A GIS Based Model to Estimate Flood Consequences and the Degree of Accessibility and Operability of Strategic Emergency Response Structures in Urban Areas

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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 model to estimate flood consequences was developed in this study that is based on GIS, and integrated with a model that estimates the degree of accessibility and operability of strategic emergency response structures in an urban area. The majority of the currently available approaches do not properly analyze road network connections and dependencies within systems, and as such a loss of roads could cause significant damages and problems to emergency services in cases of flooding. The proposed model is unique in that it provides a maximum impact estimation of flood consequences 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, given limited financial resources.

Keywords: floods; urban; flood loss estimation; GIS; emergency management;

1 Introduction

Urban flooding is a serious and growing challenge. Against the backdrop of demographic growth, urbanization trends and climate change, the causes of floods are shifting and their impacts are accelerating (Jha et al. 2012).

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 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 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 new policies for increasing resilience to flooding (Djordjević et al., 2011), ‘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 more traditional standard-based approach as it involves ‘whole systems’ and ‘whole life’ thinking. However, this is its main strength and a prerequisite for more integrated and informed decision making in the face of flood emergencies (Sayers at al., 2013). For example, in the Netherlands, seeking to provide ‘room for the river’, scientists, policy-makers and stakeholders have focused their attention on warning and evacuation systems, improvements in maintenance standards, and a decision-making process that reflects greater attention to economic efficiencies (Sayers at al., 2013). Flood forecasting, warning, emergency management and other non structural measures are increasingly being seen as critical for reducing flood consequences. As part of this, there is a need to refine methods to estimate flood risk and consequences, with particular attention on emergency management.

The Hyogo Framework for Action 2005–2015 (ISDR, 2005) highlights the central role of emergency planning in ensuring that a flood event does not become a flood disaster.
The internationally accepted and most common flood damage models [FLEMO model (Apel et al., 2009 and Vorogushyn et al., 2012); HAZUS-MH (FEMA, 2009 and Scawthorn, 2006); Damage Scanner Model (Klijn et al., 2007); Multi-Coloured Manual (Penning-Rowsell et al., 2005)] place 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. The latter 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 case of emergency. Hence, indirect damages in the field of emergency management, are not considered in these currently available consequence estimation 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 infrastructure in the maintenance of the performance of the rescue, and also its degree of vulnerability). On one hand, the latter papers have not estimated 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 estimation of dependences within an urban system in the case of floods and/or landslide events by studying the "systemic" 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 impact estimation. The proposed model couples the flow approach (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 impact of road networks and dependencies between hotspots, i.e. buildings at risk (e.g. schools, private building, industries, etc..), and strategic structures, i.e. rescue centres (e.g. hospitals, fire stations, etc..), are estimated with a spatial analysis approach based on flows and topologies in order to evaluate the indirect impacts to the system during the emergency phase. Finally, the latter accessibility and operability model is integrated with a consequence estimation model for urban areas based on the main concepts that drive the internationally used flood damage models that were previously cited in order to evaluate the maximum impact of a chosen flood event in terms of direct and indirect damages during the emergency phases of a flood event.

The proposed model does not aim to estimate all the wide range of indirect impacts that may have effects on time scales of months and years (i.e. macro-economic effects or long-term barriers to regional development (Merz et al., 2010)). Instead, the model focuses on how the impact of a flood hazard on individual elements of strategic infrastructure or single nodes in network systems may influence the system as a whole (Meyer et al., 2013) in the emergency phase of a flood.

Hence, the proposed model for consequence estimation in urban areas provides a quantitative evaluation of direct damage, to inform decision-making in terms of loss of life and structural and economic damages, that is useful in order to support an innovative methodology 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 present framework, integrated in a GIS (Geographic Information System) framework, aims to estimate the direct and indirect damage of a flood event in order to understand the strengths and fragilities of a particular urban area. The scope is to define 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 management. The proposed model can aid in prioritizing the decisions on flood mitigation strategies that should be planned. This could support the maximization of the benefit of limited investments by selecting the highest priority ones for emergency service. In section 2, the overall GIS framework is outlined, in section 3 the application and results of the proposed model on a real flood event are described, and an overall conclusions are provided in section 4.

2 Overall Framework

This section describes the integration of a methodology that estimates the impact on accessibility and operability of strategic emergency response structures within an urban system, and a methodology for flood consequence estimation in urban areas, with the aim of prioritizing actions for flood consequence reduction (Fig. 1). The Sects. 2.1 and 2.2 describe the preliminary phases needed for the implementation of the methodology. Sect. 2.3 summarizes the proposed GIS methodology for the rapid estimation of the consequences for an urban population, which can also be used to estimate the direct structural and economic damages for residential, commercial, and industrial buildings. Sect. 2.4 describes the proposed approach to explore the dependencies among the structures and infrastructure of a city during the emergency phase of a flood event (i.e. during or immediately after a flood), in terms of the accessibility of flood prone areas and the operability of road networks for emergency service.

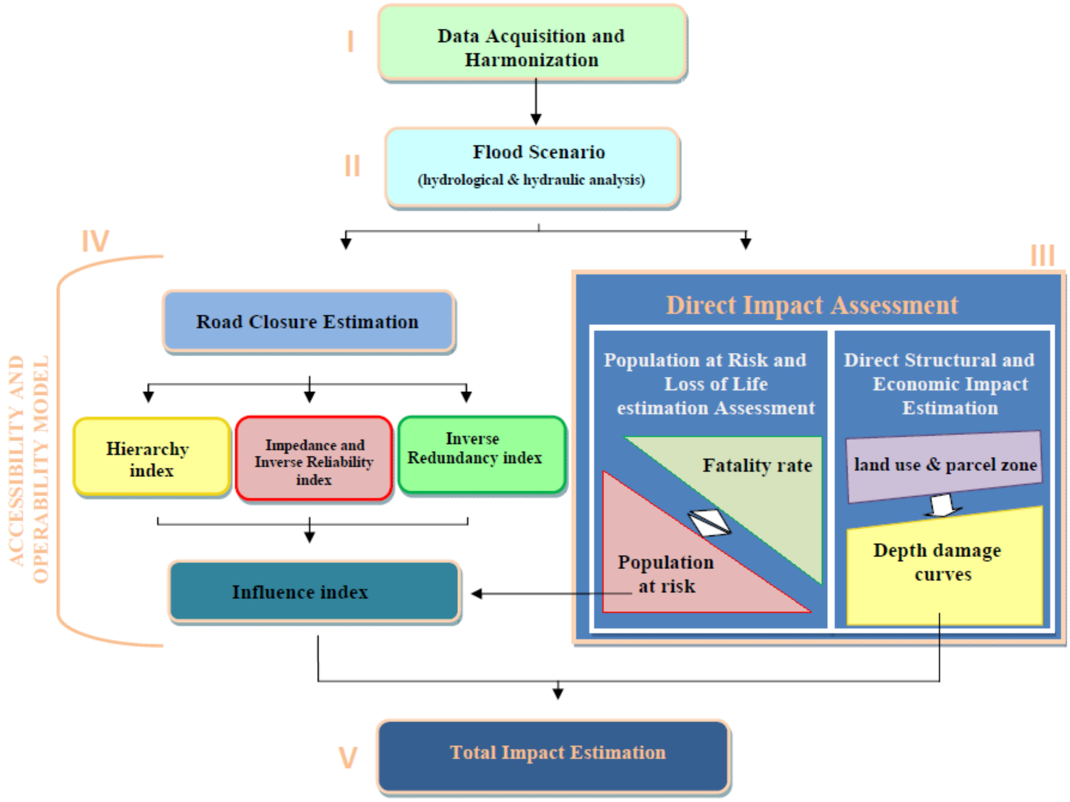

Figure 1. Phases of the proposed methodology

2.1 Data Acquisition and Harmonization

The level of uncertainty in estimating potential damage by the model depends on available data (data collection, site visits, etc..). An analysis of the data considered land use distribution, data population census, digital elevation terrain models, buildings and roads categorized on the basis of the function/typology (e.g. main roads, local roads, industries, resorts, hospitals, etc..). Therefore, 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..).

