, all data were required to be converted into grid format.

The outputs of the hydrodynamic model, (in this study, MIKE Flood was used because it was deemed to be the most suitable for the selected case study, as highlighted in Sole et al., 2012), were processed to derive the information required for the analysis (e.g., Flood Wave Arrival Time, Peak Unit Flow Rate, etc. Using GIS scripts, a Flood Wave Arrival Time (Twv) grid was obtained. Twv at night is defined as a time period 15 min lower than Twv during the day. In addition, the two components of the vector unit flow rate were combined to obtain the maximum "Peak Unit Flow Rate" values ($m^2\,s^{-1}$). These values, termed parameter DV, are representative of the general level of destruction that would be caused by the flooding. The DV values were then categorized, as illustrated in Fig. 2, based on guidelines, (i.e. Department of Homeland Security, 2011) widely used by the Department of Homeland Security in the United States. The values were classified into ranges defined as low, medium, and high severity zones.

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It was assumed that for different DV values of the fields that their distribution within the polygon was homogenous. Hence, the vector polygons of the population census block were converted into grid format. By overlaying grid maps of flood with the grid of the population, it was possible to develop a map of Population at Risk (PAR).

The estimate of loss of life was obtained by multiplying the PAR with the Fatality Rate (fraction of people at risk projected to die from (severe) flood events). In this study, the SUFRI Fatality Rate (Escuder Bueno at al., 2012) was adopted because it is based on a literature study and procedures that cover the life-loss estimation of historical flood events (Graham, 1999), and it has been applied with good results in Italy (Escuder-Bueno at al., 2012)

Seven categories were established by Escuder Bueno et al. (2012) to assess potential loss of life in urban areas in the case of river flooding. This classification of categories (C1 to C7) was developed based on levels of public education on flood risk, warning systems, risk communication, and coordination between emergency agencies and authorities. It defines a certain level of flood severity understanding for each category, linked to fatality rates and based on a compilation of historical data and existing reference values on loss of life (Escuder-Bueno et al., 2012). Consequently, different fatality rates are considered for each category (C1 to C7) depending on available warning times (from 0 to 24 h) and three flood severity levels described previously (Fig. 2).

The final step for life-loss estimation relies on the combination of fatality rates and population at risk to obtain the number of potential fatalities for each flood scenario.

2.1.2 Direct structural and economic impact estimation

Methods and values of the parameters used in this section are drawn mostly from the report of the Department of Water Resources Division of Flood Management on Flood Rapid Assessment Model Development (F-RAM, 2008). The model is widely used in the evaluation of structural damage because it was evaluated in laboratories and real survey data from recent flood events in the United States.

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The methods presented in this subsection (phase III of Fig. 1) were based on the use of depth–damage relationships that assign a percentage of damage from the resulting water depth during the flood. An economic value of assets or land use was established and economic losses were obtained from the destruction rate (e.g. percentage of damage) within the flooded area. These curves are related to the assessment of the direct economic damage for residential, commercial, and industrial buildings. The input data consists of maps of land use and parcel zones of the study area. As mentioned earlier, for the analysis all the data were preliminarily converted into grid format.

The assessment allows for the estimation of the damage to buildings and their contents, and when applied to different scenarios, allows for an effective comparison of the impact. The extent of damage to buildings and their contents was estimated from the depth of flooding by the application of a depth-damage curve associated with each occupancy type. Depth damage curves demonstrate the relationship between the depth of the flood relative to the first finished floor level of buildings, and the damage caused to the structures and contents. Damage is typically expressed as a percentage of depreciated building replacement value. Adopting a non-traditional approach, the adopted method models measure the content damage directly as a percentage of structure value rather than using a content–structure value ratio.

To calculate damage, each structure must be assigned to a structure occupancy type. For each structure occupancy type an estimated replacement value, a structure depth-damage and a content depth–damage relationship must be defined. Figure 3 the graph of the depth-damage curves used in this study.

In assigning an occupancy type to each parcel, we chose values according to those shown in Table 2.

2.2 GIS accessibility and operability model for emergency management

This section describes how we analyzed the infrastructural transport interdependencies in the urban area during the emergency phases of a flood event (i.e. the performance of rescue activities taking into account the connections/paths between areas at risk and rescue centers such as hospitals, fire stations, etc.). In terms of emergency management, the failure of some part of the transport infrastructure would have the most serious effects on access to specific locations and overall system performance. The road closures due to flood waters, evaluated on the basis of velocity and water depth values, could create residual damage and hence could alter the emergency travel operations from normal conditions. In this context, an analysis of the paths of the emergency travel activities could open the possibility to evaluate the operability of the strategic emergency structures and highlight weaknesses (e.g. the most inaccessible area at risk or the strategic connectivity road that are most damaged). We focus on the emergency operations, and not on the evacuation of the people that could have been done in the pre-event phase of the flood event.

2.2.1 Road closure evaluation

First, it is necessary to estimate road closures due to flood waters in order to assess the potential inaccessible areas and inoperable roads (phase IV of Fig. 1). The possible road closures due to flood waters or large debris transport (i.e. the first step in phase IV of Fig. 1), were evaluated on the basis of literature studies that evaluate a weight related to critical threshold values of hydraulic instability for idealized vehicles (Teo et al., 2012). If the vehicles on these streets are dragged by the water flow, the road is inaccessible.

The envelope curves developed by Teo et al. (2012) considered three color zones (i.e. green, yellow, and red), in which the hydraulic stability for each idealized vehicle was easily identified by color. The stable zone is shown in green (left zone), the transition zone in yellow (central zone), and the unstable zone in red (right zone). All vehicles in the red zone of the graph are dragged by the water flow; hence they could block, for example, an emergency vehicle during rescue actions. The curves are utilized in the study only when incoming flow depths are less than the vehicle height, shown in the lower part of the graph in Fig. 4. When the incoming flow depth is greater than the vehicle height, the roads are considered to be always inaccessible.

