



Preparedness against mobility disruption by floods

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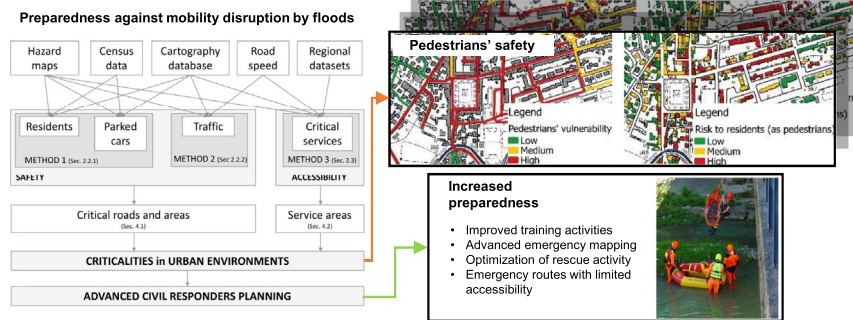
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HIGHLIGHTS

- A flood risk analysis is developed to increase Civil Protection preparedness.
- Detailed data and models, e.g. hydraulic and transport, provide operational tools.
- Safety and accessibility issues are modelled to evaluate urban resilience.
- Safety issues include risk for pedestrians, parked vehicles and drivers.
- The reduction of service areas in accessing critical structures is evaluated.

GRAPHICAL ABSTRACT



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ABSTRACT

Civil responders currently have limited information available to them to support flood incident planning. A new generation of tools are emerging that produce more detailed understanding of flood impacts on people and accessibility during floods. These are typically applied in isolation, providing only a partial assessment of impacts. This paper integrates analysis of flood hydraulics, transport accessibility and human safety to explore the impact of flooding on pedestrians and drivers, and its implications on emergency routes and service areas. A reference scenario, developed and used by the local Civil Protection Agency, is applied to Galluzzo in Florence (Italy). Results shows that 37% of inhabitants live close to roads where they can be swept away, and 78% live in locations where parked vehicles can be transported by floodwaters. Furthermore, at its worst 22.5% of road extension is inaccessible; and all hospitals, fire and police stations cannot be reached, highlighting the need to take preventative action from the outset of an event that is predicted to lead to substantial inundation. Integration of multiple indicators of flood impacts, especially those most relevant to human safety, is fundamental to civil responders if they are to successfully planning and implement emergency response operations in urban environments.

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1. Introduction

Preparedness is crucial to reduce the impact of extreme events such as floods on lives, livelihoods and communities (Petrucci et al., 2017), and is a key component of the Sendai Framework (UNISDR, 2015). Prevention and emergency provisions serve primarily to plan preparedness

and limit the impact of hazardous events, like flooding. Climate change is projected to further increase the magnitude and frequency of extreme events (IPCC, 2012). Preparation measures may include: (i) readiness for intervention; (ii) emergency operation and rescue; (iii) early warning systems; (iv) recovery and recondition (FOCP, 2014). This paper focuses on the first two of these.

Floods affect more people worldwide than any other hazard and are the main risk faced by European emergency management authorities (EC, 2017; Guerreiro et al., 2018). In Europe, Article 6 of the Floods

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Directive (EU Parliament, 2007) requires preparation of flood hazard and risk maps at appropriate scales. In Italy, the Protezione Civile or Civil Protection (CP) department is responsible for emergency and preparedness. Similar organisations can be found in the UK (Environmental Agency), Switzerland (Crisis Management Board), USA (Federal Emergency Management Agency) and in other countries around the world.

1.1. Limited existing flood risk information for preparedness

The CP carries out exercises to improve the logistics of emergency operations, to evaluate the coordination system and to increase citizens' awareness and education. These involve people and organisations responding to a simulated flood event. The CP's emergency planning relies on flood maps issued by river basin districts which have a number of shortcomings. Flood depths are not always mapped and the main information consists in an aerial extent of inundation. Furthermore, the information on flow velocity, which is crucial to assess risk to people (Arrighi et al., 2017; Arrighi et al., 2015; Jonkman and Kelman, 2005; Milanese et al., 2015), is not available.

A more in-depth analysis is needed for the identification of both vulnerabilities and risks, in order to increase the effectiveness of emergency plans, especially at municipal scale (Dawson et al., 2011; Pilone et al., 2017). In particular, to understand the vulnerability of the population, requires consideration of the density of the population and roads used by a high number of vehicles (Demichela et al., 2014).

Studies have shown that the majority of fatalities during floods occur outdoors when people attempt to drive or walk in floodwaters (Fitzgerald et al., 2010; Kellar and Schmidlin, 2012; Salvati et al., 2018). Floods also affect the road network, with consequent traffic disruption and service interruption (Pregolato et al., 2017a; Pregolato et al., 2017b). Roads underpin mobility within urban areas and are especially important during emergencies because the resilience of a community relies upon fast connection to shelters, critical infrastructure and blue light services (Abdan and Zairul, 2017). A crucial concern for emergency activities is the logistics of operations and road accessibility (Green et al., 2017; Mejia-argueta et al., 2018; Coles et al., 2017; Rodríguez-Espíndola et al., 2018). Roads therefore play two important roles for vehicles and pedestrians mobility during floods: on one hand, they are scene of fatalities; on the other hand, they allow for rescue and evacuation operation. Identifying the areas more likely to be cut off in case of hazard is fundamental for flood risk management and preparedness (Jalayer et al., 2014).

1.2. Aim and overview

This paper integrates three state of the art flood risk analysis components developed to support flood incident response and improve preparedness by enabling civil protection organisations to answer the following questions:

- How many residents are at risk of being swept away either on foot or by car in proximity of their properties?
- How many roads are inaccessible during and after the event?
- How many critical locations (e.g. school, hospitals) are accessible by emergency vehicles during and immediately after the event?

Following this introductory section, the methodology is described in Section 2, the case study location in Florence is introduced in Section 3, with results from the analysis provided in Section 4. These are discussed in Section 5 before drawing conclusions.

The results of a detailed 2D hydraulic model are used to (i) assess the population at risk based on state of art methodologies, (ii) evaluate dynamically the dangerous roads to be closed to traffic, (iii) identify service areas to hospitals and hotspots. This work represents a non-

standard application of flood risk mapping (EU Parliament, 2007) with the following peculiarities with respect to existing literature:

- (i) The work is oriented towards a reduction of vulnerability through flood preparedness (Rodríguez-Espíndola et al., 2018) rather than territorial planning/management (Molinari et al., 2016), addressing the challenge of stimulating risk reduction where no extreme event occurred in the recent past (Kreibich et al., 2017);
- (ii) The risk analysis is carried out at the micro-scale to respond to the needs of emergency planning as advocated by CP experts (Pilone et al., 2017; Demichela et al., 2014);
- (iii) Several aspects of mobility (i.e. pedestrians, parked vehicles, travelling vehicles, service areas) are integrated to produce a complete picture of flood impacts, as opposed to silo-based approaches (Coles et al., 2017; Green et al., 2017; Pregolato et al., 2017b; Singh et al., 2018). These aspects can be related to different exposure conditions (e.g. night-time or holidays are better represented by the analysis for pedestrians close to their homes; for working days issues for travelling vehicles are more relevant);
- (iv) It is a quantitative, scenario-based analysis focusing on functionality loss and safety issues, as opposed to traditional monetary estimation of losses (e.g. for buildings or agriculture (Oubennaceur et al., 2018; Merz et al., 2010), as appropriate for infrastructure (Pregolato et al., 2017b).

2. Material and methods

Flood Risk Assessment (FRA) comprises a number of factors, not limited to rainfall or discharge, but inclusive of socio-economic and physical characteristics. When assessing risk, three elements are considered: the hazard (key metrics of the hazard like flood depth), exposure (e.g. land use), vulnerability (e.g. damage-loss functions) (Hall et al., 2003; Apel et al., 2004; Grossi and Kunreuther, 2005; De Moel and Aerts, 2011). This modular consideration of risk is functional to take into account the characteristics of both the natural (hazard) and built environment (assets).

