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Flood damage: a model for consistent, complete and multipurpose scenarios

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Abstract. Effective flood risk mitigation requires the impacts of flood events to be much better and more reliably known than is currently the case. Available post-flood damage assessments usually supply only a partial vision of the consequences of the floods as they typically respond to the specific needs of a particular stakeholder. Consequently, they generally focus (i) on particular items at risk, (ii) on a certain time window after the occurrence of the flood, (iii) on a specific scale of analysis or (iv) on the analysis of damage only, without an investigation of damage mechanisms and root causes.

This paper responds to the necessity of a more integrated interpretation of flood events as the base to address the variety of needs arising after a disaster. In particular, a model is supplied to develop multipurpose complete event scenarios. The model organizes available information after the event according to five logical axes. This way post-flood damage assessments can be developed that (i) are multisectoral, (ii) consider physical as well as functional and systemic damage, (iii) address the spatial scales that are relevant for the event at stake depending on the type of damage that has to be analyzed, i.e., direct, functional and systemic, (iv) consider the temporal evolution of damage and finally (v) allow damage mechanisms and root causes to be understood. All the above features are key for the multi-usability of resulting flood scenarios.

The model allows, on the one hand, the rationalization of efforts currently implemented in ex post damage assessments, also with the objective of better programming financial resources that will be needed for these types of events in the future. On the other hand, integrated interpretations of flood events are fundamental to adapting and optimizing flood mitigation strategies on the basis of thorough forensic investigation of each event, as corroborated by the implementation of the model in a case study.

1 Introduction

In the context of the decennial World Conference organized by the United Nations (UN) in Japan in March 2015, the Sendai Framework for Disaster Risk Reduction (UN, 2015) was approved as guidance for all UN countries that committed to improve the way they are dealing with risk governance. Among its guiding principles, the following ones are of particular interest in this paper: (i) the call for mainstreaming disaster risk reduction in all societal sectors, (ii) the requirement to develop follow-up mechanisms to assess the effectiveness of risk mitigation policies and programs, (iii) the application of the "build back better" approach after disasters, and (iv) the reduction of human suffering and disaster loss according to measurable indicators in the coming years. These objectives require the damage and loss due to natural hazards to be much better known than is currently the case. In fact, to mainstream disaster risk reduction in all societal sectors, it is important to be able to show how they are actually impacted and damaged by natural hazards; therefore, a multisectoral understanding of societal vulnerabilities and loss suffered in individual events is needed. To assess whether or not risk prevention policies are effective, monitoring the evolution of damage encountered in the course of time is key. To build back better, one has to first analyze why the damage has occurred and what its main root causes have been, including the characteristics of the natural triggering phenomena and the vulnerability of exposed assets and systems, according to what has been labeled as "forensic investigation" (IRDR, 2011; De Groeve et al., 2013). For a more comprehensive discussion on the meaning and interpretation of forensic investigation, the reader should consider the introduction to the Special Issue "Natural hazard event analyses for risk reduction and adaptation" that this article is part of. Here forensic investigation is considered as a crossing field of analysis, encompassing the more traditional engineering expertise provided in courts to support one of the disputants or the judge in a litigation case (for a reference see Loaiciga, 2001) and the search for social and political root causes of disasters as intended by the Forin project (see Oliver-Smith et al., 2016).

What is not yet fully acknowledged in the current literature is that a forensic investigation would significantly benefit from an underlying consistent damage model, which helps to fully understand what exactly occurred, how the different societal sectors have been impacted and at what spatial scale. Such a damage representation may provide a useful basis for further in-depth analysis that will elicit the causes of the damage itself in its multiple forms (from direct physical damage to secondary indirect damage, intended to deduce both systemic and functional negative consequences and ripple effects for entire sectors). In this paper a comprehensive damage model is proposed and applied to a case study of a flood event.