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2.2.2 Accessibility and operability analysis of the urban system

Emergency management systems operate their vehicles in different ways during an emergency such as a flood. For example, they might use local streets in order to take the shortest path to their destination since the lower speed limit of local streets may not apply to those emergency vehicles. As a result, the shortest path will provide them with the shortest time distance. In this situation, a road closure due to a flood could alter the path that connects different elements in an urban area, such as the path between a hospital and a damaged school, thereby increasing the distance between them which would result in a lower level of accessibility. Equation (1) is proposed to evaluate the degree of inaccessibility of an area that requires rescue (i.e. the impedance index), as well as the degree of inoperability of a path within the system (i.e. the reliability index, see the central part of phase IV of Fig. 1):

$$\Delta \mathrm{PI}_{\mathrm{od}} = 1 - \left\{ \sum_{\mathrm{od}} \left[\frac{\sum_{i=1}^{n} \frac{\mathrm{Ps}_i}{\mathrm{Pe}_i} \cdot \frac{\mathrm{Ps}_{\max}}{\mathrm{Ps}_i}}{\sum_{i=1}^{n} \frac{\mathrm{Ps}_{\max}}{\mathrm{Ps}_i}} \right] \right\} \quad (1)$$

where Ps is the length of the generic standard path, and Pe is the length of the emergency path (i.e. the path that the aid vehicles have to travel due to the flood event). $\mathrm{Ps}_{\max}$ is the value of the longest standard path between all the standard paths that connects the aid centers with buildings at risk. A path is defined as "standard" if the latter connects aid centers with buildings at risk in the normal functioning of system connections. These are defined as "emergency" paths if the system is affected by a flood event. Equation (1) is an average of the ratio Ps/Pe weighted on the ratio $\mathrm{Ps}_{\max}/\mathrm{Ps}$ in order to consider the whole accessibility system (i.e. all the shortest paths among the elements at risk and all the emergency centers in the system). If an emergency path does not exist, (i.e., the elements are completely isolated), a value of 0 is assigned to the ratio Ps/Pe. In this case, access to alternative services (such as hospitals and businesses) does not exist. Therefore, the disruption costs to households, businesses and communities can therefore be more critical for the whole system.

The index, evaluated by Eq. (1), highlights the travel distance reliability of the path. Travel distance reliability considers the probability that a trip between an origin-destination pair can be completed successfully via the shortest distance possible. Hence, it highlights the paths that connect the elements of the system in more efficient ways. This index is also utilized to evaluate the impedance of nodes (i.e. buildings at risk). The impedance is an index of remoteness derived from measures of road distance between populated localities and service centers. It highlights the buildings that are more difficult to reach by the emergency authorities.

Considering that each shortest path is composed of a number k of arches, an index to evaluate the strategic importance of single arches is evaluated, and is known as the redundancy index. A network link is critical if loss or substantial degradation of the link significantly diminishes the accessibility of the network or of particular nodes. Therefore, the arches that are involved in a greater number of path connections (i.e. the ones that could be used more often by aid vehicles to reach the areas with flood risk) are the more important arches for maintenance of the emergency management performance.

The redundancy index (the box in yellow of the centre part of phase IV in Fig. 1), developed in this study represents the number of paths Ps that connect the relations "origins/destination" hereafter, "o/d", using the arc j, where the origins are the core rescue buildings and the destination is each element at risk (i.e. private or public building, factory, and so on):

$$\mathrm{RI}_{\mathrm{od}} = \sum_{\mathrm{od}} \left(\frac{k_{a_j}}{N_{p_{\mathrm{S}}}} \right) \tag{2}$$

where k_{a_j} is the count k of the times that the shortest paths Ps used the arch a_j to connect the multiple relations o/d. The evaluation of this index can help to identify the arches most affected by infrastructural relations o/d in order to define a hierarchy between the various infrastructures through the identification of those components in which operation and efficiency are fundamental to the maintenance of network connectivity.

Another measure of network performance in flood emergency conditions is the evaluation of possible alternatives for each single arch (i.e. the number of outgoing arcs i from the arc j) being considered in the normal functioning of the system weighted on the ratio between the number of outgoing arcs i from the arc j in case of emergencies $a_{ij\text{E}}$ and $a_{ij\text{S}}$:

$$\text{OI}_{\text{od}} = \left(\frac{1}{a_{ij\text{S}}}\right) \cdot \left(\frac{a_{ij\text{S}}}{a_{ij\text{E}}}\right) \tag{3}$$

The index suggests the number of potential alternative connections between arch j and the others related to that being considered in the emergency phase.

Finally, the value of the cube root of the product for each arch derived from the three Eqs. (1)–(3), represent the index of weakness of each arch in the emergency phase. This value, that coupled the flow and functionality approach with the topology analysis, defines a hierarchy between the various arches through the identification of those arches whose operation and efficiency are fundamental to the maintenance of network connectivity and accessibility in the whole system during a flood emergency. For the structures, Eq. (1) is used (i.e. the impedance index, in order to evaluate the weakness index).