The study employs a typical framework for risk assessment that includes hazard and impact analysis, but integrates across a number of human safety and mobility functions (Fig. 1) to provide a more comprehensive understanding of risks to people during a flood emergency.

This integrated method represents an advanced instrument for civil responders, since it mitigates the shortcomings of current hazard zonation (maps by river basin district, issued for catchment scale flood management), which do not provide information on inundation dynamics and spatial distribution of flood velocities. Flow velocities are particularly relevant to assess safety issues concerning people, i.e. pedestrian and driver's vulnerability in a certain flood scenario. Moreover, the CP implements training exercises and emergency plans mostly based on expert judgement with regards to road closures, detours, shortest/safest routes to hospital. The methodological framework here presented provides a quantitative tool to assess both safety and accessibility issues and facilitates the decisions of civil responders.

2.1. Hydrology and hydraulic modelling

The starting point involves production of hazard (flood) maps. To be consistent with the approach of the CP, a reference rainfall event has been used. The MOBIDIC (MOdello di Bilancio Idrologico DIstribuito e Continuo) hydrological model is used to transform the rainfall data into river discharge. MOBIDIC is a distributed and raster-based hydrological balance model (Yang et al., 2014; Castelli et al., 2009; Campo et al., 2006). MOBIDIC is the official operational tool of the regional hydrologic service of Tuscany for flood prediction since 2005.

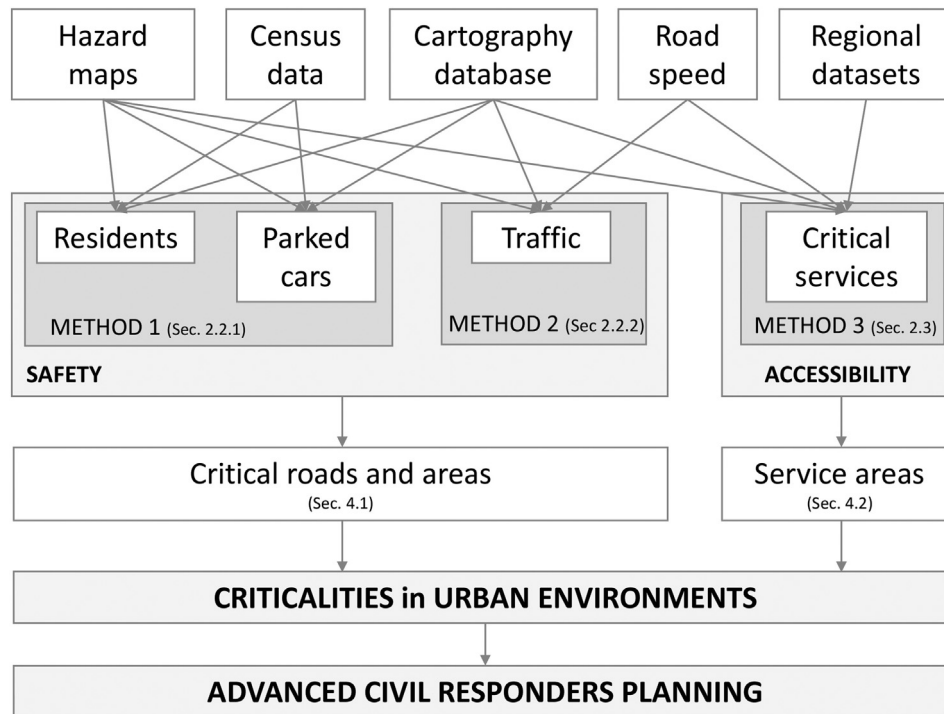


Fig. 1. Methodological framework to assess urban vulnerability by considering a range of factors, namely: (i) pedestrians; (ii) parked cars; (iii) travelling vehicles; (iv) critical services (such as hospitals).

Inundation is simulated using the hydraulic model TELEMAC-2D, which solves the shallow water (Saint-Venant) equations using the finite-element or finite-volume method and a computational mesh of triangular elements (Hervouet, 2007). 2D representation with a high-resolution Digital Terrain Model is the best compromise because allows for a proper description of flood parameters (i.e. water depth and velocity) in the street-building pattern. The mesh is generated in Blue Kenue and provides rectangular grid and triangular mesh. The triangular mesh generator allows the user to specify “hard points” and “break-lines” which are preserved during node/element creation. Break lines are used to properly represent buildings with an assigned minimum element size of 2 m at the building boundary to capture complex flow arrangements in the urban environment, but up to 8 m in open areas. The Blue Kenue interpolator tool allows the user to assign to each mesh node the elevation of the 1 m resolution LiDAR-derived Digital Terrain Model with 0.15 m of vertical accuracy. Input data to the grid generators can include GIS shapefiles, such as building and road polygons (see Table 2). The outputs of the hydrological and hydraulic modelling are high-resolution (raster) flood maps of flood depth and velocity, output at 15 min intervals, for the given flood scenario.

2.2. Safety issues

2.2.1. Impact to pedestrians and parked vehicles

In case of flood warning, the CP warns people to stay at home and go to upper floors when possible. However, analysis of fatalities has shown that people suffer injuries while moving in the surrounding of their homes (i.e. their local neighbourhood). In particular, walking and driving in floodwaters are identified as the main danger for people during floods (Fitzgerald et al., 2010; Salvati et al., 2018; Kellar and Schmidlin, 2012; Ashley and Ashley, 2008).

2.2.2. Vulnerability of pedestrians

The stability of a human body has been investigated through conceptual models (Abt et al., 1989; Milanesi et al., 2015), experimental analysis (Abt et al., 1989; Foster and Cox, 1973; Jonkman and

Penning-Rowell, 2008; Karvonen et al., 2000; Xia et al., 2014; Martínez-Gomariz et al., 2016) and 3D numerical models (Arrighi et al., 2017). Similarly, also the stability of parked vehicles has been investigated by a range of studies (e.g. Arrighi et al., 2015; Shu et al., 2011; Xia et al., 2011).

Arrighi et al. (2017, 2015) identified relative submergence (i.e. the ratio between flood depth and person’s height) and the Froude number, Fr , as the most relevant parameters to assess the vulnerability of pedestrians and parked vehicles, thus the critical thresholds can be evaluated by using the existing experimental data represented through these dimensionless variables (Fig. 2). A regression curve from experimental data of human stability (Karvonen et al., 2000; Foster and Cox, 1973; Jonkman and Penning-Rowell, 2008; Xia et al., 2014; Martínez-Gomariz et al., 2016) can be written as:

$$\frac{H_{crP}}{H_p} = \frac{0.29}{0.24 + Fr} \quad (1)$$

where H_{crP} is the critical flood depth, and H_p is the height of the subject, the ratio H_{crP}/H_p is the relative submergence. From Eq. (1), H_{crP} can be easily derived and compared to actual flood depth H . If H/H_{crP} is lower than one the human subject is stable, if the ratio equals one the subject is at the threshold of instability, else it is unstable (i.e. extremely vulnerable).