2.2 Definition of the Flood Scenario

The second phase, ("II Flood Scenario: hydrological analysis and flood scenario evaluation"), is concerned with the definition of a flood scenario, or flood scenarios, required to estimate the potential damages and/or in order to determinate the possible flood events. A flood scenario can be identified by a return period, a combination of loads that determine a failure scenario, the result of flood routing, etc. If the model runs several times for different flood scenarios with different return times, the model can relate probabilities of each flood event to potential consequences.

However, the evaluation of a flood scenario could be performed via a hydrological analysis, which could be important to evaluate the probability of a scenario or of more scenarios, coupled with a flood simulation, that should preferably be conducted using a 2D 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. The latter parameters are essential to estimate the flood severity of the chosen scenario; flood severity is usually assigned using a flood depth multiplied by average velocity value.

2.3 GIS Direct Impact Estimation

This phase of the methodology is composed of two parts and it provides two principal results: the estimation of the loss of life and of the direct economic damages due the flood event.

2.3.1 Population at Risk and Loss of Life estimation

During urban flooding events, consequences in terms of loss of life can be estimated as the combination of population exposed to the flood, i.e. population at risk 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, 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), i.e. the time of occurrence of the flood wave, grid was obtained. In addition, the two components, (x-coordinate and y-coordinate), of the vector unit flow rate were combined to obtain the maximum "Peak Unit Flow Rate" values (m^2/s) (i.e., the flow discharge for each linear meter of cross-section). These values, termed parameter DV, proposed by Graham in 1999, are representative of the general level of destruction that would be caused by the flooding. The DV values were then categorized, as illustrated in Table. 1 based on guideline of Department of Homeland Security, (2011) widely used in the United States. The values were classified into ranges defined as low, medium, and high severity zones that define the rating of the flood severity.

Flood Severity Rating	Rating Criteria
Low	DV less than $5m^2/s$
Medium	DV equal to or greater than $5m^2/s$ and less than $15m^2/s$

High	DV equal to or greater than $15m^2/s$ combined with rate of rise at least 3m in 5 minutes

Table 1. Flood severity rating criteria (Source: Department of Homeland Security, 2011).

If the information on population is aggregated at the census area level, it could be hypothesized that it is distributed homogeneously within the vector polygon that represents the census areas. 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). The fatality rates proposed in the SUFRI project (Escuder-Bueno et al., 2012) were adopted in the model 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)

Ten categories were established by Escuder Bueno et al. (2011) to estimate potential loss of life in urban areas in the case of river flooding. In the model, seven categories have been implemented because the categories C8, C9, and C10 are useful only in the case of a dam-break event (Escuder Bueno et al., 2011). 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 (see Tab.2). 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 (Graham, 1999 and 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 24h) and three flood severity levels described previously (Tab. 1). The warning time, that is a function of the Twv, at night is defined as a time period 15 minutes lower than the warning time during the day, such as in Escuder-Bueno et al. (2011). If there is no warning time or data is not available, the available warning time is estimated from the difference between the time of occurrence of the first-notice-flow and the first-damage-flow, such as in Escuder-Bueno et al.(2011).

Table 2. 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	0.9	0.3	0.02
		0.25	0.9	0.3	0.02
		0.625	0.7	0.08	0.015
		1	0.3	0.06	0.0006
		1.5	0.3	0.0002	0.0002
		24	0.08	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	0.9	0.3	0.02
		0.25	0.9	0.3	0.02
		0.625	0.675	0.075	0.014
		1	0.3	0.055	0.00055
		1.5	0.3	0.0002	0.0002
		24	0.075	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	0.9	0.3	0.02
		0.25	0.85	0.2	0.015
		0.625	0.6	0.07	0.012
		1	0.3	0.05	0.0005
		1.5	0.3	0.0002	0.0002
		24	0.075	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	0.9	0.3	0.02
		0.25	0.75	0.15	0.01
		0.625	0.5	0.04	0.007
		1	0.3	0.03	0.0003
		1.5	0.15	0.0002	0.0002
		24	0.04	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	0.9	0.3	0.02
		0.25	0.75	0.15	0.01
		0.625	0.5	0.0375	0.0065
		1	0.3	0.0275	0.000275
		1.5	0.15	0.0002	0.0002
		24	0.375	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	0.9	0.3	0.02
		0.25	0.75	0.15	0.01
		0.625	0.475	0.035	0.006
		1	0.3	0.025	0.00025
		1.5	0.15	0.0002	0.0002
		24	0.035	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	0.9	0.3	0.02
		0.25	0.65	0.1	0.0075
		0.625	0.4	0.02	0.002
		1	0.3	0.01	0.0002
		1.5	0.1	0.0002	0.0002
		24	0.02	0.0002	0.0001

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.

2.3.2 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.

The methods presented in this subsection (phase III of Fig. 1) is 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 estimation 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 show 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 measures the content damage directly as a percentage of structure value rather than using a content-structure value ratio, i.e. the ratio between the unitary value of the content and the unitary value of the building structure.

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 (Figure 2) and a content depth-damage (Figure 3) relationship must be defined. The depth-damage curves implemented in the model were obtained from USACE (Department of Water

Resources Division of Flood Management, 2008). The methodology, here presented, could use other depth-damage curves that are more suitable for the area of interest; however, in the present model the USACE curves were implemented since they were suitable with the case study described in the next section, because they were also proposed in the 'SUFRI' Methodology (Escuder Bueno et. al, 2011) and are more precautionary that the one proposed by Luino et al., (2003) for Italy. In assigning an occupancy type, taken usually from a city map at micro-scale, to each parcel, we chose values according to those shown in Table 3.

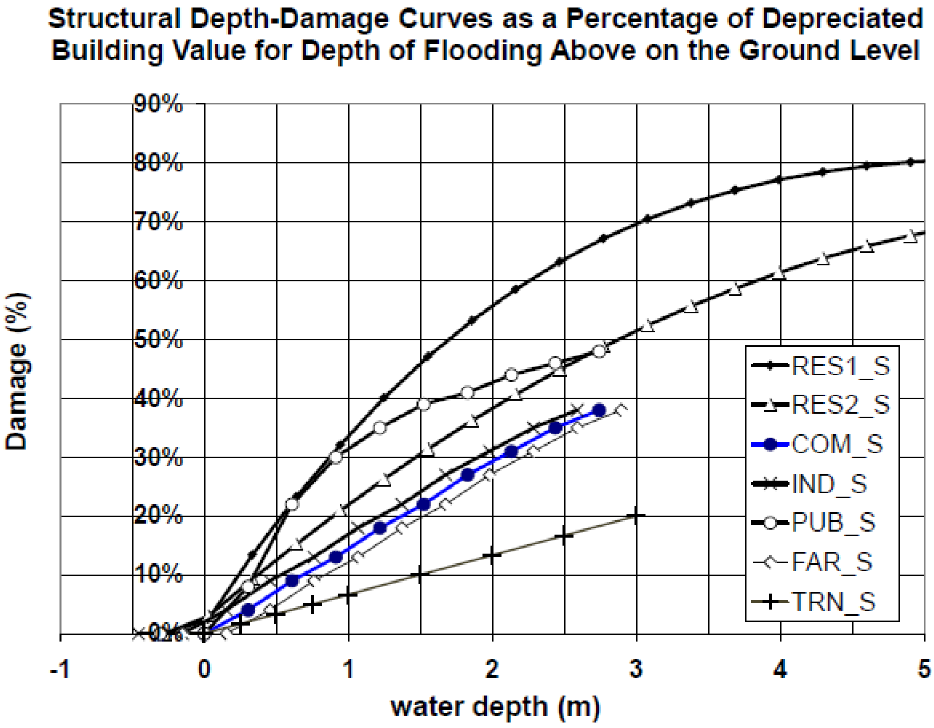

Figure 2. Structural depth-damage curves implemented in the model (Source: Department of Water Resources Division of Flood Management 2008).