We intend to use the word "model" here as engineers do, that is, as a simplified representation of reality that helps to explain and derive instances of relevant variables that constitute the model itself. As suggested by Oreskes (2003), "a model is a simplification – an idealization – of the natural world. We simplify problems to make them tractable, and the same process of idealization that makes problems tractable makes our models of them open". She refers mainly to the natural world, while the model we are proposing comprises both natural phenomena and the impact they have on the built environment and on the affected community. In this respect, the model we obtain is certainly open, in that it wishes to represent a reality that is wide and complex; variables that are used are not all quantitative, so that the final representation of damage we may obtain is partially quantitative and partially qualitative. By neglecting the latter, we risk underestimating components and features of damage that are very relevant for decision makers.

The model has been developed through the interaction between stakeholders with different competence and expertise, namely researchers and officials of civil protection authorities. Furthermore, the model has been shared with many others, including municipal authorities, officials from the Italian national Civil Protection and the EU Civil Protection, researchers and lifeline (energy, water and sewage) managing companies. This is coherent with the objective to support risk mitigation policies and actions, similar to the intention underlying the forensic investigation according to Oliver-Smith et al. (2016).

The paper is organized as follows: first the most advanced experiences available worldwide in damage data collection and modeling are discussed in Sect. 2; in Sect. 3 the model we propose is described in detail, and an application to the flood event that occurred in the Umbria region, central Italy, in 2012 is provided in Sect. 4. In Sect. 4.5 some examples of how the proposed model is able to support forensic analysis of the damage will be illustrated. In Sect. 5 a discussion regarding the procedural and practical viability of the proposed damage model is conducted.

2 Enhanced experiences of disaster damage data collection and reporting

Given the objectives of better understanding disasters and of providing a sounder basis for assessing the financial sustainability of proposed mitigation measures, it is not by chance if there is an increased interest in the enhancement of methods and tools to collect and analyze damage and loss data. Such interest leads, in turn, to the definition of enhanced procedures and more standardized methods to produce post-disaster impact appraisals. Australia, for example, issued guidelines to assess loss due to natural hazards' impacts a decade ago (EMA, 2002), though we were unable to find examples of comprehensive damage reports. In the Recovery Plan after the Queensland floods in 2010–2011, damage to infrastructures was accounted for and described in detail, but it was not appraised in an independent document devoted to the comprehensive and multisectoral analysis of the overall flood impact. King (2002) describes the experience developed in rapid post-event assessments conducted at the University of John Cook as a "research-oriented" activity, limited to the aftermath of the immediate events and with a focus on social impacts.

Another relevant example, that we also took as a reference for our own research, is provided by the Post-Disaster Needs Assessments (PDNA) (GFDRR, 2013), developed initially by the United Nations Economic Commission for Latin America and the Caribbean (UN-ECLAC), and then improved through the collaboration of several international entities, including the World Health Organization (WHO), the Pan American Health Organization (PAHO), the World Bank, the Inter-American Development Bank, the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the International Labour Organization (ILO). The PDNA is made of two parts: the DaLA (Damage and Loss Assessment) and the Needs Assessment, and it is meant to be adopted in large disasters where international aid is required. There are several examples of applications in Latin America and Asia, and a few in Europe. Several floods have been reported according to the PDNA standards, for example, in Pakistan for the 2010 flood, Nigeria for the 2012 flood and Serbia for the 2014 flood. The most relevant feature of the PDNA methodology is that it covers all sectors in a comprehensive fashion, and provides an overview of how the disaster has impacted society and assets; yet it is a methodology that has mainly been intended for international relief in developing countries, where needs are only partially derived from the damage caused by the disastrous event, as they are often pre-existing in terms of sanitation and access to public services and utilities. There is also a timescale issue as the PDNA is mostly concentrated at rapid appraisal after disasters and has been used far less for monitoring damage during longer recovery times.

In Europe, significant effort in the last years has been put into the improvement of damage data collection and appraisal capability at the national level, partly because of the need to respond to European and international risk reduction programs (e.g., Floods Directive, European Solidarity Fund, Hyogo Framework for action), partly as a consequence of the economic crisis. In fact, it has forced governments to spend more carefully and become more accountable for their expenditure, including after disasters. This is certainly the case in Italy, where local and regional governments have produced much better damage assessment reports than before to access national aid, and where the national Civil Protection has been increasingly introducing standards for improved and more comparable reports. The audit at the Senate held by the former head of the Italian Civil Protection, Franco Gabrielli (Gabrielli, 2014), is a good example of how comparable reports can support policies and decision-making. Based on the last 4 to 5 years of reports provided by affected regions, he was able to summarize the need for funding to cover just the first emergency expenses as EUR 2.3 billion a year. This is not just a programming need, but also responds to the significantly increased liability and transparency of public administration in Italy.