2.2.3. Vulnerability of parked vehicles

The regression curve evaluated from the experimental data of the stability of parked vehicles (Xia et al., 2011; Shu et al., 2011) can be written as:

$$\frac{H_{crV}}{H_v} = -0.05 \cdot Fr + 0.34 \quad (2)$$

where H_v is the height of the vehicle and the ratio H_{crV}/H_v is the relative submergence. If the water depth is larger than the critical water depth

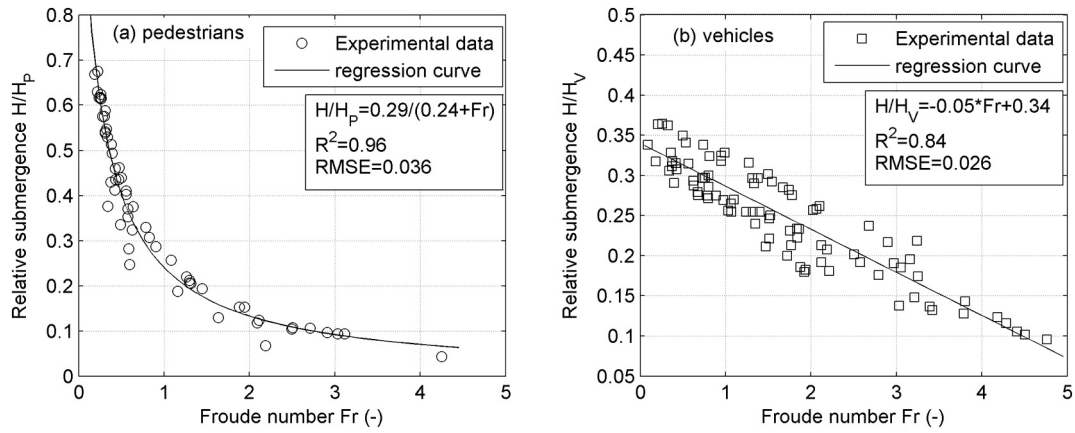


Fig. 2. Regression curves used to assess the vulnerability of pedestrians (a) and parked vehicles (b) based on the experimental data by Jonkman and Penning-Rowse (2008), Xia et al. (2014), Martínez-Gomariz et al. (2016), Karvonen et al. (2000), Foster and Cox, (1973), Xia et al. (2011), Shu et al. (2011) and on the dimensional study by Arrighi et al. (2017, 2015).

H_{crv} , the vehicle is expected to be mobilised by floodwater (i.e. highly vulnerable).

In this work, for mapping purposes the vulnerability of pedestrians and parked vehicles is represented by means of the ratio between flood depth and the critical depth. When the ratio equals 1, the person or vehicle is at the equilibrium; when the ratio exceeds 1 the person or vehicle is highly vulnerable to being moved by the floodwater (see Table 1 for vulnerability classification, V_{ped} for pedestrians, V_{vp} for parked vehicles).

2.2.4. Exposure

We assume people to be in the surrounding of their homes (e.g. for checking the status of their property or trying to move the car to a safer position), the residential population density is used as a proxy of the distribution of people (i.e. exposure) during a flood warning. Residents' exposure is evaluated at the building scale by downscaling population data available at the scale of census polygon. Census polygons coincide with building blocks in dense urban settlements, while in less dense districts may reach an extent of the order of 0.5–1 km². To analyse at a street-building scale, census data are disaggregated with the following procedure. First, in the census polygons, a volumetric people density DP_{vol} is calculated using the population P , the total residential built-up area A and the average number of floors f to obtain the average density of people for each floor.

$$DP_{vol} = \frac{P}{A \cdot f} \tag{3}$$

Then, DP_{vol} is assigned to the residential buildings inside the census polygon in a GIS environment. Finally, the people density DP (people per square meter) is evaluated at the building scale by multiplying DP_{vol} for the number of floors of the buildings

$$DP = DP_{vol} \cdot f \tag{4}$$

Risk to people is evaluated considering the two main circumstances of fatalities, by combining vulnerability (of pedestrians and parked

vehicles) and exposure (residents' density). Based on the criteria of Eqs. (1), (2) and vulnerability classes for roads (Table 1), buildings are assigned a vulnerability value according to the mean value of vulnerability in a buffer of the building polygon. The vulnerability value assigned to each building is a measure of how much the surrounding area of the building is dangerous for pedestrians' instability or mobilization of vehicles. The population density at building scale DP is then multiplied by the vulnerability class, and finally normalized over the maximum to obtain the risk.

2.2.5. Travelling vehicles

Journey time reliability is considered the key output measure to assess the performance of a transport network (Smith and Blewitt, 2010). Transport models allow the mathematical modelling, or simulation, of transportation systems to inform the design process, by representing the stretches of roads (links, and their nodes), users, and users' routing.

Here, changes in time and distance between origin and destinations as a result of flooding is analysed by coupling a network model with the hazard assessment, using a transport network disruption model developed by Pregolato et al. (2016). This evaluation consists of calculating the disruption to network links as a result of the flooding simulation, comparing pre- and post-event travel times. The simulated floodwater depths (see Section 2.1) are spatially overlapped with the road network, defining the impacted portion of roads for the analysis. Floodwater reduces speeds, or stops entirely traffic flows according to the depth of inundation. A disruption function, developed by Pregolato et al. (2017b), relates water depth to safe driving speed (Fig. 3).

Roads are considered impassable (therefore closed) when the flood depth reaches 300 mm, the depth at which a standard saloon or estate car is unable to operate (Gissing et al., 2016; Kramer et al., 2016; Pyatkova et al., 2015; Shand et al., 2011; Yin et al., 2016). For the flooded scenarios, the network properties of a link (e.g. travelling speed) are modified according to this relationship, and traffic parameters recalculated for this perturbed state. Subsequently, journey travel time will increase in comparison with the baseline scenario.

Similarly to the approach for parked vehicles (Section 2.2.1) for mapping purposes the vulnerability of travelling vehicles is summarised using three vulnerability classes using the ratio between the simulated flood depth and the critical threshold of 300 mm. Travelling vehicles stop when the ratio equals 1, while for values lower than 1 they can still move but at a reduced speed (Table 1).

2.3. Accessibility to critical locations

Flood emergency plans usually lack detailed information on accessibility and evacuation operations, on the basis of prior analysis of critical structure and infrastructure (Coles et al., 2017; Green et al., 2017). This

Table 1
Classification into vulnerability classes based on the ratio between flood depth and critical depth.

Ratio between flood depth and critical depth	Vulnerability class (V_{ped} for pedestrians' vulnerability; V_{vp} for parked vehicles; V_{vm} for moving vehicles)
<0.5	Low
0.5–1	Medium
≥1	High

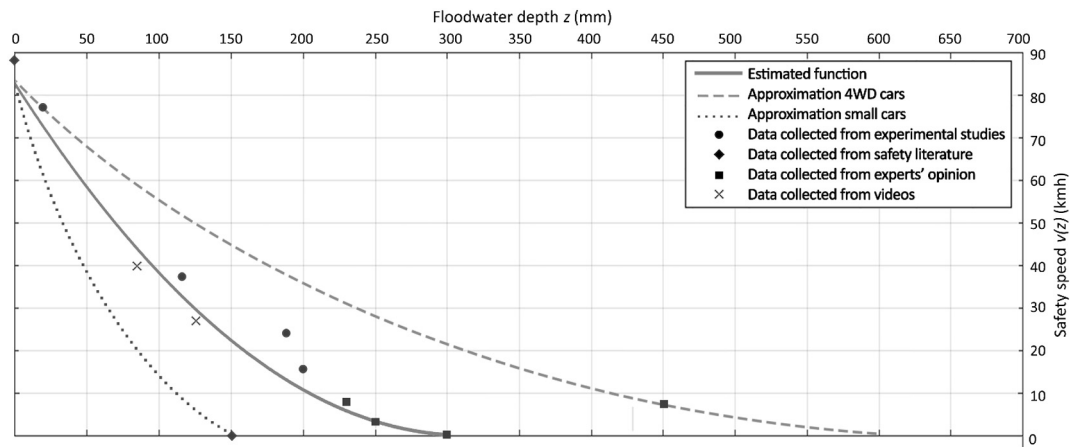


Fig. 3. The flood-transport curve that establishes the relationship between floodwater depth and safety speed of travelling vehicles (Pregolato et al., 2017b). 300 mm is the ultimate limit for passenger cars (e.g. Suzuki Swift).

is important in the light of considering potential needs of vulnerable groups, such as pupils in the schools, who may need rescue or assistance.