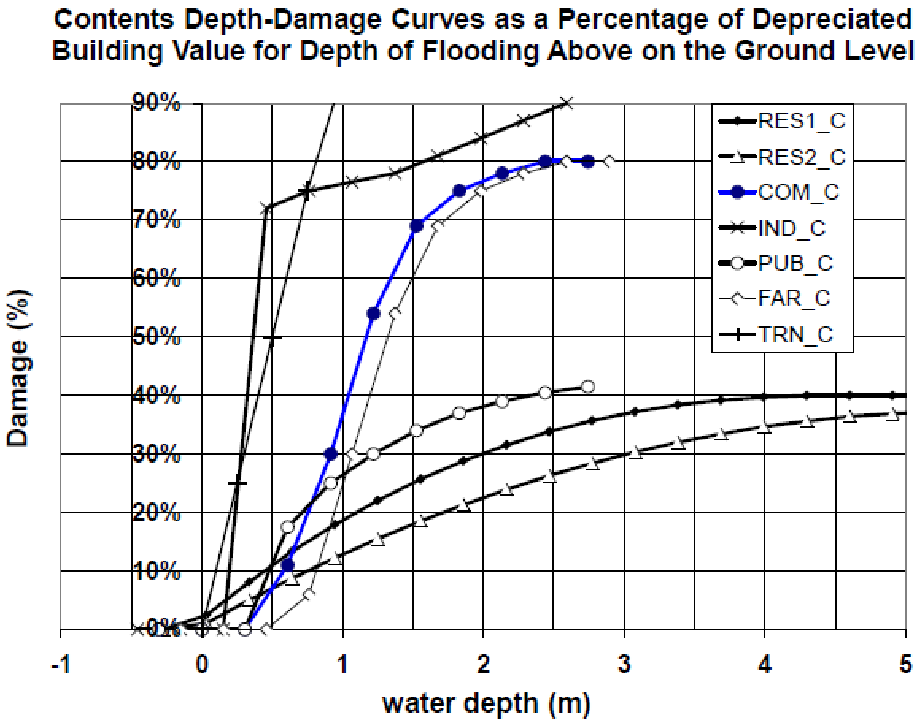

Figure 3. Content depth-damage curves implemented in the model (Source: Department of Water Resources Division of Flood Management 2008).

Table 3. 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

2.4 GIS Accessibility and Operability Model for Emergency Management

This section describes how the infrastructural transport dependencies were estimated 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, estimated on the basis of velocity and water depth values, could create damages 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 estimate 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.

2.4.1 Road Closure Estimation

First, it is necessary to estimate road closures due to flood waters in order to estimate the potential inaccessible areas and inoperable roads (phase IV of Fig. 1). The possible road closures due to flood waters or large debris transport, were estimated on the basis of literature studies that estimate 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.

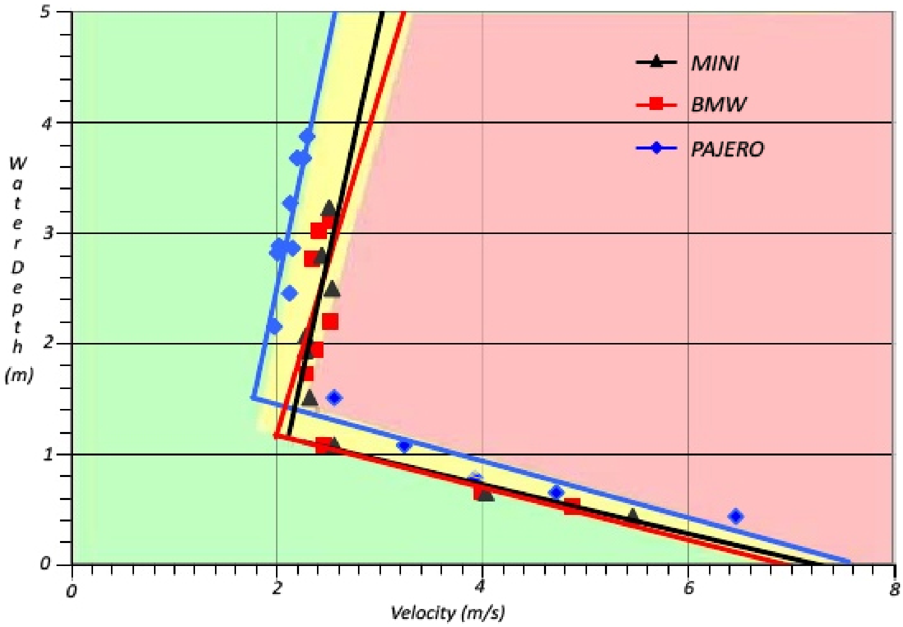

Figure 4. Critical threshold values of hydraulic instability for specific vehicles (taken from Teo et al., 2012).

The envelope curves developed by Teo et al. (2012) consider 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 implemented in the model are used when incoming flow depths are lower 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. This choice is justified by the possible presence of emergency vehicles that could work in worse conditions than cars (e.g. firefighter trucks, ambulances, small boats, etc.). As such, the methodology, on the one hand, aims to give more importance to closure of roads due to vehicle transport, which is a frequent phenomena in urban areas as highlighted in Albano et al. (2014), Gruntfest (2000) and Gruntfest and Ripps (2000) and, on the other hand, aims to be precautionary and independent of the type of vehicles available in a specific scenario in the analysis.

2.4.2 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 estimate the degree of inoperability of a path within the system (i.e. the inverse (connectivity) reliability index, where the concept of reliability is introduced by Taylor et al. (2006)) - see the central part of phase IV of Fig. 1:

$$R_i = 1 - \left\{ \sum_{od=1}^{n} \left[\frac{\sum_{i=1}^{n} \frac{Ps_i}{Pe_i} \cdot \frac{Ps_{\max}}{Ps_i}}{\sum_{i=1}^{n} \frac{Ps_{\max}}{Ps_i}} \right] \Bigg/ \sum_{od} \right\} \tag{1}$$

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). 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 Ps_{max}/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), normalized on the basis of all the relations "origins/destinations", hereafter "*o/d*", where the origins are the core rescue buildings and the destinations are buildings at risk (i.e. private or public buildings, factories, etc.). 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 inverse reliability index, estimated 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 (see figure 5) can be completed successfully via the shortest distance possible for the normal functioning of system connections, this is represented by the blue line in Fig. 5, and in the case of a flood event, this is represented by the red line in Fig. 5. The ratio between *Ps* and *Pe* is weighted on the basis of the distance between "*o/d*" in order to relate this ratio to the urban system network dependencies in the emergency phase; the estimated value for each path is normalized on the basis of the multiple "*o/d*" relationship because there can be more than one origin in the system (i.e. core rescue buildings).