In other European countries, comprehensive ex post flood reports have been produced to fine tune the analysis of the loss for and impacts on multiple sectors to identify key lessons and weaknesses to be addressed by national policies. This is the case for the Pitt report after the 2007 Severn flood in the UK (Pitt, 2008), and for the various "return of experience" reports that have been produced in France after severe storm and flood events (Agence de l'Eau Artois-Picardie, 2006; Direction Territorial Mèditerranée du Cerema, 2014).

In such a context, this paper responds to the need of developing post-flood damage and loss assessments that are (i) multisectoral, (ii) address the spatial scales that are relevant for the event at stake depending on the type of damage (e.g., direct, functional, systemic) that has to be analyzed and (iii) consider the evolution over time of damage that may be suffered or gain relevance as the time passes. In this paper, a model for representing and analyzing flood damage is discussed, showing how it is able to address the multiple purposes for which loss data are collected, purposes that can be synthesized in the following: damage accounting, disaster forensic and improved risk assessment as suggested by the EU expert working group on disaster damage and loss data (De Groeve et al., 2013), and also responding to the affected communities' needs, as the PDNA does, particularly in terms of loss compensation.

The model has been actually implemented in real cases, after the floods that affected the Umbria region in November 2012 and 2013 and that constituted a unique real-life laboratory to test the model. The Umbria reporting system has been the result of joint work of researchers and professionals, including, as well as public officials (i.e., the regional Civil Protection in the first instance), volunteer technical experts such as builders, architects and engineers, local stakeholders (municipal officials) and the private sector (businesses and lifeline providers). It has also been mentioned as good practice by the EU expert working group on disaster damage and loss data (De Groeve et al., 2014).

3 Material and methods: a model for complete event damage scenarios

By adopting the model, a much more extensive and comprehensive overview of the different types of damage that affect communities and territories as a consequence of floods is possible, contributing to an understanding of why damage occurs and how it can be remediated reducing pre-event vulnerabilities. We have called such an overview a "complete event damage scenario" (Menoni, 2001) that depicts not only the immediate, direct, physical impact of a triggering event, but also the indirect, systemic consequences across space and time that are mainly due to the high interdependency and interaction of systems in urban and regional environments. In order to produce such a complete event scenario, a formalized and structured damage model that assists in data collection and analysis is necessary. Furthermore, a model that is agreed upon is essential in order to produce damage reports that are comparable for events occurring at different times and in different areas as well as for upscaling the information to higher levels, such as national and global.

The proposed model organizes available knowledge according to five logical axes.

1. Exposed sectors: observed impacts/damage must be assessed for all affected sectors (i.e., people, critical services and infrastructures, economic activities, properties – including residential buildings and cars, environment and cultural heritage) in order to supply a comprehensive view of flood impacts and, coherently, mainstream flood risk reduction in all societal sectors (see Introduction). Besides impacts/damage to the different exposed sectors, costs due to emergency management (like sandbags, volunteer rewards, evacuation, etc.) must be reported as they can represent a significant share of the total loss to the affected community.

2. Types of damage: not only physical damage (either tangible or intangible) must be analyzed due to the contact of water with exposed items. The disruption of functions due to physical damage can be even more important than the damage itself, for both the return to normalcy for affected communities and in economic terms (Menoni et al., 2012). Moreover, it is often the case that physical or functional damage is not due to direct contact with floodwater, but to damage to other interconnected systems/items. Root causes and damage mechanisms change in the two scenarios.

3. Spatial scales of analysis: they depend on the objective of the analysis and on the types of damage under consideration. It is possible that the scale of the analysis for a particular type of damage differs from the scale at which the damage manifests and/or is surveyed. In the model, three spatial scales of analysis are considered: (i) the level of the individual item (like a person, a building, a road or a factory), (ii) the municipality level and (iii) the meso- or macroscale (like a province, a region or a country).