The response of emergency service is legislated as 8 min for urban areas in Italy (GU n.126 30/5/1992). Flooding can produce main disruption on road networks as indirect damages to services and undermine response times.

During emergencies, critical structures include hospitals, fire stations and Civil Protection sites; vulnerable structures include schools and care homes (Coles et al., 2017; Green et al., 2017). Such hotspot identification provides strategic information regarding urban dynamics and urban planning, which can be used to understand the most likely impacted structures. Accessibility can be studied by means of a network service area, which consists in a region that covers all accessible streets within a specified impedance time. For instance, given a point on the network, all the accessible roads within ten minutes from that point represent the 10-min service area. Following the methodology outlined by Coles et al. (2017), service areas were used for evaluating accessibility, and analysing for which hazard scenarios a district has to deal with reduced or without emergency service provision.

The transport model in Pregolato et al. (2016, 2017a, 2017c) is used to compute service areas of emergency vehicles for two conditions:

(i) normal, unperturbed conditions (baseline); (ii) following disruption due to floods (disruption scenarios). The transport model can provide information on traffic flows and accessibility, by considering speed reduction, road closures and re-routing of vehicles as a result of floods.

3. Application

3.1. Case study description

The methodology described in Section 2 is applied to Galluzzo, a southern district of the city of Florence (Central Italy, Fig. 4a). Galluzzo has a population of around 12,000 inhabitants and is located at the confluence of Ema and Greve creeks, which have a catchment area of 121 and 283 km² respectively. The district is located at the crossing of two important traffic arteries (via Senese and via Volterrana) and close to the highway exits. Thus, Galluzzo is a crucial route for accessing the city of Florence from the southern municipalities (Fig. 4b).

The CP of the municipality of Florence has selected the Galluzzo district for a real scale exercise because the area is mapped in the Flood Risk Management Plan at high flood hazard (Fig. 4c). A key part of this involved undertaking a live exercise of a simulated incident to help:

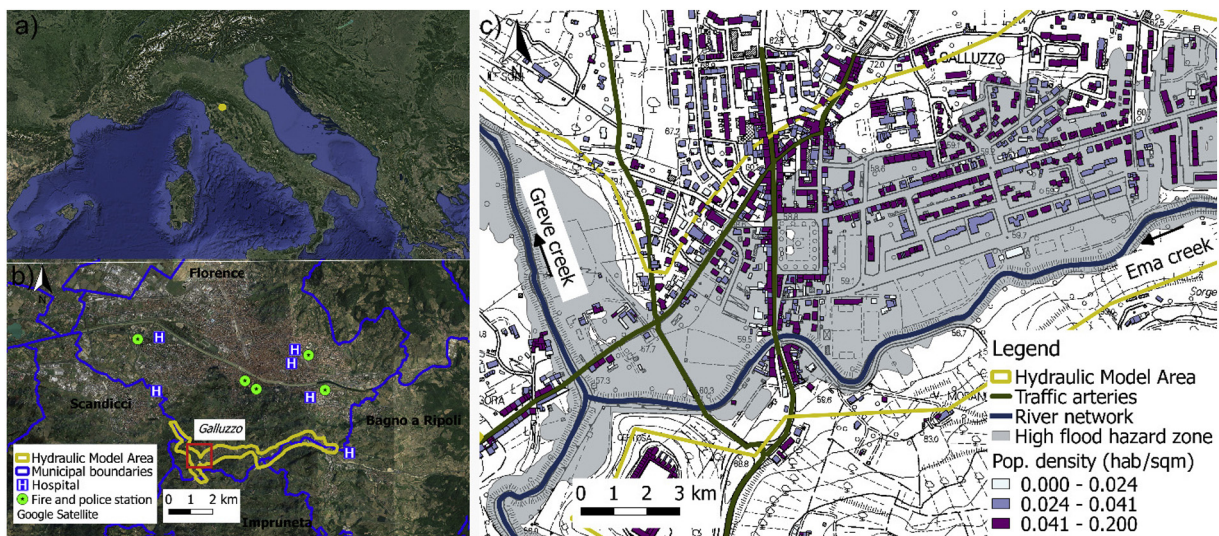


Fig. 4. Location of the study area in central Italy (a), hydraulic model area comprising four municipalities and location of Galluzzo district (b), zoom of the Galluzzo district with main traffic arteries, creeks, population density and high flood hazard zone from Flood Risk Management Plan (c). (Source: Autorità di Bacino Distrettuale dell'Appennino Settentrionale- Web Gis).

i) train CP personnel and volunteers, ii) test coordinating system and logistics, iii) raise citizen awareness.

A what-if scenario based on a rainfall event that occurred in October 2013 in a nearby catchment (Servizio Idrologico Regione Toscana, 2013) was selected as reference. Thus, the 2013 event was shifted 65 km in the northern direction to affect the Greve and Ema catchments.

3.2. Data

The different models used in this work rely on several sources of geospatial data. The hydrologic model requires pieces of information about precipitation, terrain morphology (i.e. slope, altitude), soil properties, land use. The hydraulic model requires Digital Terrain Model (DTM), road network, river network and buildings to create the computational mesh and assign a roughness coefficient. The areal extent of the hydraulic model is about 4.2 km² (Fig. 4b); the modelled Greve and Ema reaches are 4.2 and 8 km long respectively.

The traffic model requires spatial information about the road network, including the road type for each link (e.g. regional cartography database). Speed limits are attributed by road type using the national road regulation. Location and name of main critical structures (e.g. hospitals, fire or police stations) could be obtained from regional datasets or search engine (such as Google).

The risk assessment requires census data for apartments and population (ISTAT, 2011) and building footprint. Table 2 summarizes the data used in the work, their description and source; similar datasets are available for most countries worldwide, albeit in cases where global datasets they are likely to be at a coarser resolution.

4. Results

4.1. Flood maps

The reference rainfall event comprises two peaks (T1, T2) with hourly maximum rainfall of 30 mm and 45 mm for Greve and Ema respectively, and cumulative rainfall of 635 and 780 mm over the 15 h duration. These rainfall peaks correspond to river discharge peaks of about 370 m³/s and 500 m³/s for Greve and Ema respectively (see Fig. 5a and b) that occur approximately 2 h after peak rainfall. Fig. 5a and b show the precipitation and discharge for the Greve and Ema creeks respectively. For the first flood peak (T1) water depth reaches 1 m (Fig. 5c); the flood map is compared to the extent of the official high flood hazard zone (green line, recurrence interval of 30 years) showing a good accordance and consistence with the cumulate rainfall of the beginning of the event. For the second flood peak (T2), water depths exceed 1 m for the whole district and reach 3 m (Fig. 5d); the flooded area exceeds the official high flood hazard zone and shows a strong similarity with the medium hazard zone (between 100 and 200 years recurrence interval).

Table 2
Summary of the data used and their source.

Models	Data	Source
Hydrology	Rainfall event	Regional hydrologic service report
	DTM (10 m resolution)	Regional hydrologic DTM
	Land Use-Land Cover (1:25000)	Regional Land-Use map
Hydraulics	Pedology (1:25000)	Regional cartography database
	High-resolution DTM (1 m)	Municipal high resolution DTM
	Road network (1:2000)	Regional cartography database
	River network (1:2000)	Arno river catchment authority
	Building footprint (1:2000)	Regional cartography database
Traffic	Roughness coefficient	Arno river catchment authority
	Road network (1:2000)	Regional cartography database
Residents	Hotspots (1:2000)	Regional road regulation
	Population and apartment census	Regional cartography database
	Building footprint (1:2000)	ISTAT
		Regional cartography database

Flow velocities during the event are locally of the order of 3–4 m/s in the Ema and Greve creeks and reach peaks of about 1.5 m/s at T1 and 3 m/s at T2 in the urbanised area. Flow conditions are supercritical also during flood propagation in the road network, but most of the district is characterized by subcritical flows ($0.2 \leq Fr \leq 0.5$). The inundation dynamics can be viewed in the two videos submitted as Supplementary material (Videos 1 and 2).