Equation 1 is assigned to each shortest path and, therefore, to each arch a_i that composes the path, but it was used, see Eq. (2), also in order to estimate the degree of inaccessibility of an area that requires rescue (i.e. the impedance index, introduced by Taylor at al. (2006) but here modified in order to consider accessibility in the whole system for emergency service), assigning the estimated value to each building at risk that requires rescue:

$$I_i = 1 - \left\{ \sum_{od=1}^{n} \left[\frac{\sum_{i=1}^{n} \frac{Ps_i}{Pe_i} \cdot \frac{Ps_{\max}}{Ps_i}}{\sum_{i=1}^{n} \frac{Ps_{\max}}{Ps_i}} \right] \Big/ \sum_{od} \right\} \qquad (2)$$

The impedance index in Eq (2) is utilized to estimate the impedance of nodes (i.e. buildings at risk), i.e. the remoteness derived from measures that aims to indentify the buildings that are more difficult to reach by the emergency services. In Fig. 5, the black building has the highest degree of impedance. The inverse (connectivity) reliability index, instead, in Eq. (1) is useful to highlight the strategic paths that connect the elements of the system. The inverse reliability and impedance index ranges between 0, i.e. no impedance, to 1, the highest value of inverse reliability or impedance, i.e. where the building is completely isolated.

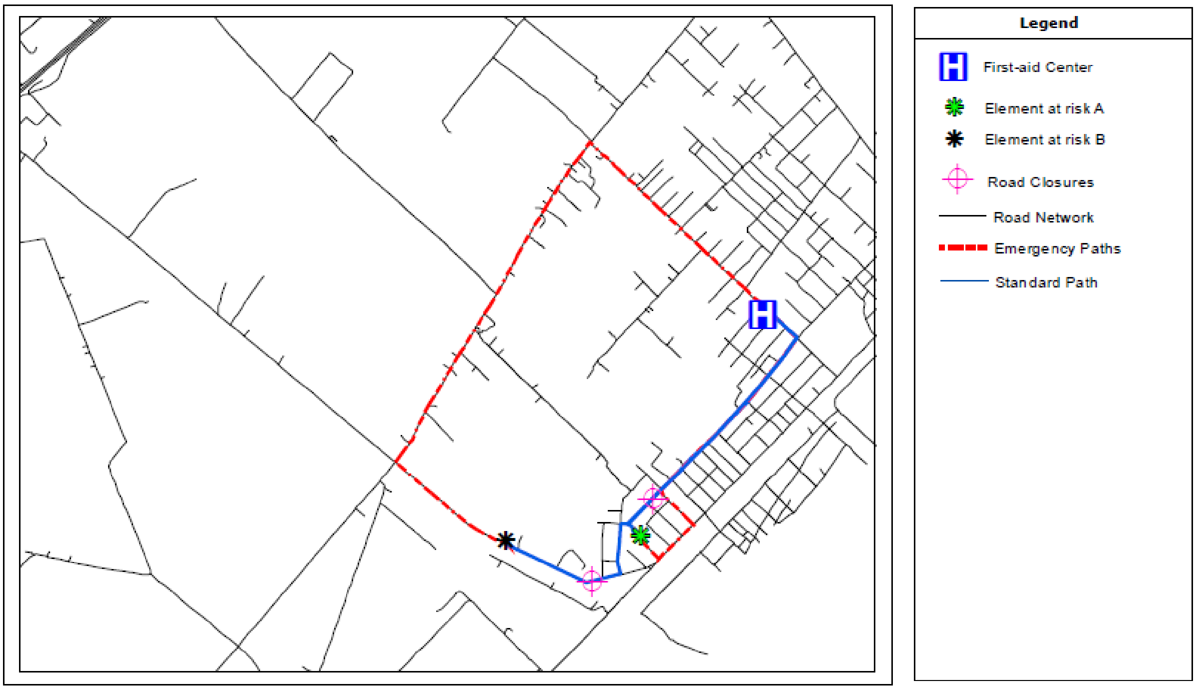

Figure 5. Graphical example of the elements (e.g. standard and emergency shortest paths, origin, (i.e. first-aid centre) and destinations (i.e. buildings at risk), node in which there are road closures) involved in equation 1 and 2.

Considering that each shortest path is composed of a number *k* of arches, an index to estimate the strategic importance of single arches is estimated, and is known as the hierarchy 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 flood prone areas) are the more important arches for maintenance of the emergency management performance.

The hierarchy index, *Hi*, developed in this study represents the number of paths *Ps* that connect the relations "*o/d*", using the arc a_i:

$$Hi = \sum_{od} \left({}^{k_{ai}} \Big/ {}_{NP_{s_{od}}} \right) \tag{3}$$

where k_{ai} is the count *k* of the times that the shortest paths *Ps* used the arch a_i to connect the multiple relations "*o/d*". NP_s is the number of shortest paths *Ps* that connects the multiple relationship "*o/d*". The arch that is more utilized by the shortest paths, i.e. the one with highest k_{aj} (e.g. the one in red in Fig. 6), is of significant importance for the system during emergency management because the performance of emergency services can be affected in a significant way by its inoperability. *Hi* can range between 0 and 1.

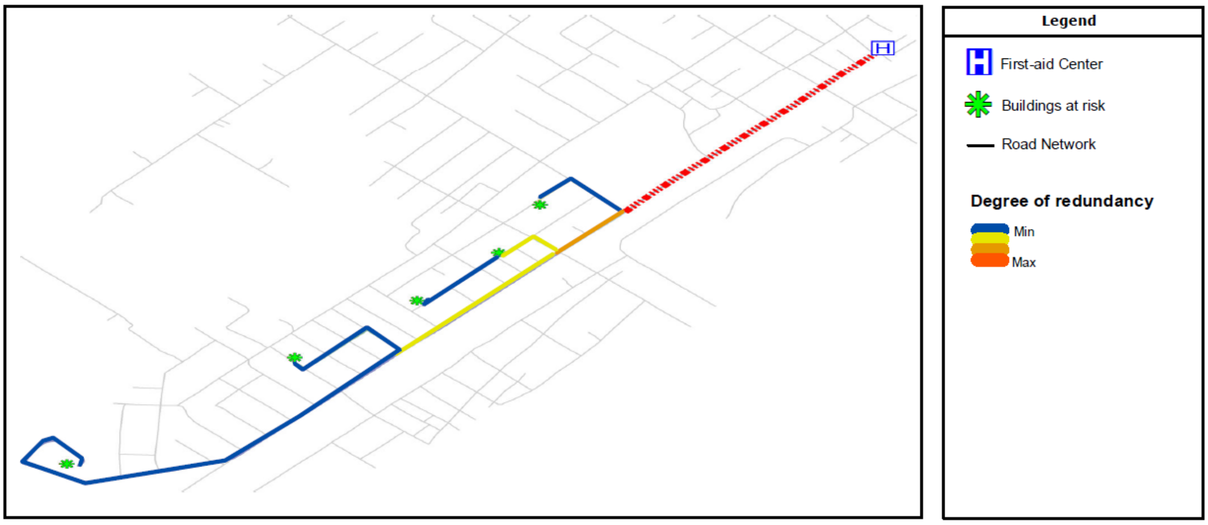

Figure 6. Graphical example of the degree of redundancy of arches that can be utilized by emergency services during the shortest paths that connect "origin" (i.e. in the example, a first-aid centre) with diverse destinations (i.e. the buildings at risk)

The estimation of the hierarchy 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 estimation of possible alternatives for each single arch (i.e. the number of outgoing arcs a_i from the arc a_j) in the case of a flood event:

$$IR_j = 1 - \left[\left(a_{ijs} - a_{ijE} \right) \Big/ a_{ijs} \right] \qquad (4)$$

where a_{ijE} is the number of outgoing arcs a_j from the arc a_i that are inoperable due to the flood events, and a_{ijS} is the number of outgoing arcs a_j from the arc a_i in the normal functioning of the system. The redundancy concepts was introduced by Lhomme et al. (2013) but here is modified in order to considered the situation before and after the flood event. The inverse redundancy index, that ranges from 0 to 1, suggests the number of potential alternative connections between arch a_j and the others related to that being considered in the emergency phase, and, therefore, the number of available and non available arches, in case of flooding, that could be utilized by emergency services, if the arc a_j is inoperable.