4. Temporal scale of the analysis: it depends on three main factors – first, the type of damage under consideration; some damage is evident by nature some time after the event, like physical damage due to humidity or business disruption. Second, knowledge requirements to support the emergency, recovery and reconstruction phases, including information needed to accomplish administrative commitments (like loss accounting), is considered. Finally, the availability of data counts, which is strictly linked to the previous two points and also to other factors like skills and possibility of collecting data, must be considered.

5. Variables: reported information must refer not only to the damage itself but also to its explicative variables in terms of hazard, exposure and vulnerability of affected assets and systems. This information is crucial to understand damage causes and mechanisms in order to create more resilient societies (i.e., to build back better as suggested by the Sendai Framework for Disaster Risk Reduction). When possible, damage must be described in terms of both physical units and monetary value. Physical measures are undisputable, while associated monetary value depends on the estimation method, underlying assumptions, stakeholders, etc.

The proposed model is portrayed in Table 1. In the table, only three logical axes are considered: exposed sectors, types of damage and spatial scales of analysis. Types of damage are identified for each exposed sector and possible scales of analysis for each type of damage (and sector) are also indicated.

With regard to damage types, they are the same for every exposed sector (i.e., physical damage, functional damage and physical or functional damage due to systemic interconnections), with some exceptions.

In the case of population, referring to functional damage is meaningless. However, besides physical damage to individuals, it is important to assess the impacts of the flood on the affected communities: the number of evacuated people, psychological distress, unemployment or loss in salary due to damage in economic sectors and lack of services because of damage to critical infrastructures or public goods. The last two categories can actually be considered as systemic damage. With respect to properties, an additional type of damage has been added to the "standard" ones i.e., the properties' loss of value because of the occurrence of the flood. This has been observed several times in the past and may represent a significant share of the total damage associated with properties.

As for the spatial scales of analysis, in Table 1 the scale at which the analysis supplies significant results, for each sector and type of damage, is shown. Where upscaling does not modify the nature of information, only the minimum scale of the analysis is marked. For example, physical damage is typically analyzed at the level of individual items; at larger scales, the physical damage to a certain sector is simply the sum of individual instances of damage. In contrast, the analysis of functional damage at various spatial scales may supply different information. For example, the functional disruption of an hospital (i.e., a public service) has different impacts on the society when analyzed at the level of the individual hospital, or within the network of municipal and regional hospitals; the functional disruption of all the firms of a certain industrial district has different effects on the economy when analyzed at the level of single firms or at the whole district level, taking into account its importance for a municipality or a region.

Some exceptions to the above general rule can be observed in the table. The minimum scale of analysis of physical damage to people should be the individual level. However, information on injured and dead people is usually available at the level of municipality; accordingly, both individual and municipal scales are marked. The same is true for physical damage to cars (i.e., a property). Physical damage to environment and cultural heritage may require analysis through the whole range of scales as some environmental and cultural goods have a wide extension, like in the case of rivers, parks, etc. From another point of view, the damage to a city due to the loss of cultural heritage is not the simple sum of damage to individual artifacts; it is a much more complex value to appraise.

The level of disaggregation of each logical axis must be defined at the beginning of the analysis, and may differ from the one proposed in this paper. For example, insurance companies are generally interested in the knowledge of damage at component level, like damage to pavements, doors, windows and plants within a building. Trade associations may be interested to know damage in each economic sector (man-

Table 1. The structure of the model according to three main logical axes: sectors, types of damage and spatial scale.