4.2. Safety issues

4.2.1. Drivers and parked cars

The impact of flooding was assessed on the roads of Galluzzo. By spatially overlapping the output of the flood model and the road network, the disruption to roads was assessed. Fig. 6 compares the vulnerability of parked vehicles (Fig. 6a and b) and traffic disruption (Fig. 6c and d) for two selected simulation times corresponding to the two flood peaks T1 and T2 (see Fig. 5). The maps highlight that the threshold of 300 mm for road closure is more conservative than the one for parked vehicles vulnerability, i.e. a road is not accessible to drivers before the threshold of instability of parked vehicles is reached. This may not be verified in case of highly supercritical flows and water depths lower than 300 mm where parked vehicles are mobilised. For the Galluzzo district, the traffic is partly disrupted for T1 and highly impacted at T2 where all the main arteries are affected, with heavy consequences on emergency activities (see Section 4.3, Fig. 8).

4.2.2. Risk to residents

The vulnerability of pedestrians and parked vehicles are calculated for all timesteps, the peak values are presented here. The critical flood depth H_{crp} is calculated for an adult 1.7 m tall (the average Italian adult) then the ratio between actual flood depth and critical flood depth is evaluated. Fig. 7a shows the peak pedestrian vulnerability, i.e. the worst conditions of the event, at single road scale. Several roads are classified at high vulnerability (red lines in Fig. 7a) especially in the centre of the district where most of the activities and the main square are located (left hand side of the map) or at strategic crossings (e.g. the river crossings). The risk to the resident population (pedestrian) is computed by combining the maximum vulnerability and the exposure (i.e. the population density) (Fig. 7b). Residents at risk are evaluated at building scale counting the people living in each vulnerability class. Table 3 summarizes the resident population in proximity of the different dangerous areas for pedestrians and parked vehicles.

Results shows that about 37% of the resident population lives in high vulnerability areas for pedestrians. The situation is more severe for the risk related to parked vehicle instability. In the study area, about 78% of the resident population lives in high vulnerability areas. This means that attempting to move a parked car to a safer position is extremely dangerous for the residents for the reference scenario. This is a crucial piece of information to citizens in order to be better prepared on how to behave during flood warnings.

4.3. Accessibility issues

City-wide disruption is assessed by considering the accessibility to critical assets, such fire station and hospitals. Flood maps were integrated with a geographical analysis of the areas served by emergency services vehicles (e.g. ambulances) considered the accessibility to the town centre (e.g. public schools). The service areas were calculated using the transport model (Section 2.2.2) for the baseline, at the times T1 and T2, considering the maximum time allowed by the Italian legislation to emergency response, i.e. 8 min.

Fig. 8 shows the area accessible by emergency vehicles in 8 min of travelling time in normal condition (Fig. 8a), at T1 (Fig. 8b) and at T2 (Fig. 8c). Visual comparison shows the substantial scale of disruption caused by flooding to the town, with the service area/number of people

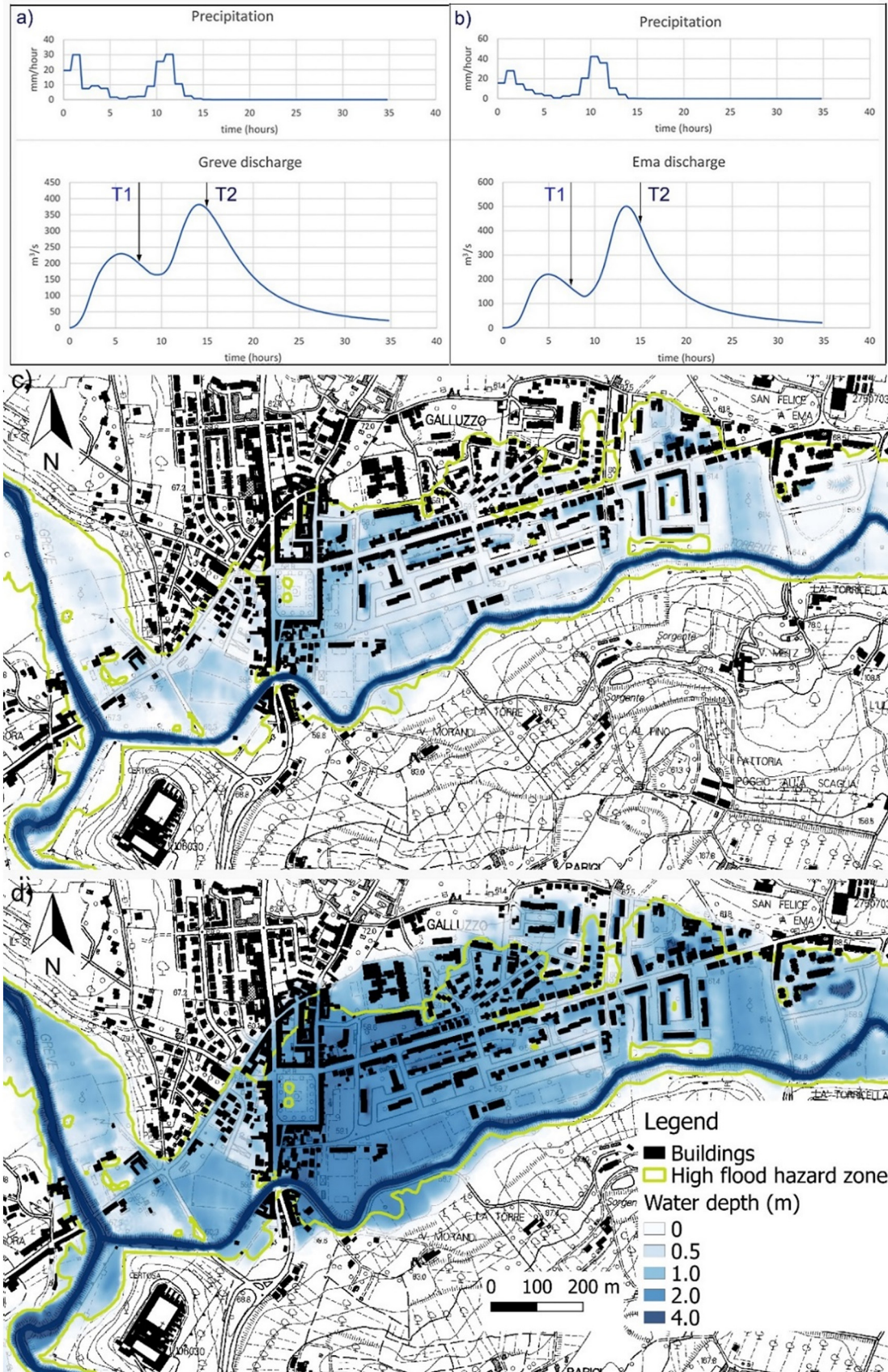


Fig. 5. Rainfall event and discharges obtained by the hydrologic model for Greve (a) and Ema (b) creeks. Flood depths at T1 (c) and at T2 (d) respectively occurs after 7 h and 15 h from the start of the rainfall event.