Figure 7 shows an example of parameters involved in Eq. (4): the red line is the arc a_i, i.e. the arc to which will be assigned the value of inverse redundancy index; in blue outgoing arcs a_j from the arc a_i that are inoperable due to the flood events, and in green the arcs a_j from the arc a_i that are operable even in the case of a flood event. Therefore, the inverse redundancy of arc a_i in the system could be affected by the presence of more arcs a_j that are inoperable due to the flood events. It means that in the case of inoperability of arc a_j, more arcs a_i are inoperable because the flood event will represent a slowing down in the performance of emergency service that can use less alternatives to the arc a_i during the emergency rescue activities.

Figure 7. Graphical example of the elements, (i.e. arc a_i and its outgoing arcs a_j), involved in equation 4.

Finally, the value of the cube root of the product for each arch derived from the three Eqs. (1), (3) and (4), 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, i.e. buildings at risk, only Eq. (2) (i.e. the impedance index) is used in order to estimate the weakness index of structures at risk for each building.

Finally, an influence index for structures and for infrastructures is estimated based upon the typology of each building or road 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):

$$y_i = a \cdot \frac{e^{-\partial \cdot x_i^{2.2}}}{\left(1 + e^{-\partial \cdot x_i^{2.2}}\right)} \qquad (5)$$

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 estimate 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. It can range between 0 and 1.

Eq 5, as in Pascale et al. (2010), is modified by introducing a correction factor that takes into consideration the population affected by the event, calculated previously in Sect. 2.3.1. The roads and the buildings at risk located in the census area with higher numbers of population at risk have higher values of the influence index, for the same value of the weakness index and the same functions in the system in the case of an emergency.

The influence index takes into account the role of each element in the system in the emergency phase. In this light, the 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 elements at risk 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.

2.4.3 Maximum Impact estimation

Finally, the direct consequence estimation is coupled with the indirect systemic impact in emergency management through a maximum impact index (i.e. phase V of Fig. 1). The maximum impact of each element within the system is estimated by the equation:

$$v_i = \max(y_i, s_i) \tag{6}$$

where s_i is the structural damage, estimated by depth-damage curves as described in the previous subsection (phase III of Fig. 1); and y_i is the influence of the road network on the elements of the territorial systems. The maximum impact index v_i is chosen as a precautionary measure since it highlights the maximum of the direct and indirect consequences. The value of the maximum impact, which can vary in the range [0,1], is the recapitulatory index and it is also precautionary since it considers the highest value between possible direct and indirect damages. The innovative proposed systemic approach that is integrated in a consequence estimation model can only increase the value of the damage by taking into account the inoperability of roads or the isolation of buildings due to the flood event. The choice of taking the higher value between the direct and indirect consequences is justified by the evidence that the summation of the indirect impact index, which represents the influence impact in the system (Sect. 2.4.2), and direct damage, described in Sect. 2.3.2, can cause an underestimation of the maximum impact value due to a flood event: the ratio between the potential maximum value of the summation of the direct and indirect impacts and the estimated impact value is lower than the ratio between the potential maximum value that could be estimated with this methodology, i.e. value 1, and the maximum value, estimated by this methodology, between the direct and indirect impact value, as previously described.

3 Case Study

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 estimation was derived from an analysis of historical data on hydrogeological disasters between the period 1918 to 2000, 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 March 1st, 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

3.1.1 Characterization of the urban system of Ginosa

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 population data are taken from the Italian Institute of Statistics, which stores all the demographical statistics, also in geographical form, for all of Italy ("Geo demo database at demo.istat.it"). The population is aggregated at the census level scale.

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. The discrepancies are related to the different times of the acquisition of the population data (ISTAT, National Institute of Statistics, 2001) and the map of the city which represents buildings and roads, at a scale of 1:5000 (SIT Puglia database, 2011). These discrepancies are not believed to affect the final results of the model application.

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, 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 consequences analysis.

3.1.2 Hydrological and Hydraulic Characterization of the Simulated Scenario.

The scenario utilized for the application of the model is a simulated event that has a return time period closer to the real event of March 1 2011, which occurred in Ginosa, Italy. The maximum discharge of the chosen event, i.e. March 1st 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 2D commercial flood model. For this case study, the Mike Flood model was used since it was deemed to be the most appropriate model for this area as highlighted in Sole et al. (2012), who calibrated the model for the study area, using the Digital Elevation Model of the study area, which includes cross sections of the river embankment extrapolated from laser scanner data. The friction coefficient of the flooded area was evaluated by the land use map at a scale of 1:5000, which is available on the online database of the Puglia Region (SIT Puglia database, 2011).

3.2 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.

Table 4. Flooded area for the different categories of water depth H.

Water depth (m)	Flooded area (m2)
0.0-0.5	9707000
0.5-1.0	7902700
1.0-1.5	5366700
1.5-2.0	2692600
2.0-2.5	1192700
2.5-3.0	687600
3.0-3.5	529800
3.5-4.0	509800
4.0-4.5	471800
4.5-5.0	424100
5.0-5.5	284700
5.5-6.0	153700
6.0-6.5	118900
6.5-7.0	88100
7.0-7.5	81400
7.5-8.0	68000
>8	282300