The influence index is evaluated based upon the typology of each element in the system during the emergency response phase. It can be defined by a Gaussian curve corresponding to a mathematical function of an exponential type (Pascale et al., 2010):

$$y = a \cdot \frac{e^{-\partial \cdot x_i^{2.2}}}{\left(1 + e^{-\partial \cdot x_i^{2.2}}\right)} \tag{4}$$

where: x_i is the weakness index of each of the elements previously described; a is a constant which takes on a value equal to 2 and is calculated by fixing the boundary conditions ($x_i = 0$, $y = 0$, where $y = 0$ represent 0 % of vulnerability equivalent to no loss); α is a parameter calculated by fixing boundary conditions as: $3 < x_i < 6$, $3 < y < 6$ in a condition of medium to high vulnerability and equal to 0.02 (Pascale et al., 2010). The role of this function is to assess the degree of influence among the elements of the system considering the degree of connectivity, accessibility, and the role of each in the system in the emergency phase.

For this purpose, components such as buildings or communication networks were subdivided into categories A, B and C. These elements were divided in these categories relative to the element functions in the systems in the case of an emergency. For instance, if a hospital is damaged, the whole system is affected by an increase in the rescue workload for other forms of assistance. The risk elements with different roles and importance in the emergency management are set in Categories A, B and C. The importance of these features move from Category A to C in the following manner:

- Category A includes the most important elements in the case of an emergency, such as hospitals, fire stations and civil protection stations. These are all elements that give assistance when catastrophic events occur. This category also includes main roads.

- Category B includes all the major socio-economic and environmental elements such as factories, which can also deal with dangerous materials, large shopping centers, as well as all other public buildings including universities, libraries and churches. All of these can contain a large number of people and can be important from a historical, artistic and cultural perspective. This category also includes secondary roads.

- Category C includes private buildings, small business activities, and local roads.

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2.2.3 Systemic vulnerability analysis

Finally, the traditional direct loss analysis is coupled with the indirect loss analysis in emergency management through a systemic vulnerability index (i.e. phase V of Fig. 1). The systemic vulnerability of each element is estimated by the equation:

$$v_i = \max(y_i, s_i) \quad (5)$$

where s_i is the structural damage, evaluated by depth-damage curves as described in the previous subsection (phase III of Fig. 1); y_i is the influence of the road network on the elements of the territorial systems. The systemic vulnerability index v_i is chosen as a precautionary measure since it highlights the maximum risk.

This index is recapitulatory and it is also precautionary since it considers the highest value of possible damage. The innovative proposed systemic approach that is integrated in a traditional flood loss model can increase the value of the damage by taking into account the inoperability of roads or the isolation of buildings due to the flood event. This is essential information to assess flood risk during the emergency phase.

3 Case study area

Ginosa is a city in the Puglia region of Italy, located near the mouth of the "Bradano" River. The choice of this case study site was justified by the flat morphological characteristics of the river, determined using significant field data collected in recent years as well as the use of high resolution DTM from laser-scan data. Moreover, the study area includes the mouth of the "Bradano" River, which is particularly at risk for flooding. This assessment was derived from an analysis of historical data on hydrogeological disasters between the period 1918 to 2001, conducted as part of the "Affected Italian Areas" by the National Research Council (CNR).

As mentioned, analysis of the data shows that the area at the mouth of the "Bradano" River has been affected in the past by a significant number of natural disasters. The most recent flood event occurred on 1 March 2011. This flood event was deemed so severe that authorities declared a state of emergency. The flood event of 2011 at the mouth of the "Bradano" River affected the town in the first days of March when the majority of the hotels, resorts and tourist attractions were essentially closed or empty. Therefore, in the analysis presented in this case study, seasonal variability in tourist numbers was not taken into account because in March there are very few tourists in this area. This flood event was particularly intense, causing damage to economic activities and residential buildings, as well as provincial and national roads which became unusable due to water and mud. The local administration is still in the process of developing both structural and non structural measures to cope with flood risk in Ginosa, as well as in the neighbouring towns. Regarding this study, it was deemed preferable to validate the model proposed in this study with an event that has actually occurred, rather than a generic simulated event.

3.1 Data

The total population of Ginosa is approximately 22 146 (ISTAT, National Institute of Statistics, 2001) with 32 % comprising children under 14 years and adults over 65 years. The typical building topology is more than 90 % 1–2 floor cottages (SIT Puglia database, 2011). It should be noted that the ISTAT database and Puglia regional databases were developed at different times, resulting in discrepancies between the data. These discrepancies are not believed to affect the final results of the model application. The input data, listed above, were coupled with data extrapolated by Remote Sensing orthophoto images.

The principal vulnerable hotspots in the Ginosa territorial system are the two most important throughways. These include the "S.S. 106 Jonica Main Road", and the railway "Taranto-Reggio Calabria". In addition, there is a first aid unit located in the part of the city closer to the sea as well as diverse operative units that could support rescue activities. Several schools, churches and banks are also identified in the town. The urban area is mainly composed of residential and agricultural areas but also key resorts,

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zootechnical activities and Small and Medium enterprises (SMESs). More than 45 % of the workers are employed in the service sector, such as in key resorts and hotels located in the area. Seasonal variability of the demography and tourist numbers could have a significant impact in the flood risk analysis.

The maximum discharge of the chosen event, i.e. 1 March 2011, can be assimilated to an event with 30 years return time, estimated using the VAPI method, which is recommended by local authorities (e.g. the Basin Authority of Puglia Region) in Southern Italy (Claps et al., 2005). Hydraulic simulations of flood scenarios were performed using a 2-D commercial flood model (in this case the Mike Flood model since it was deemed to be the most appropriate model for this area as highlighted in Sole et al., 2012), from the Digital Elevation Model of the study area, which includes cross sections of the river embankment extrapolated from laser scanner data.

4 Results

Simulations provided hydraulic characteristics of the chosen flood scenario. Data of water depth, velocity, and wave arrival times were obtained in the urban area of the study case.

Due to the flat nature of the flooded zone, the flow velocity was average-low, and the water depth high, in most of the zone (Figs. 5 and 6). Hence, the damage estimation was performed only on the basis of the water depth parameter. The total flood area was determined to be approximately 30 561 900 m^2.