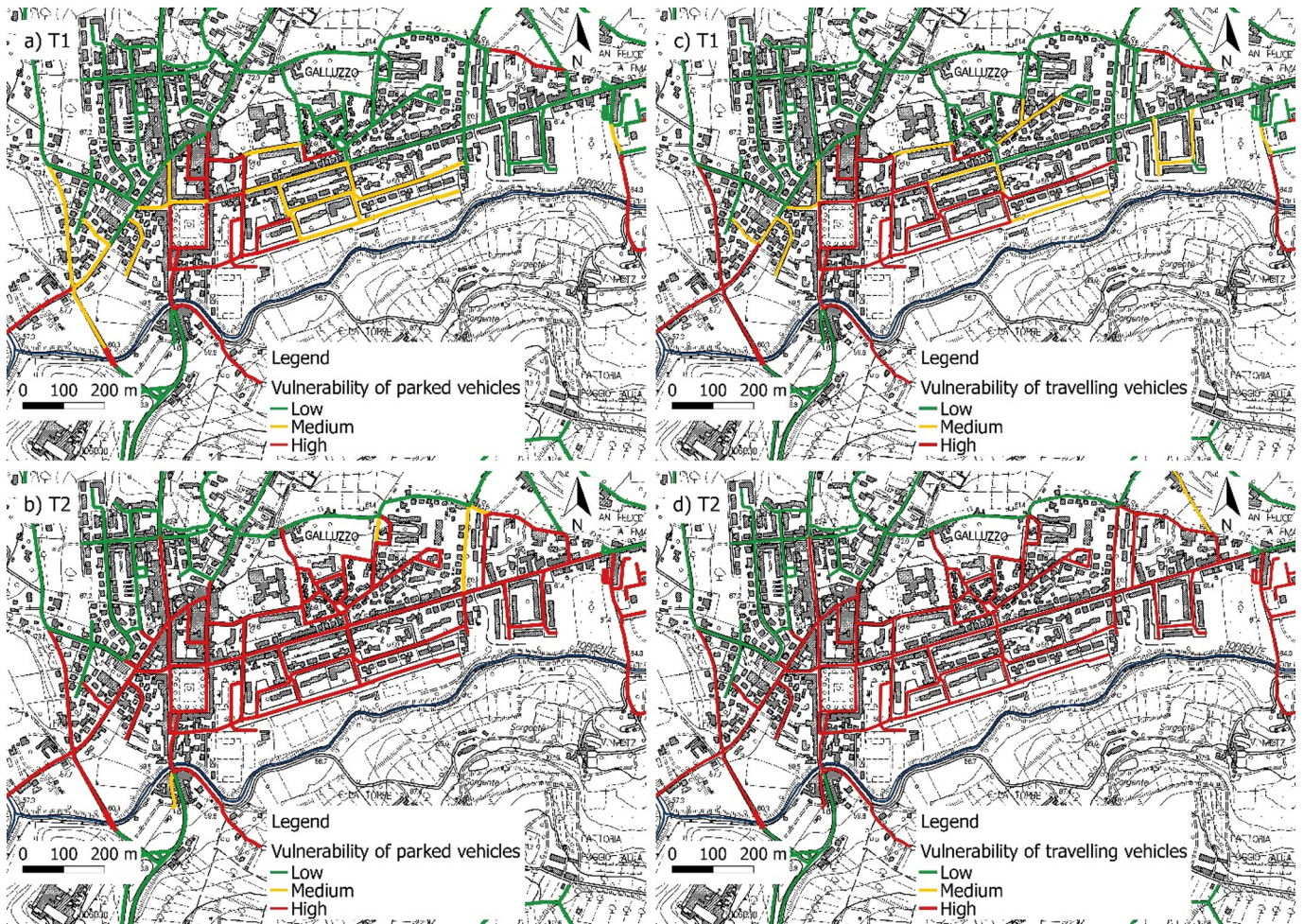


Fig. 6. Comparison at times T1 and T2 between potentially dangerous roads for parked vehicles (a, b) and travelling vehicles (c,d). The vulnerability is represented by means of the ratio between flood depth and the critical depth (the higher the ratio the higher the vulnerability).

that can be serviced shrinking from 110.5 km² to 56.3 km² and 4.1 km² at T1 and T2 respectively.

For the baseline (a), the critical structures serve a wide part of the region, including the town centre of Galluzzo. For T1 (b), the town centre can still be reached for evacuation operations, although the overall coverage is reduced, i.e. one of the closest hospitals cannot be reached. For the peak T2 (c), the town centre cannot be accessed by any hospital or fire/police station, and they are cut off from emergency operations.

5. Discussion

5.1. Limitations and implications of assumptions

The use of resident population as proxy for exposure is an important assumption for risk assessment. This working hypothesis is selected both to extend the risk assessment method and fit the needs of a real scale application. It is justified by the observation of recent flood events in Italy (e.g. 2017 flood in Livorno and 2018 flood in Cagliari), where most of the fatalities occurred in proximity of the victims' property. Generally, population exposure shows relevant differences according to the time of the day, particularly for those districts which are mostly residential and/or are important traffic junctions as the one in this study. For particular case studies also the presence of tourists or workers may present a seasonal pattern and can be clustered around special areas (e.g. museums or attractions). With the information provided about pedestrians or drivers, the CP itself may decide its priority on vulnerability depending on the time of the day the flood is expected. For

instance, for late evening or early morning events (which correspond to the peak traffic times) the CP can refer to the results for travelling vehicles.

The service area analysis is strongly dependent on the scale of the study. According to the critical origins and destinations of interest, the considered network could widely vary and include metropolitan areas outside the administrative jurisdiction where the flood event is taking place.

The impact resulted from the transport model is a minimum estimation for various assumptions (Pregolato et al., 2016; Pregolato et al., 2017a). Among these, the transport model assumes that drivers have optimal knowledge of the network and of the disruptions due to flooding on their journeys, so that they can re-route their journey minimizing the travel time. Vehicle-to-vehicle interactions, traffic lights and non-flood disruptions (e.g. roadworks or accidents) are ignored. The low-complexity enables fast and low data-demanding computations, while still capturing the transport analysis underpinned by this paper. Moreover, a specific curve for emergency vehicles (similar to Fig. 3 for passenger vehicles) should be developed and implemented, since ambulances and firefighters vehicles are likely to have different characteristics (e.g. speed, engine) from common cars.

5.2. Verification of the results

While the individual components of the overall simulation (the flood model, the baseline transport model) have been validated separately, validating the disruption modelling is more complex. The