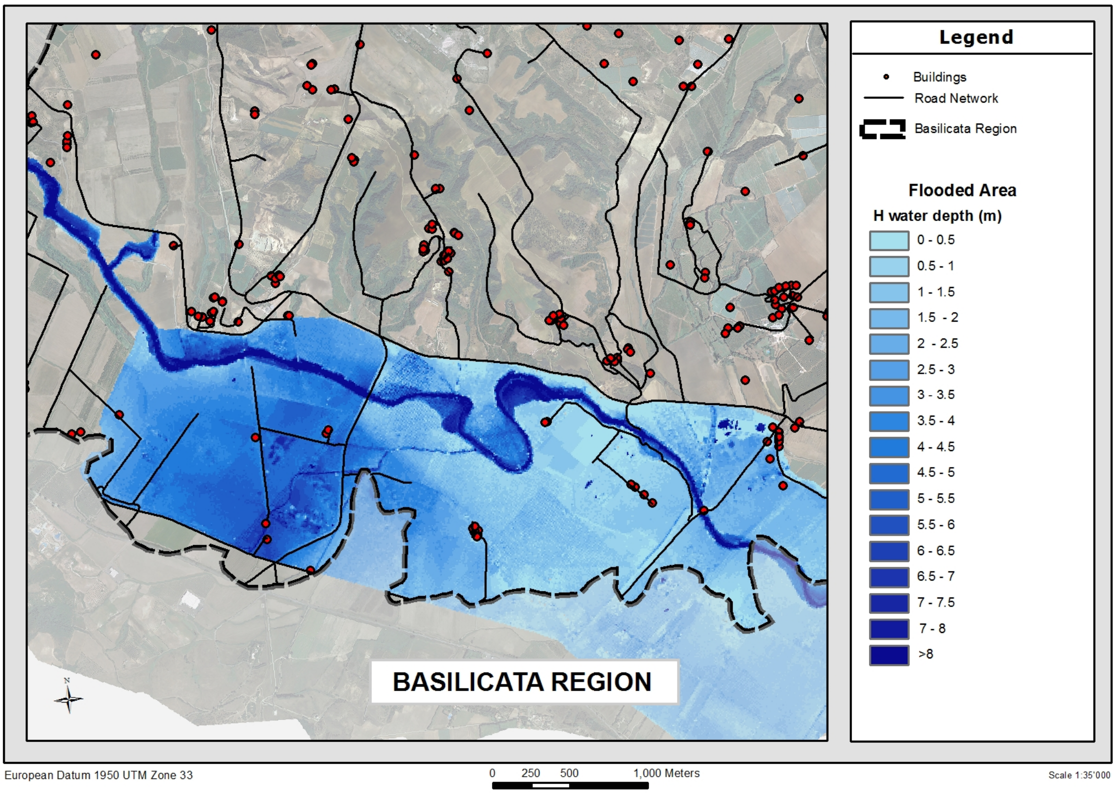

Figure 8. Water depth H from Mike Flood (up-flow).

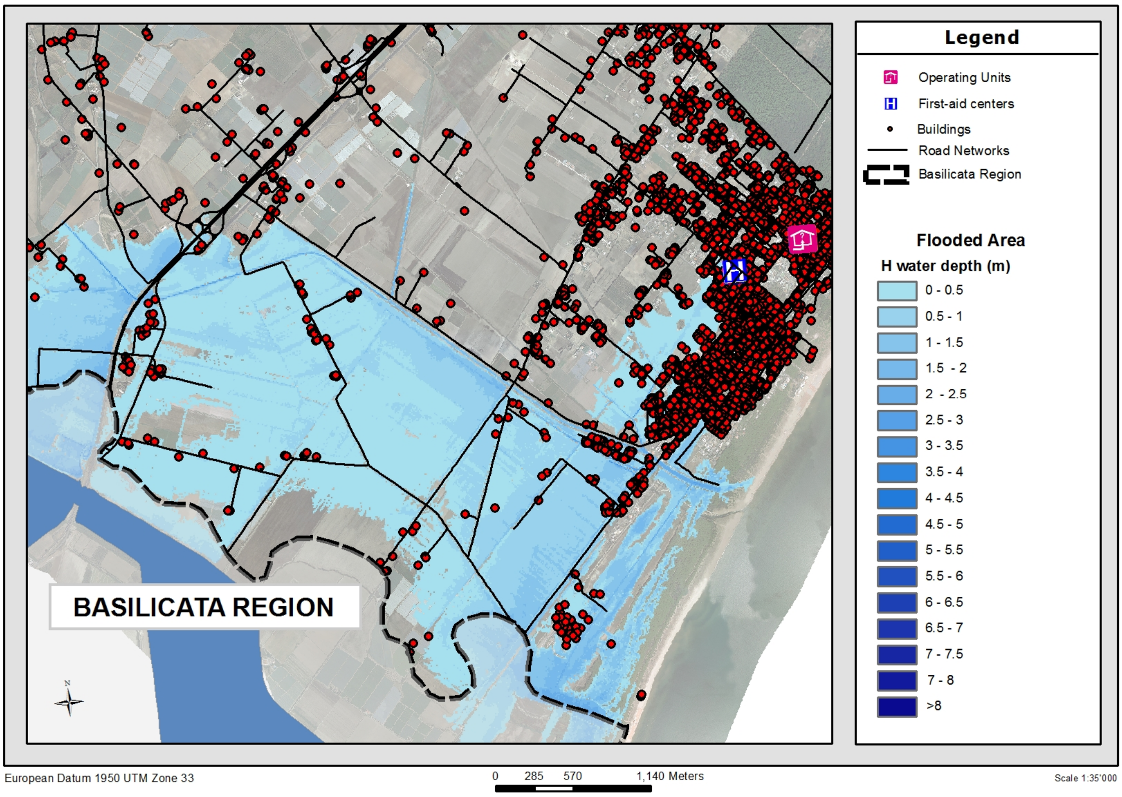

Figure 9. Water depth H from Mike Flood (down-flow).

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. 8 and 9). Hence, the direct economic damage estimation was performed only on the basis of the water depth parameter. The total flood area was determined to be approximately 30561900 m^2(Table 4).

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 flood prone area, in particular SMEs and resorts. In the flooded area, 7% of the population are children or elderly people.

A majority of the people at risk are in the down-flow area, near the sea. Further, the area characterized by the highest fatality rate estimated by the model, and shown in the area colored in red in Fig. 10, is the first zone affected by water flow. The comparison between historical data of loss of life between 2000 (AVI project, 2000) with the estimated degree of loss of life (estimated by the model), and which is represented in Fig. 10 in categories from low to high, is justified by the fact that during the event of March 1 2011, there was no loss of life. As such, it is likely important to validate, in a spatial way, the degree of the potential loss of life in the system.

Historical data on loss of life for 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. 10. 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, in the literature and on the web there is evidence that there has been no public education on flood risk, risk communication, and recent events have highlighted the lack of coordination between emergency agencies and authorities. The low value of loss of life estimated by the model is addressed by the fact that, even though there is evidence of a lack of a warning system and government risk education activity, the Peak Unit Flow Rate is really low in the area due to the lower flow velocity estimated by the 2D numerical flood model..

The total loss of life estimated by the model corresponds to less than 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 March 1st 2011, there were no reported fatalities but substantial displacement of populations and damage to infrastructure, farms and resorts, as highlighted in Table 5 that provides information on the direct economic damage, estimated by the model, considering this chosen flood scenario.