The flood extension maps were able to define the areas of the territory directly affected by the flood event, and incorporate the necessary hydraulic characteristics for the study. Using GIS, flooded areas were identified to estimate the element at risk. Specifically, it was found that less than 10 % of the residential buildings are at risk because the more populated area of the town is located outside the flooded area. However, 30 % of business activities are located in the risk area, in particular SMEs and resorts. In the risk area, 7 % of the population are children or elderly people.

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A majority of the people at risk are in the down-flow area, near the sea. Further, the area characterized by the highest probability of loss of life, shown in the area colored in red in Fig. 7, is the first zone affected by water flow. Historical data on landslides and floods has highlighted that a single flood event in Ginosa prior to the year 2000 resulted in casualties. The largest number of victims was found to be in the area highlighted as most prone to fatalities according to our application shown in Fig. 7. It was assumed that there was minimal warning of flood threats in this zone. Warning time is defined as the time difference from the first notice flow and the first damage flow. We made the assumption that the first notice peak corresponded to the first damage flow since Ginosa does not have a flood warning system. Additionally, there is no public education on flood risk, risk communication, and coordination between emergency agencies and authorities despite the low flood severity due to low values of the Peak Unit Flow Rate, which is directly correlated to water flow velocity values.

The total loss of life estimated by the model corresponds to 1 fatality due to the low population density of the area as well as the low percentage of people at risk. In the event of 1 March 2011, there were no reported fatalities but substantial displacement of populations and damage to infrastructure, farms and resorts, as highlighted in Table 4 that provides information on the direct economic damage, estimated by the model, considering this chosen flood scenario.

Figure 8 provides a comparison between the proposed model and several site surveys during or after the events. It gives an overview of the consequences of the event and the potential reliability of the model. The area in which damage potential is greatest and most affected during the flood event is that closest to the river, where residential buildings and a resort are located in "c/da Marinella". Meanwhile, the area on the far end of the riverbed (i.e. "Via Ancona Road") received minimal damage (Fig. 8). During the actual flood, the majority of claims from damage associated with the natural disaster came from residents and proprietors of factories and industries closest to the river.

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The flood event of 1 March 2011 also caused serious damage to the main infrastructural systems, as well as indirect damage to most of the surrounding area. Indeed, the failure of some parts of the transport infrastructure would have the most serious effects on access to specific locations and overall system performance. Based on the criteria described earlier, the road closures are illustrated in Fig. 9. This assessment allows for the identification of potential inoperable road arches that could affect the whole system during the emergency response activities.

Figure 10 outlines the potential fragility in connectivity between emergency centers and the risk area. The main road, "S.S. 106", is very important because it crosses through the town, dividing it into two parts (e.g., Ginosa Marina located in front of the sea and Ginosa town in the inland). The neighboring roads and the main street act as a connection between the area at risk and the middle of the town and beaches. The zone located in "c/da Marinella" also had a high value for this index because it is almost completely isolated (Fig. 10).

The validations performed by comparisons with the case study illustrate the reliability of the model, which allows for a satisfactory representation of the fragility of the territorial system. It is possible that a similar conclusion could have been obtained simply through expert advice due to the relative simplicity of the territorial system studied. However, the results we show here can be viewed as important given the reliability of the methods adopted and the value of flood emergency management planning.

The proposed model outlined in this paper provides a quantitative estimate of flooding vulnerability on the basis of direct impact assessment, i.e. structural and economic loss evaluation, and an assessment of areas prone to loss of life, taking into account the operability of the strategic emergency structures, their accessibility, and connection within the urban area during the emergency phase of a flood.

The model can support emergency planning through the definition of a hierarchy among the various structures and infrastructure by identifying those structures and infrastructure whose loss of operability and accessibility could cause vulnerability in the entire system and problems with the performance of rescue activities and victim as-

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sistance. In this manner, emergency flood planners can recognize which infrastructure is critical to the maintenance of network connectivity, as well as the structures whose operability and safety are critical during the emergency phase to improve the planning of possible mitigation interventions.

5 Conclusion

This paper has presented a new approach to integrate the analysis of an accessibility and operability model for vulnerability assessment of the strategic elements in the emergency phase associated with traditional risk analysis during a flood event. The aim is to support decision making regarding the prioritization of preventative measures in order to optimize investments. The innovative aspect of the proposed model is to provide a quantitative estimation of flood risk on the basis of the operability of strategic emergency structures, their accessibility and connection with the urban system of a city in emergency phases. The accessibility of an operability model, illustrated in the GIS model and integrated in the risk analysis model, help to define a hierarchy among the various structures and infrastructure by identifying those structures and infrastructure whose operation and efficiency are fundamental to the maintenance of network connectivity. In this way, the model identifies the structures and infrastructures whose maintenance of performance, in terms of connectivity or operability, could be essential in order to facilitate assistance to victims and rescue activities.

The proposed model was piloted and validated in an urban area of the Puglia Region, Southern Italy to demonstrate its operability for providing planners with a tool to identify the hotspots in the urban system affected by floods and to aid in prioritizing interventions.

Future developments of the proposed model could deal with the estimation of the economic cost of systemic loss during the emergency phase, which could provide more information on prioritizing risk reduction measures in terms of cost-benefit analyses of interventions.

Finally, the integration of local stakeholders in the development and use of the model could assist authorities to facilitate the quality and fairness of flood risk management. Incorporation of diverse stakeholder views can increase the legitimacy of such processes given the significant uncertainty surrounding climate change and the dynamics of socio-economic systems.

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Table 1. Fatality rates in case of river flooding (Escuder Bueno et al., 2012).