Exposed sector	Type of damage	Spatial scales of analysis		
		Individual item	Municipality	Meso-/macroscale (province, region, country)
Population	Physical damage	X	X	
	Evacuated people		X	
	Psychological distress	X		
	Unemployment, loss in salary, etc.			X
	Lack of services		X	X
Infrastructures (installations and lines)	Physical damage	X		
	Functional disruption		X	X
	Physical and functional systemic damage		X	X
Public services	Physical damage	X		
	Functional disruption	X	X	X
	Physical and functional systemic damage		X	X
Economic activities	Physical damage	X		
	Functional disruption	X	X (district)	X (district)
	Physical and functional systemic damage	X		
Private properties (residences and cars)	Physical damage	X	X (cars)	
	Functional disruption	X		
	Physical and functional systemic damage	X		
	Loss of value		X	
Environmental and cultural heritage	Physical damage	X	X	X
	Functional disruption	X	X	X
	Physical and functional systemic damage		X	X
Civil protection	Costs of emergency services		X	X

ufacture, craftsmanship, trade, tourism, etc.). Civil Protection officials need a general overview of flood impacts at different moments, soon after the occurrence of the flood (Molinari et al., 2014c). Researchers may be interested to know a very detailed set of damage explicative variables that is usually not considered by other stakeholders. Table 1 has been designed so as to meet requirements of these multiple stakeholders.

4 The complete event scenario for the November 2012 flood

The model described in the previous section has been applied to analyze and report damage due to the flood that hit the Umbria region in 2012. The region is located in central Italy (Fig. 1), covers 8456 km^2 and has a population of 906 500 (source: National Statistical Office, www.istat.it).

The event was the consequence of a widespread, high-intensity storm, with rainfall exceeding a return period of 200 years in most locations, and leading various rivers to exceed the alarm and flooding discharge thresholds. Because of the morphology of the Umbria region, flooding occurred with different features in areas ranging from flat floodplains to narrow mountain valleys. Consequently, flood duration ranged from several days to a few hours, assuming the typical features of riverine or flash floods: the persistence of almost steady water in the first case, and high-velocity flows with significant sediment load in the second. Observed discharges in the plain area correspond to a return period of 100 years for the main rivers (Paglia and Nestore).

Out of 92 municipalities, 58 were affected during the event, and in particular the municipalities of Marsciano, the hamlets of Ponticelli (Città della Pieve) and Orvieto Scalo (Orvieto). The monetary value of damage that occurred in the whole region was about EUR 115 million, corresponding to 0.6 percentage points of the regional GDP. This figure is emblematic of the real impact of the flood on the regional economy. To compare, damage that occurred in Germany af-

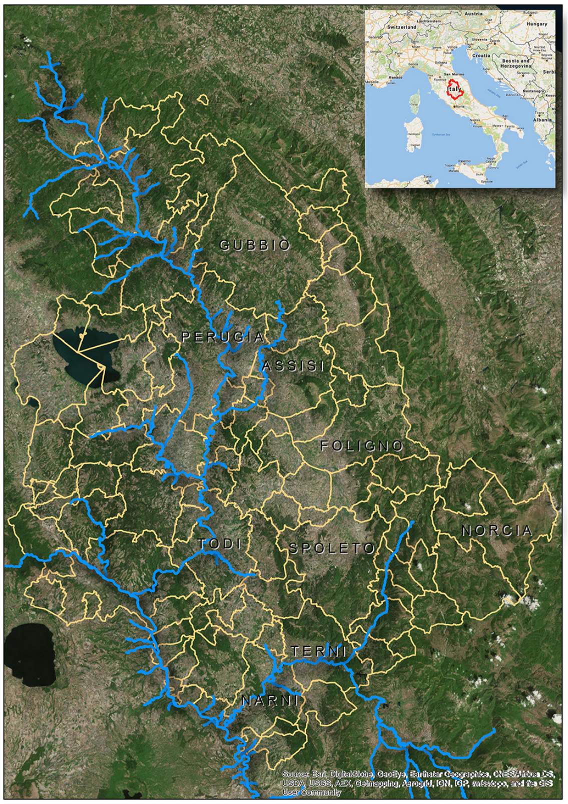

Figure 1. The case study area.