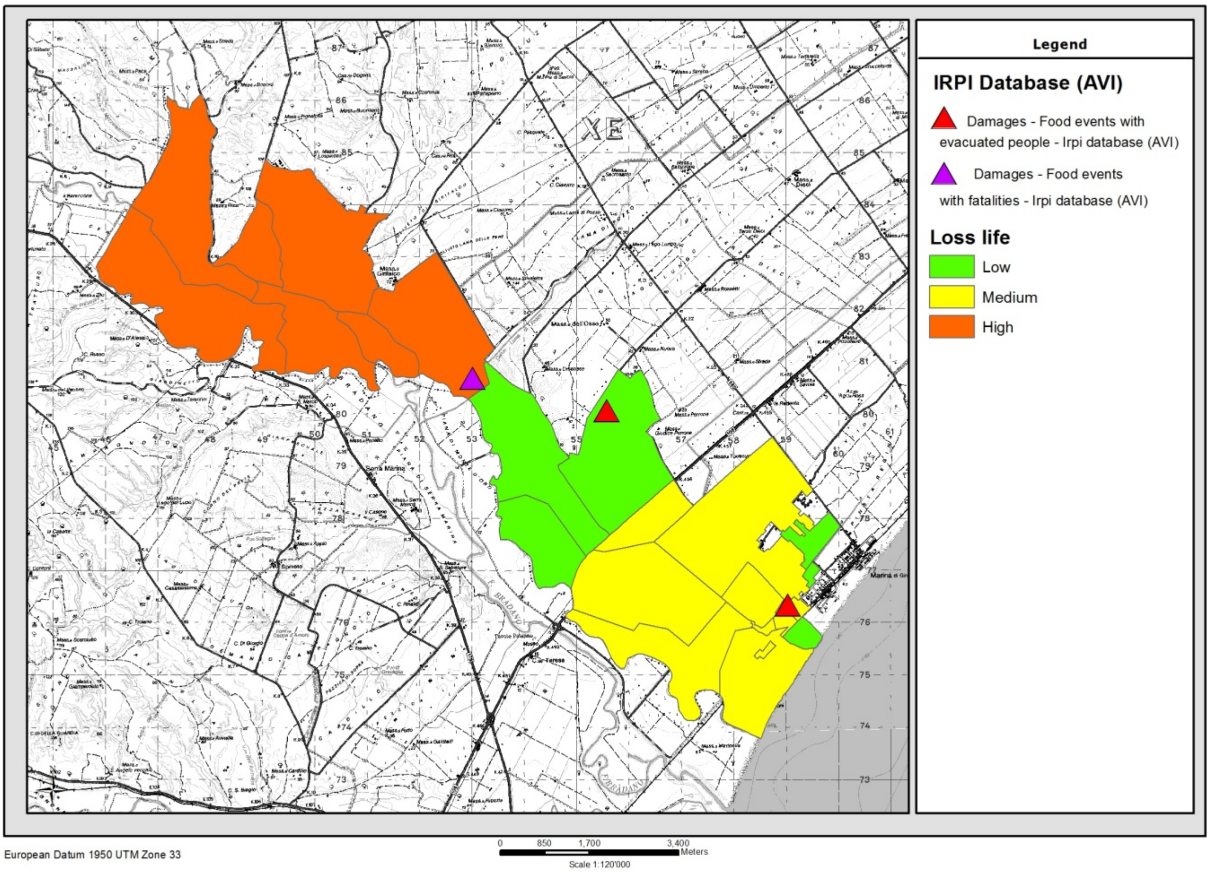

Figure 10. Map of the estimated loss of life divided in categories, (low, medium and high) for the flood event simulated by the model, compared with historical information on the loss of life and evacuation of people (AVI project, 2000).

Table 5. Direct economic damage due to the event simulated by the model.

Occup. Type	Description	Structural value (Euro)	Contents value (Euro)	Structural damage (Euro)	Contents damage (Euro)
IND	Zoothecnical activities	9800000	34300000	0	0
IND	SMEs	12560000	43960000	24000	84000
ReS1 and	Residential Buildings	452300000	226150000	1620000	752500

RES2					
PUB	Public services	7540000	15080000	0	0
TRN	Main roads	48516000	1940676	2528915	735294
TRN	Urban roads	145932500	5836807	6743983	2101124
TRN	Raylways	30694000	1534700	1098666	433887
COM	Hotels and resorts	19050000	38100000	928125	1327500
FAR	Agricultural areas	0	5999187	0	5999187
FAR	Forest areas	0	597750	0	63280

After the March 1st event, the total amount of money requested on the basis of a self-estimation by the citizens of Ginosa to the Italian Government for the damages to their proprieties due to this flood event was around 6'501'741 € (source: "Ordinanza ministeriale del 5 luglio 2012 n. 4024"), in comparison to the 4'736'125 € estimated by the model as direct economic damages.

This discrepancy could be justified by the evidence that the model does not take into consideration the damage caused by pluvial contribution to the flood event (the model simulates only the river flood event). Indeed, the number of buildings affected by the flood estimated in the model is about the 63% of the number of buildings affected by the real event (about 1000 buildings). It should be noted that it is not possible to complete a validation on the other elements (i.e. roads, railways, agricultural areas) involved in the flood event due to a lack of available data from the real event. However, it is possible to make a spatial comparison with photos recorded at 10 observation points throughout the city (Figure 11-13-14), as was done in this study.

Figure 11 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. 11). 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. Indeed, one of the most damaged buildings was the "Torre Sirena" resort, which resulted in one of the highest values of the influence index because it has a high impedance index (Eq. 2 Sect. 2.4.2).

The flood event of March 1st 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. 12. This estimation allows for the identification of potential inoperable road arches that could affect the whole system during the emergency response activities.

Figure 13 outlines the potential fragility in connectivity between emergency centers and the flooded area.

Figure 13 highlights the "S.S. 106" road has a medium value of the influence index and this is justified by the important function that "S.S. 106" has in the system: this road is a highway, i.e. a "Strada Statale" in accordance with the Italia Road Classification, and it is an important connection between the operative centers located in the central part of the city and the buildings at risk located in the area closer to the sea. Figure 13 also shows that the roads closer to the first-aid centre, i.e. the element represented by the blue rectangle with the white "H", is colored in orange and this means that they have a high value of influence index. This is justified because this road has an elevated value of the hierarchy index (Eq. 3 in Sect. 2.4.2).

Figure 14 highlights that the maximum impact estimation is important to identify hotspots such as the main road, "S.S. 106", that 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. 14).

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 model adopted and the value of flood emergency management planning.

The proposed model outlined in this paper provides a quantitative estimate of flooding consequences on the basis of direct impact estimation, i.e. structural and economic loss estimation, and an estimation 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.

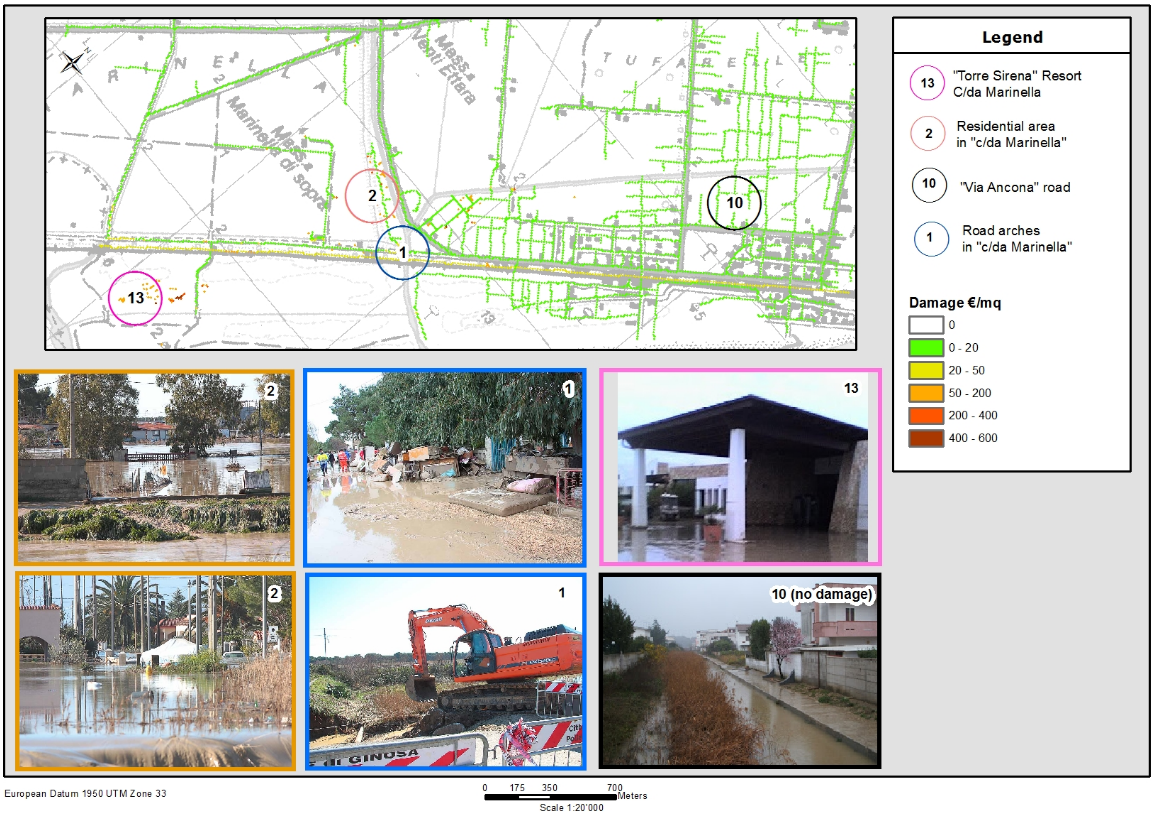

Figure 11. Direct damage estimation.