ID	Category for the case study	Warning Time (h)	Flood Severity High	Medium	Low
C1	– There is no public education on flood risk terms. – No warning systems, no EAP (Emergency Action Plan). – There is no coordination between emergency agencies and authorities. – No communication mechanisms to the public.	0 0.25 0.625 1 1.5 24	0.9 0.9 0.7 0.3 0.3 0.08	0.3 0.3 0.08 0.06 0.0002 0.0002	0.02 0.02 0.015 0.0006 0.0002 0.0001
C2	– There is no public education on flood risk terms. – There is no EAP, but there are other warning systems. – There is no coordination between emergency agencies and authorities. – No communication mechanisms to the public.	0 0.25 0.625 1 1.5 24	0.9 0.9 0.675 0.3 0.3 0.075	0.3 0.3 0.075 0.055 0.0002 0.0002	0.02 0.02 0.014 0.00055 0.0002 0.0001
C3	– There is no public education on flood risk terms. – There is EAP, but it has not been applied yet. – Some coordination between emergency agencies and authorities (but protocols are not established). – No communication mechanisms to the public.	0 0.25 0.625 1 1.5 24	0.9 0.85 0.6 0.3 0.3 0.075	0.3 0.2 0.07 0.05 0.0002 0.0002	0.02 0.015 0.012 0.0005 0.0002 0.0001
C4	– There is no public education on flood risk terms. – EAP is already applied. – Coordination between emergency agencies and authorities (there are protocols). – No communication mechanisms to the public.	0 0.25 0.625 1 1.5 24	0.9 0.75 0.5 0.3 0.15 0.04	0.3 0.15 0.04 0.03 0.0002 0.0002	0.02 0.01 0.007 0.0003 0.0002 0.0001
C5	– There is no public education on flood risk terms. – EAP is already applied. – Coordination between emergency agencies and authorities (there are protocols). – Communication mechanisms to the public (not checked yet).	0 0.25 0.625 1 1.5 24	0.9 0.75 0.5 0.3 0.15 0.375	0.3 0.15 0.0375 0.0275 0.0002 0.0002	0.02 0.01 0.0065 0.000275 0.0002 0.0001
C6	– There is no public education on flood risk terms. – EAP is already applied. – Coordination between emergency agencies and authorities (there are protocols). – Communication mechanisms to the public.	0 0.25 0.625 1 1.5 24	0.9 0.75 0.475 0.3 0.15 0.035	0.3 0.15 0.035 0.025 0.0002 0.0002	0.02 0.01 0.006 0.00025 0.0002 0.0001
C7	– Public education. – EAP is already applied. – Coordination between emergency agencies and authorities (there are protocols). – Communication mechanisms to the public.	0 0.25 0.625 1 1.5 24	0.9 0.65 0.4 0.3 0.1 0.02	0.3 0.1 0.02 0.01 0.0002 0.0002	0.02 0.0075 0.002 0.0002 0.0002 0.0001

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Table 2. Reclassification table: from Zoning type to occupancy type.

Zoning Type	# Stories	Occupancy Type
Commercial	any	COM
Industrial/Wholesale/Manufacturing	any	IND
Institutional/Government	any	PUB
Office	1	RES1
Office	2 or more	RES2
Open space/Recreation/Agricultural	any	FAR
Residential	1	RES1
Residential	2 or more	RES2
Transport	any	TRN

Table 3. Flooded area for the different categories of water depth H.

Water depth (m)	Flooded area (m^2)
0.0–0.5	9 707 000
0.5–1.0	7 902 700
1.0–1.5	5 366 700
1.5–2.0	2 692 600
2.0–2.5	1 192 700
2.5–3.0	687 600
3.0–3.5	529 800
3.5–4.0	509 800
4.0–4.5	471 800
4.5–5.0	424 100
5.0–5.5	284 700
5.5–6.0	153 700
6.0–6.5	118 900
6.5–7.0	88 100
7.0–7.5	81 400
7.5–8.0	68 000
> 8	282 300

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Table 4. Direct economic damage from the flood event of 1 March 2011.

Occup. Type	Description	Structural value (KEuro)	Contents value (KEuro)	Structural damage (KEuro)	Contents damage (KEuro)
IND	Zoothecnical activities	9 800 000	34 300 000	0	0
IND	SMEs	12 560 000	43 960 000	24 000	84 000
ReS1 and RES2	Residential Buildings	452 300 000	226 150 000	1 620 000	752 500
PUB	Public services	7 540 000	15 080 000	0	0
TRN	Main roads	48 516 000	1 940 676	2 528 915	735 294
TRN	Urban roads	145 932 500	5 836 807	6 743 983	2 101 124
TRN	Raylways	30 694 000	1 534 700	1 098 666	433 887
COM	Hotels and resorts	19 050 000	38 100 000	928 125	1 327 500
FAR	Agricultural areas	0	5 999 187	0	5 999 187
FAR	Forest areas	0	597 750	0	63 280