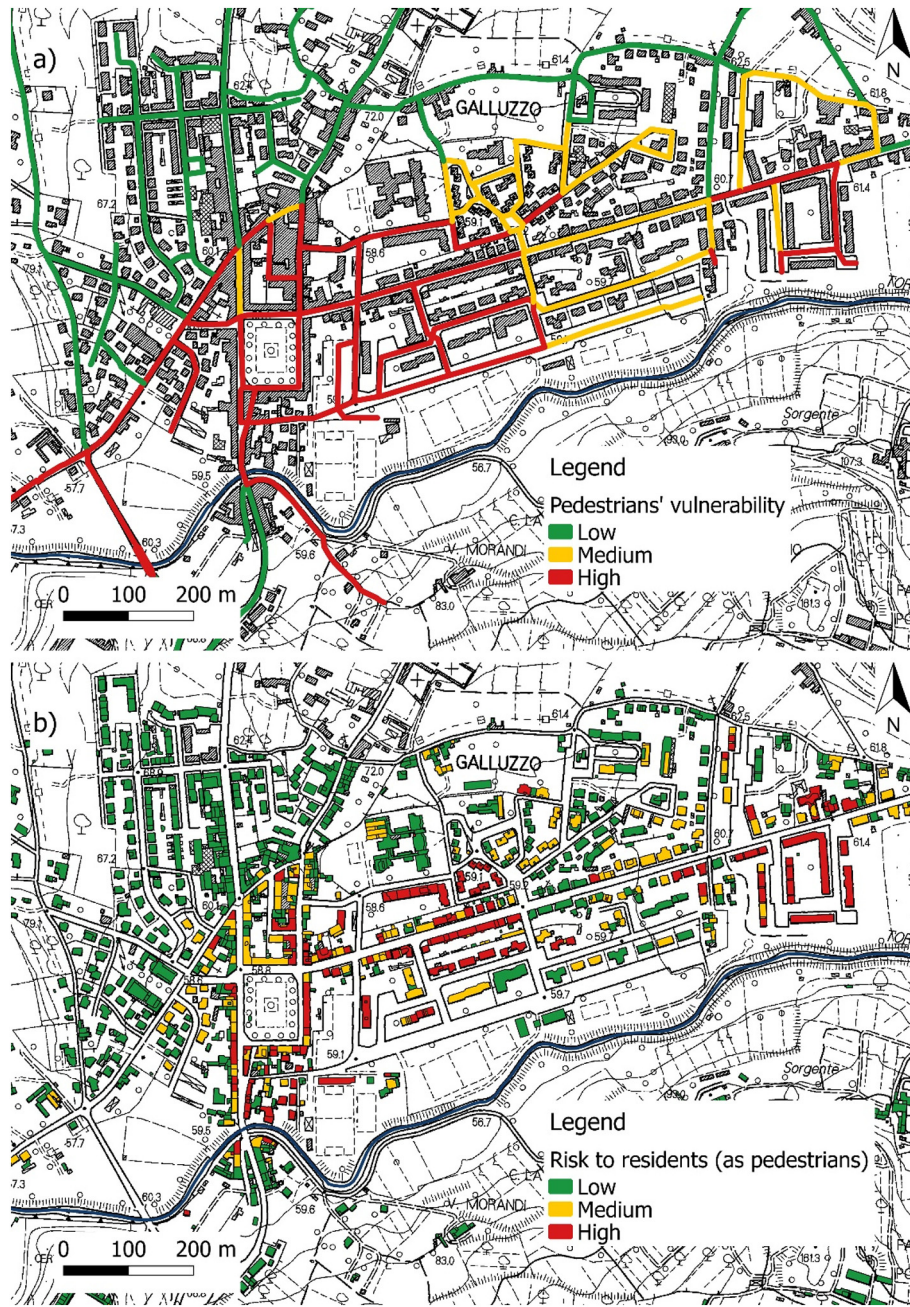


Fig. 7. Maximum vulnerability of pedestrians over the event in the flooded area (a) high vulnerability values indicate that the threshold of instability for an adult 1.7 m tall is exceeded. Risk to resident population considering the vulnerability of pedestrians (a) and population density at building scale (b). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

cooperation and exercise with the CP provided expert judgement-based validation of the overarching analysis, which has been carried out with state-of-art best available approaches.

Since past inundation data in the study area are lacking for validate modelling outputs, a sensitivity analysis of the inundation map with

respect to the roughness coefficient was carried out (see Supplementary material). The roughness parameter is assigned to the Ema and Greve streams based on visual inspection of the bed conditions (Arno River Catchment Authority, personal communication) and for the channels validated against water level measurements. A second simulation was

Table 3
Resident population at risk based on pedestrian's vulnerability (risk of being washed away as pedestrians) and parked vehicle vulnerability (risk related to mobilization of parked cars).

Pedestrians' vulnerability class	Resident people at risk (hab.)	Resident people at risk (%)	Parked vehicle's vulnerability class	Resident people at risk (hab.)	Resident people at risk (%)
Low	3954	32.7	low	1695	14.0
Medium	3638	30.1	medium	881	7.3
High	4497	37.2	high	9513	78.7
Total residents: 12089					

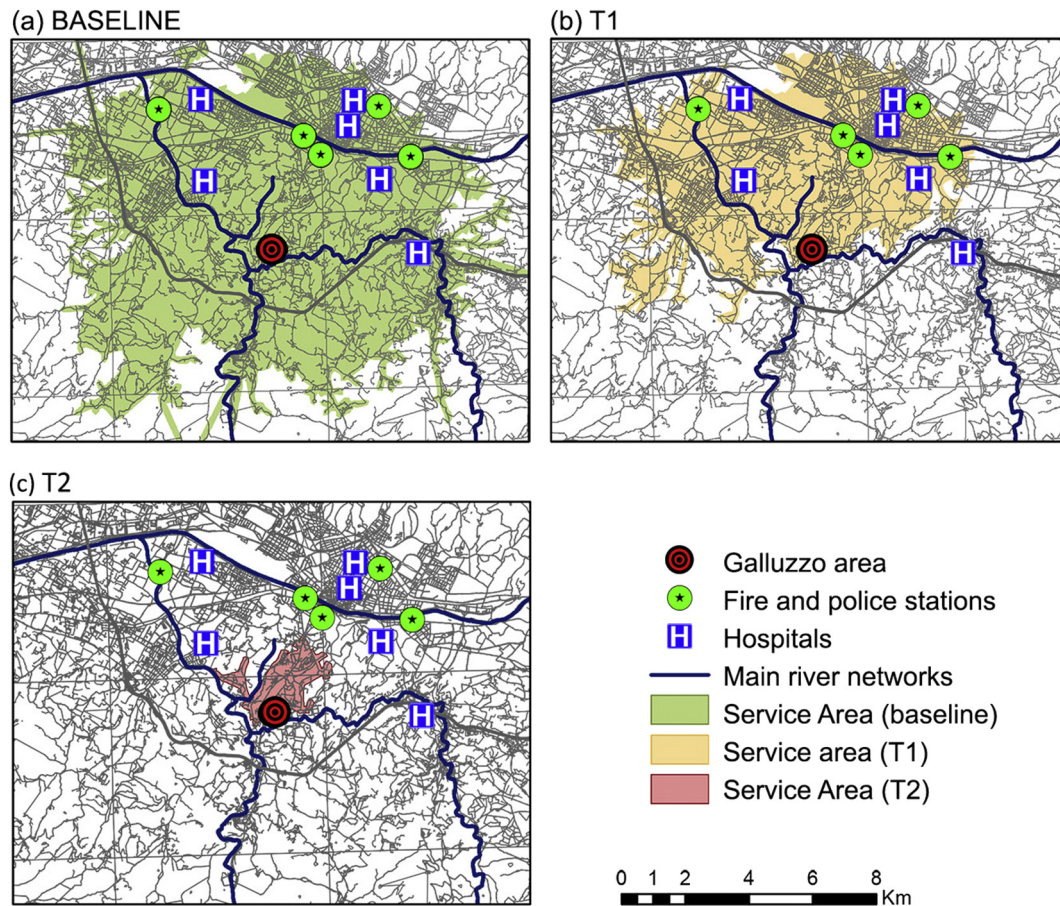


Fig. 8. Emergency responders' service areas (8 min. radius) considering the town center of Galluzzo as destination for (a) the baseline, (b) at T1 and (c) at T2.

run with roughness parameter (0.025 for clean gravel channel and 0.016 for asphalt) increased of 20%. The sensitivity analysis showed a limited influence (about 0.02 m variation in water depth, i.e. a few percent) in the urban area, so the hydraulic model was considered robust enough for the purpose of the study. Larger differences of the order of 10–20% are observed at the boundary of the inundated area due to the sharp terrain morphology. However, flood depth in flat areas can be more sensitive to local changes of roughness parameters, thus the uncertainties of the model should be clearly evaluated and communicated to the stakeholders.

Overall, the comparison with the official hazard maps showed a very good agreement in terms of inundation extent of the two flood peaks, which statistically correspond to a low recurrence interval scenario (30 years return period, T1) and to a medium recurrence interval scenario (100 years return period, T2). In such a sharp terrain morphology, a coincidence in terms of inundation extent is also positive in terms of expected flood depth.

The baseline of the transport model was verified with Google maps by comparing travel times (Pregolato et al., 2016), whereas validation of the disrupted traffic model and of the pedestrians/parked vehicles stability models was based on CP expert knowledge of past flood events occurred in the Italian context. In fact, similar criticalities (e.g. issues in hospital accessibility, road and bridges closure) to those underlined by this study arose in the discussion with the CP.