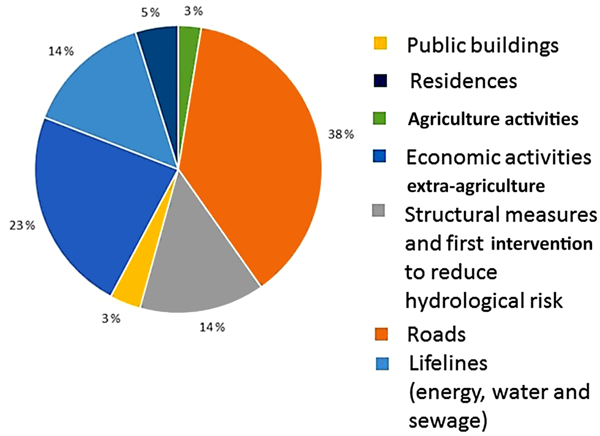

Figure 2. Distribution of damage among the different exposed sectors for the November 2012 flood in Umbria.

ter the Elbe flood in 2002 corresponded to 0.7 points of the national German GDP.

Data for the post damage assessment have been mostly acquired from local authorities and utility companies, which collect such information to accomplish existing practices related to compensation. Damage to the residential and industrial/commercial sectors was surveyed on the field instead, working side by side with the regional Civil Protection (see also Sect. 5).

Table 2 maps collected information, according to the structure proposed by our model (see Table 1).

Depending on the particular damage under consideration, four different outcomes were observed: (i) information on damage is available in physical units, (ii) information on damage is available both in physical units and monetary terms, (iii) damage did not occur, and (iv) information on damage is not available.

Generally, a good coverage of required data is observed thanks to the implementation of the RISPOSTA procedure for data collection (Molinari et al., 2014a; Ballio et al., 2015), which has been developed to feed the damage model proposed in this paper with data. Table 2 also shows some problems of data availability, due to the difficulty of obtaining them from some segments of the private sector (like in the case of some infrastructures) and due to the incompleteness of information related to some indirect and intangible damage (like damage to people and environment).

The complete event scenario for the 2012 flood is summarized in the Supplement, in which Table 2 has been filled in with a brief description of observed damage; monetary values reported in the Supplement refer to the regional expenditure to reimburse damage incurred.

A description of the complete flood scenario is beyond the scope of the paper. Interested readers can refer to the Supplement; moreover, a report is available for Italian speakers (Ballio et al., 2015). Rather, the scenario is used here to demonstrate how the information structure proposed by our model (i.e., the five logical axes) supports an integrated interpretation of the flood event that, in its turn, meets the requirements of a consistent forensic investigation among other possible uses. To this aim, the 2012 flood event is analyzed in the following subsections according to some of the logical axes of the model.

4.1 Analysis by exposed sectors

Information on the distribution of damage among the different exposed sectors is key to prioritizing interventions and to adapting future mitigation strategies (i.e., towards those sectors that were mostly affected in the past). Figure 2 displays such information for the 2012 flood. The industrial sector was the most affected by the event, together with infrastructures. Emergency costs were also relevant because of the multi-site nature of the flood event, requiring emergency services to be dislocated in the whole region (see also Sect. 3.5). Although the impact on agriculture was not as high as that on industry, it represents an important share of the total loss due to the presence of several agricultural activities in the floodplain areas. The damage to residential buildings and cultural heritage was the least significant.

The share of damage to different sectors with respect to the overall damage (Fig. 2) has been estimated, compar-

Table 2. Coverage of required flood information for the 2012 flood event in the Umbria region.

Exposed sector		Type of damage	Spatial scales of analysis		
			Individual item	Municipality	Meso-/macroscale (province, region, country)
Population		Physical damage	NA	✓	
		Evacuated people		✓	
		Psychological distress	✓		
		Unemployment, loss in salary, etc.			✓
		Lack of services		✓	✓
Infrastructures (installations and lines)	Roads	Physical damage	✓€		
		Functional disruption		✓	✓
		DDIS(*)		NA	NA
	Railways	Physical damage	✓€		
		Functional disruption		NA	NA
		DDIS(*)		NA	NA
	Electric lines	Physical damage	✓€		
		Functional disruption		✓	✓
		DDIS(*)		✓	NA
	Water and sewage	Physical damage	✓€		
		Functional disruption		NA	NA
		DDIS(*)		NA	✓
Public services	Schools	Physical damage	✓€		
		Functional disruption	NA	✓	×
		DDIS(*)		NA	NA
	Healthcare services	Physical damage	×		
		Functional disruption	×	×	×
		DDIS(*)		✓	×
	Governmental services	Physical damage	✓€		
		Functional disruption	×	×	×
		DDIS(*)		NA	NA
Economic activities	Agriculture	Physical damage	✓€		
		Functional disruption	NA		
		DDIS(*)	NA		
	Industry and commercial activities	Physical damage	✓€		
		Functional disruption	✓	NA	NA
		DDIS(*)	NA		
Properties (residences and cars)		Physical damage	✓€	NA	
		Functional disruption	✓		
		DDIS(*)	✓		
		Loss of value		NA	
Environmental and cultural heritage	Environment	Physical damage	✓€	×	✓
		Functional disruption	✓	×	×
		DDIS(*)		✓€	×
	Cultural heritage	Physical damage	✓€	×	×
		Functional disruption	×	×	×
		DDIS(*)		NA	NA
Civil protection		Costs of emergency services		✓	✓