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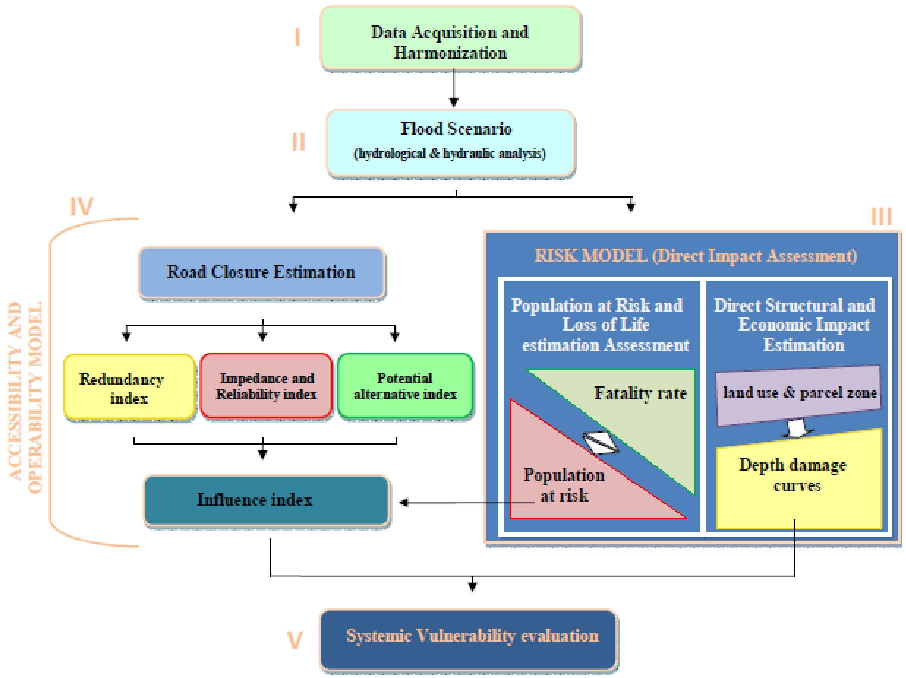

Fig. 1. Phases of the proposed methodology.

Table 8. Flood Severity Rating Criteria for Use with 2D Modeling Output (Source: LSM Users Guide)

Flood Severity Rating	Rating Criteria
Low	DV less than 50 ft^2/s
Medium	DV equal to or greater than 50 ft^2/s and less than 160 ft^2/s
High	DV equal to or greater than 160 ft^2/s combined with rate of rise of at least 10 feet in 5 minutes

Fig. 2. Flood severity rating criteria (Department of Homeland Security, 2011).

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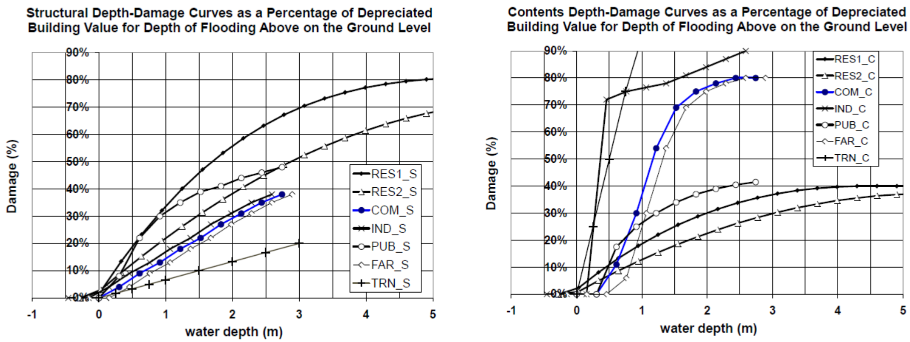

Fig. 3. Depth damage curves (USACE Generic Depth Damage Curves, 2008).

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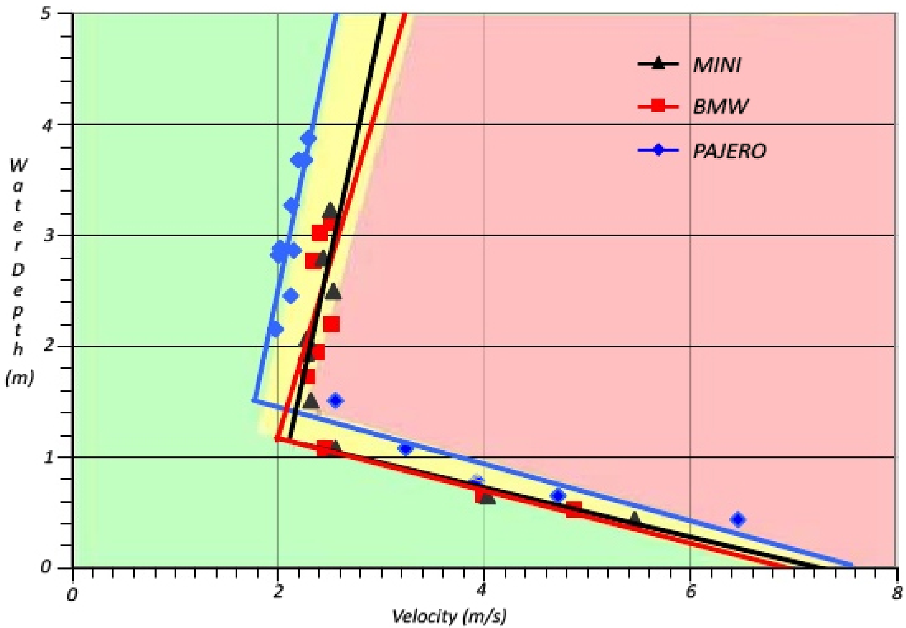

Fig. 4. Critical threshold values of hydraulic instability for specific vehicles (taken from Teo et al., 2012).