5.3. Implications of the results for emergency management

The integration of several models, i.e. hydrologic-hydraulic model, pedestrians/parked vehicles stability model and traffic model is functional for describing a comprehensive picture of the different impacts on road infrastructure and citizens, including both safety and

accessibility issues. The results demonstrate the importance of having detailed information to describe the flood extent, dynamics and magnitude, and the consequences on accessibility, pedestrians' mobility and traffic flows. The use of this approach constitutes a significant advancement for planning the preparedness of civil responders who currently organize training activities and produce emergency plans based on a coarse flood hazard zonation (at catchment scale) and expert judgement. Moreover, the proposed methodology addresses in a broad perspective, the reduction of citizens' vulnerability (awareness of risk for pedestrians, parked vehicles, drivers, analysis of criticalities in reaching hospitals) by increasing flood preparedness.

Although the CP was aware that risks to pedestrians and parked vehicles were possible in the area (see also the description of exercise activity Section 5.4 and Fig. 9), their difficulty was in spatially distributing the vulnerability and quantifying the residents at risk. This quantification is possible with the proposed methodology. The classification of the population at risk based on physical criteria can only be obtained with a high-resolution 2D analysis, as the one proposed in this work. The use of the official flood risk management plans only allows the CP to identify the number of affected people based on inundation extent, but without evaluating actual risk.

By comparing the results obtained from the analysis of pedestrians and in-motion vehicles, the study showed that vehicles in motion constituted a higher danger for the community. During the most impactful peak (T2), almost all the road of the town centre are not safely practicable, whereas only some of them (West of Galluzzo) are highly dangerous for pedestrians' mobility. This result is a crucial information for the dissemination to citizens during the exercise (Section 5.4) in order to promote safe behaviours during floods.

The analysis between parked cars and vehicles in motion raises few points of reflections. Parked cars may have a lower threshold for being

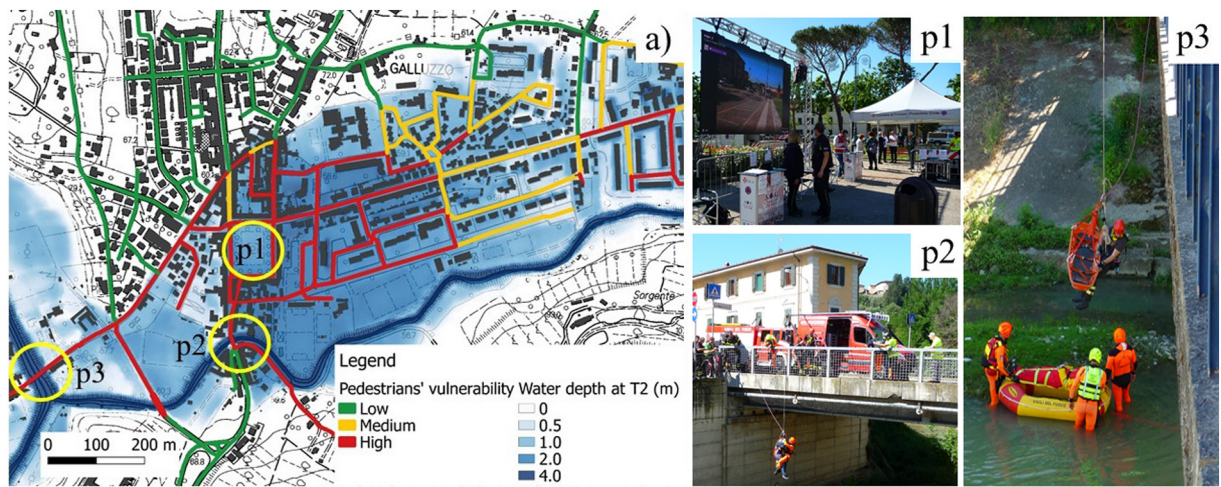


Fig. 9. Vulnerability map for pedestrians and flood depth at T2 (a) and location of some of the activities carried out during the CP exercise of May 2018. Storytelling, education and description of the event (p1), rescue activities of people in high vulnerability areas (p2, p3).

washed away with respect to the ultimate limit of roadworthiness (30 cm) for supercritical flows. Therefore, roads estimated safe for drivers could be potential location of cars swept away while parked along the streets.

Parked cars impact and residents risk correspond to a more static scenario, where the worst conditions were considered. This because, in case of event, the alarm is issued by the CP for the whole duration of the event – without distinction between the various timesteps since the affected population is assumed “static” in a safe place. When analysing travelling vehicles and emergency service areas, the analysis is more dynamic and the temporary evolution is of great interest for the emergency services. For example, this is fundamental for identifying the best “time window” during an event that allows rescue and evacuation operation. For this case study, it was demonstrated that during the first peak (T1) hospitals were still accessible, whereas they were not for the second peak (T2). This results can be translated by CP into the need to place rescue activities within the first 15 h, or for more severe events (T2) to carry out first aid activities on site instead of reaching the hospitals (Section 5.4).

5.4. Civil Protection exercise support

This case study was developed in co-working with the CP of Florence, focusing on the exercise run on the 19th May 2018 (Fig. 9). The exercise was useful to verify the results of the study, highlighting the limitations of both our models and the CP's current practice. Before the exercise, the main interactions with the CP consisted in understanding the CP's needs, sharing data (e.g. rainfall scenario information), and identifying critical aspects of the area. During the exercise, the researchers acted as external observers to check if the exercise was consistent with the simulated scenario. After the exercise, comments and suggestions were de-briefed by co-working with stakeholders.

Before the event, the CP informed the population about the process, raising awareness about risks and safety (Fig. 9, photo p1). During the exercise, one of the main tasks was the simulation of road closures by the local police in coordination with the CP. Road closures were set at the four boundaries of the district in correspondence of the edge of highly vulnerable road segments in the Northern, Eastern, Southern and South-Western directions (see Fig. 6d) to simulate the precautionary stop of traffic. Vehicle circulation on the three bridges were also temporarily interrupted (Figs. 4c, 6d). Two simulations of rescue activities of people swept away by floodwaters were also carried out in proximity of the main bridges classified as highly vulnerable for pedestrians (Fig. 9, photos p2, p3).

In these circumstances, the study showed that advanced hazards maps are optimal for developing impact analysis on pedestrians, parked cars and drivers to identify infrastructural criticalities that could not be done with currently available mapping. For example, since accessibility issues were known (i.e. the CP was aware that the routes to the closest hospitals could be impracticable), the CP planned to carry out first aid activities on site instead of reaching the hospital for the less urgent cases.

6. Conclusions

This paper developed a flood risk assessment of the safety of pedestrians, traffic and emergency provision. This was demonstrated on a case study (Galluzzo, Florence, Italy) to support the municipal Civil Protection department. The analysis provided significantly improved information on the spatial and temporal aspects of flood impacts, integrating information on the risk to pedestrians, drivers and accessibility to critical facilities such as schools, hospitals and fire stations. In this case study >33% of the population lives close to roads in which they can be swept away by floodwater, and 78% of the population lives near roads where parked vehicles can be mobilised by floodwaters. This highlights the need for clear messages to ensure people evacuate or remain in other locations or on upper building floors if flooding occurs in their local neighbourhood.

The analysis provides crucial spatial understanding of high-risk areas and enables emergency responders to prioritise evacuation and other actions. However, this action must be implemented at the earliest opportunity, ideally at the onset of a predicted extreme event, because at its peak no critical locations can be reached from Galluzzo town centre, whilst 22.5% of the roads are not safely accessible to drivers. For example, action could be taken to deploy blue light services in response to safe locations around the city that maximise access to vulnerable areas if a flood is predicted. The method, and its implementation with the Florence department of Civil Protection has been shown to provide considerably better and more relevant information to improve preparedness for emergency management.

Further work could focus on the extension of the model to fully describe a hazardous event for a longer time to include the recovery process. Moreover, a significant advancement would be in the implementation of a tool for real time analysis for CP and in the use of smart data to improve understanding of disruption processes and provide information to people to enhance preparedness.

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2018.11.191>.

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