✓ Information on damage is available in physical units.
✓€ Information on damage is available both in physical units and monetary terms.
× Damage did not occur.
NA Information on damage is not available.
(*) DDIS: physical damage and functional disruption due to damage to other interconnected systems.

ing the total values that have been obtained for each sector. Care has been taken in data preprocessing to allow for inter-sectoral comparison. The case of the industrial sector may clarify what is meant by preprocessing of data. The total self-reported amount of loss reported by entrepreneurs was as large as EUR 48 million; however, only part of it was eligible for compensation given the aid provided by the government for the 2012 event. In particular, in order to be eligible, companies needed to demonstrate a certain financial solidity and to commit to not closing their activity for a period of 5 years. In addition, only damaged structures, machinery and technical equipment were reimbursable, while damaged raw materials or finite products, particularly relevant, for example, in large commercial surfaces, were excluded from compensation. Given these conditions, the total amount of around EUR 10 million was considered as eligible loss for the industrial and commercial sector.

4.2 Analysis by variables

The analysis of both damage and its explicative variables (i.e., hazard, exposure and vulnerability) is crucial to the understanding of damage mechanisms and causes. As an example, physical damage to the residential sector is discussed in the following. From this perspective, the 2012 flood event was analyzed in terms of

- physical damage that occurred, distinguishing between damage to structural and non-structural components, such as windows, doors, walls and contents, including technical equipment (i.e., plants);
- flood parameters at buildings' locations; in particular, the flood depth both inside and outside walls, the duration of the flood and the presence of contaminants and/or sediments (see Fig. 3);
- the basic exposure/vulnerability features of buildings affected, like typology, year of construction, size, height, number of floors and existence of basement and attached areas (see Fig. 4);
- mitigation actions taken during the warning period and prior to the event like sandbagging, moving of contents and the use of pumps.

The analysis highlighted that the most damaged component is plaster. Windows and doors were only damaged in the case of long-lasting floods or high-velocity floods. Pavements were usually not damaged, except in the case where waterproof materials were not used (e.g., wood). Damage to the electrical plant was the mostly frequently observed in cases where domestic plants were affected. Contents (furniture, appliances, etc.) were generally lost, apart from those cases in which people were able to move contents to a safer place after receiving flood warnings by the Civil Protection (especially in the municipality of Marsciano where the alert

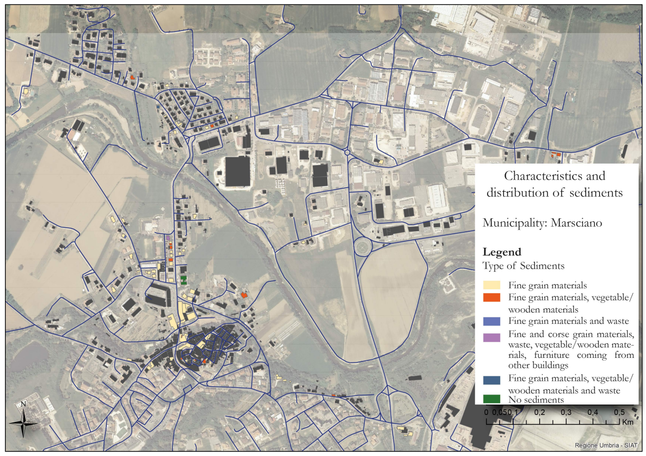

Figure 3. Sediments' distribution in Marsciano.