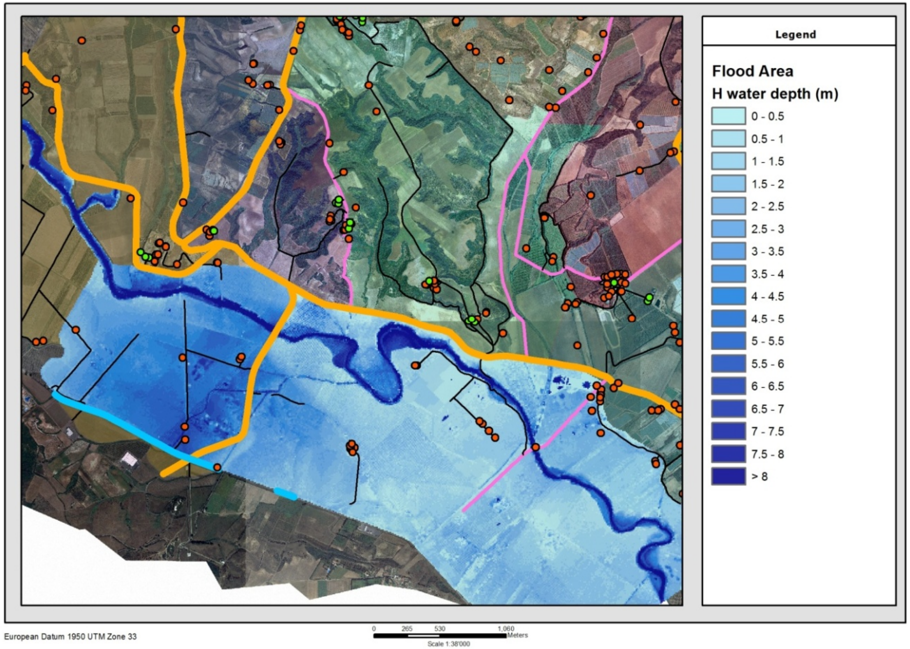

Fig. 5. Water depth *H* from Mike Flood (up-flow).

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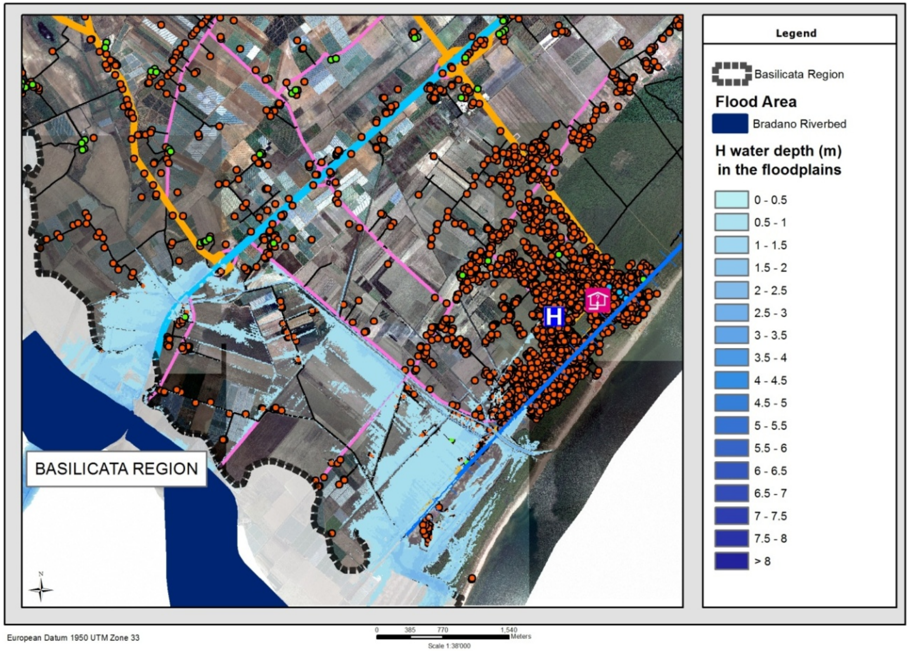

Fig. 6. Water depth *H* from Mike Flood (down-flow).

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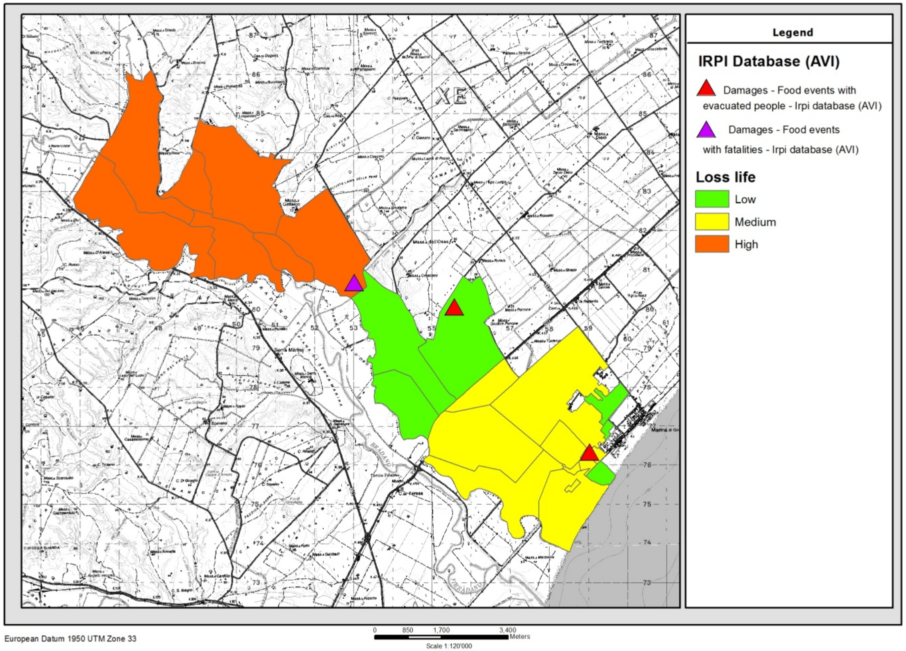

Fig. 7. Map of the potential loss of life from the flood event of 1 March 2011.