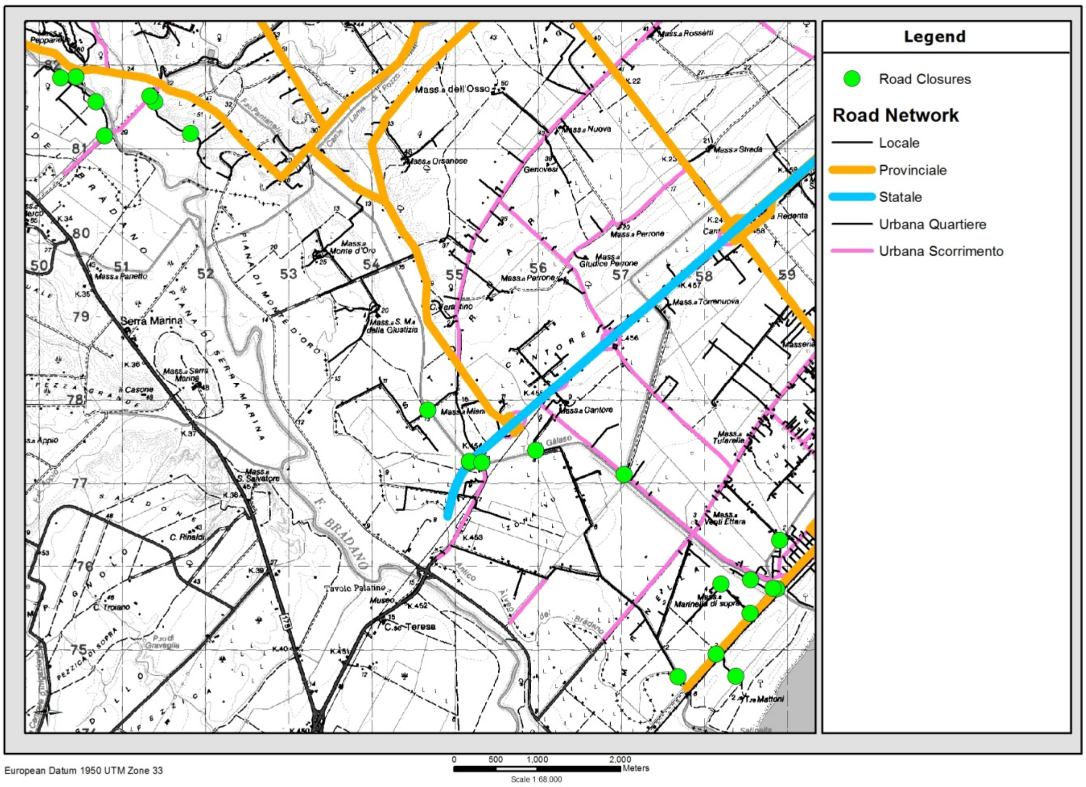

Figure 12. Road closures due the chosen scenario.

Figure 13. Influence index estimation.

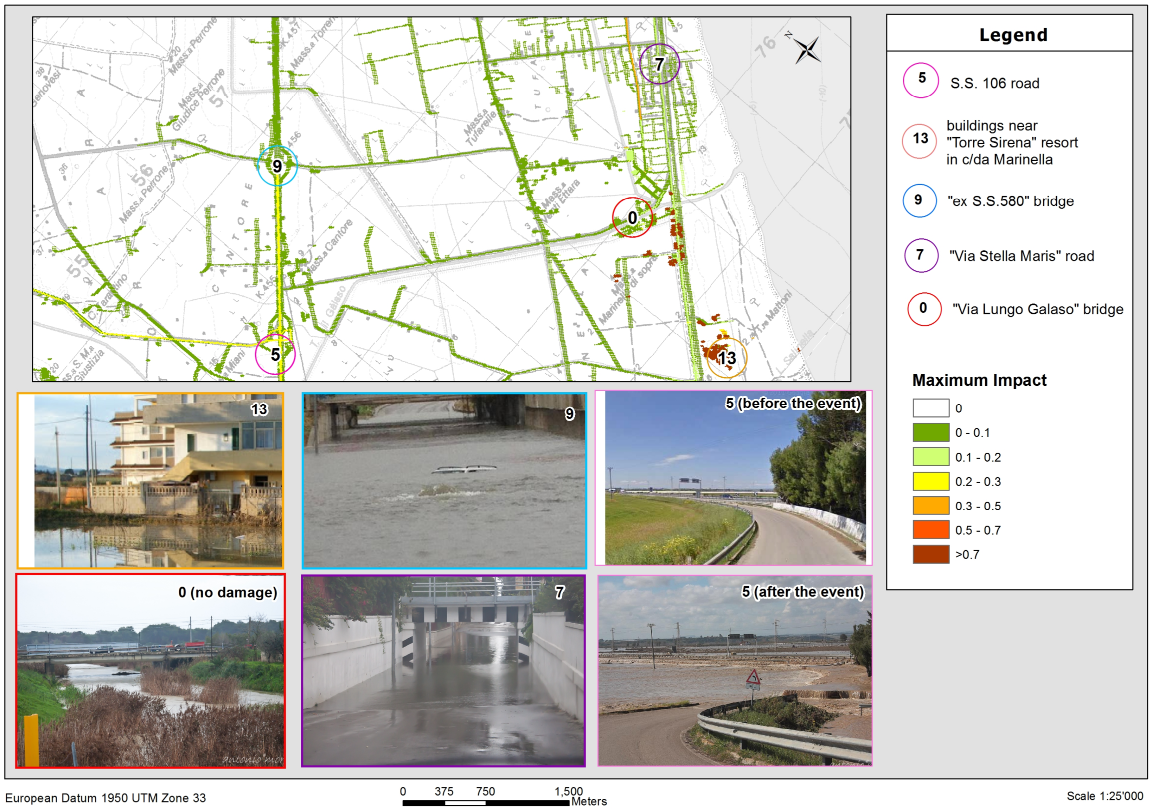

Figure 14. Maximum impact estimation.

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 assistance. 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.

4 Conclusion

This paper has presented a new approach to integrate the analysis of an accessibility and operability model for estimation of the strategic elements in the emergency phase associated with a consequence estimation model 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 direct and indirect estimation of flood consequences 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 consequence estimation 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, and could highlight the areas that need priority interventions. The latter could be extremely useful in cases of limited financial resources.

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 analysis of direct and indirect risk, implementing in the model the possibility of simulated diverse flood scenarios characterized by diverse probabilities of occurrence, in order to obtain a probability of the maximum impact of the structure and infrastructure within the system. In addition, the estimation of the economic cost of systemic loss during the emergency phase could provide more information on prioritizing risk mitigation 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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