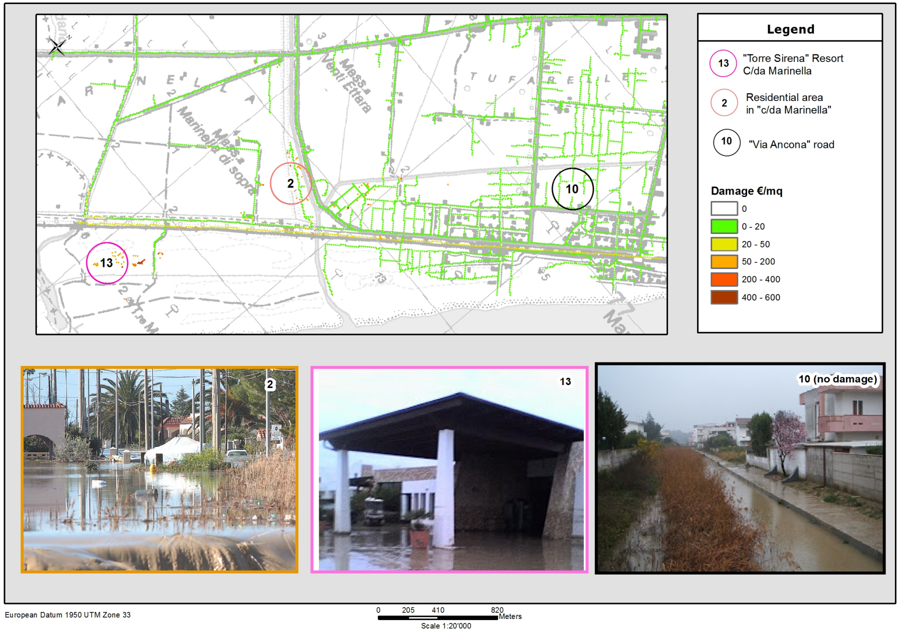

Fig. 8. Direct damage estimation.

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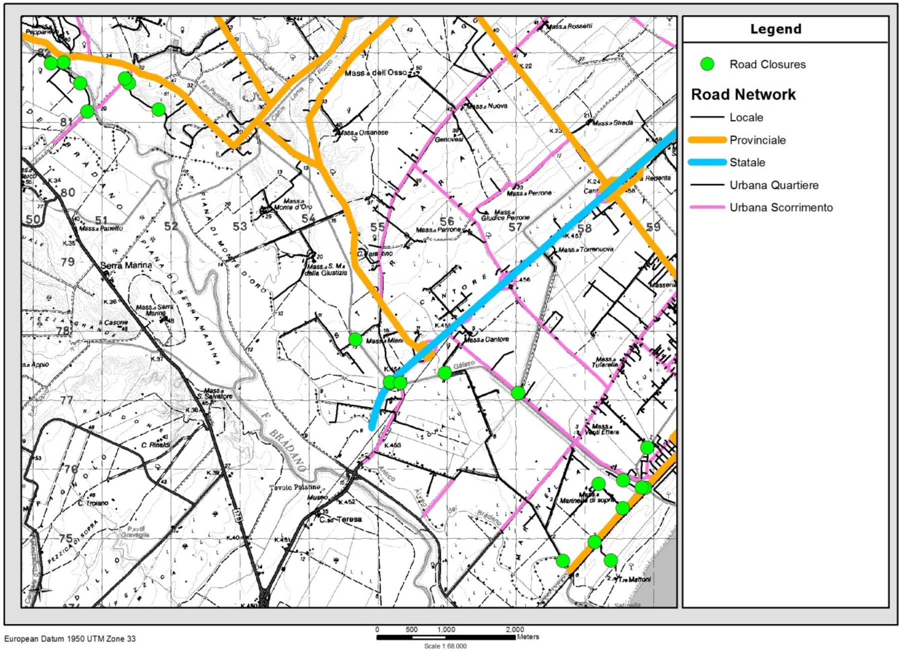

Fig. 9. Road closures due the chosen scenario.

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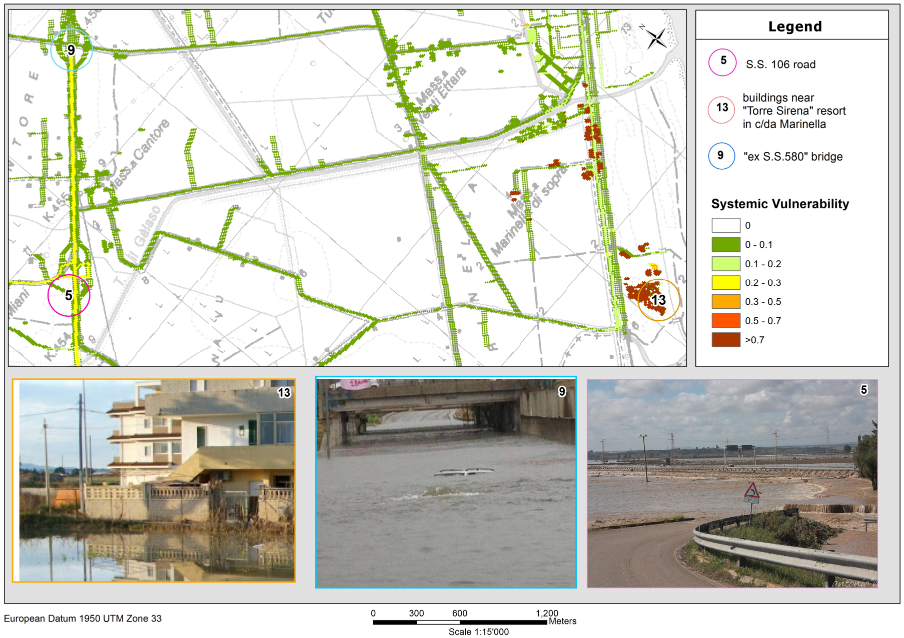

Fig. 10. Systemic vulnerability estimation.

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