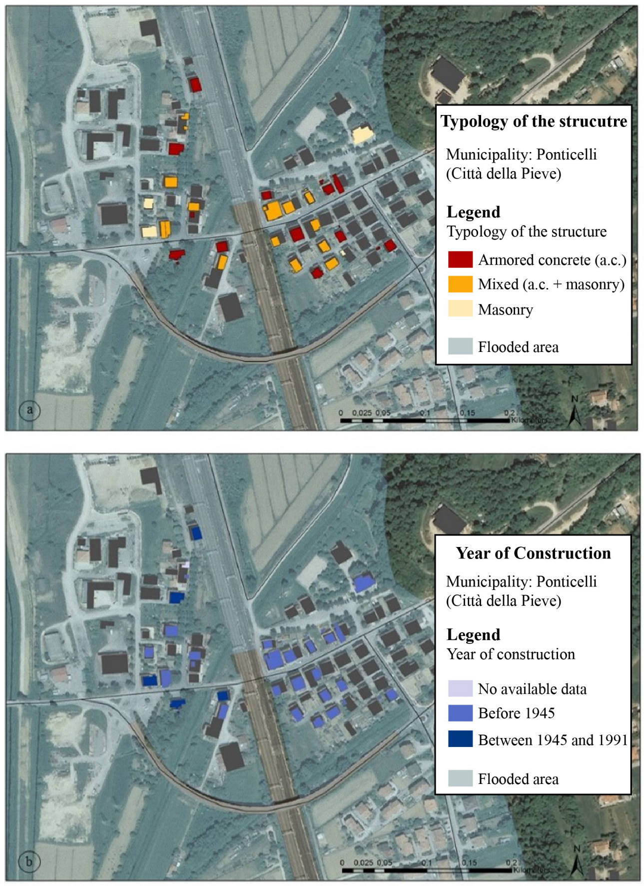

Figure 4. Features of flooded buildings in Città della Pieve: **(a)** typology of the structure, **(b)** year of construction.

was very effective and reached the local population). The same is true for vehicles.

In a forensic analysis that has been carried out on the 109 dwellings surveyed, the following have been identified as the main causes of damage. In general, structural or more severe damage to openings only occurred in the case of real flash flood incidents. Basements and first floors were very often inundated, except in those buildings that were elevated above ground level, even for few centimeters, corresponding to stairs. Interestingly enough, the analysis highlighted that the presence of the basement per se should not be considered as a vulnerability factor, as it actually acted as a small retaining basin for the water limiting the effects on the upper floors. Presence of goods or, much worse, of people in the basement should instead be considered a very high vulnerability factor that may lead to extreme consequences such as the death of those trapped in the basement and the loss of all stored items.

4.3 Analysis by spatial scales

By analyzing damage at the different spatial scales, it is possible to investigate the occurrence of the different types of damage as well as their effect on the affected communities, again with the final aim of adapting risk mitigation actions, both in the emergency and recovery phase. Here, damage to the electrical supply system is commented on, as an example of an analysis by spatial scales.

Coherently with our model (see Table 1), physical damage were analyzed at the level of individual items. This allowed damage to be pinpointed to several electrical cabins, as well as the collapse of trellis and cable, which caused the disruption of the service in many areas. Functional damage was instead investigated at upper scales. By looking at the regional scale, it was possible to identify, for example, those municipalities in which an electrical disruption occurred (see Fig. 5). At the municipality scale, electricity disruption was analyzed in terms of the temporal evolution of users without electricity (Table 3), causes of disruption, actions implemented to reduce the discomfort of people and so on.

The assessment at upper scales also allowed systemic damage to be investigated. In particular, we observed that the restoration of the electricity infrastructure was difficult because of physical damage to roads, causing the inaccessibility of damaged items. This, in turn, increased the duration of service disruption (i.e., functional damage).

From a forensic investigation perspective, it is important to understand how the interdependency of infrastructures, services and industries has occurred in a given context. In the case of the Umbria region, interdependency between lifelines was not so problematic because the region is fairly isolated from the main infrastructural networks, including large transportation roads and railways that transit only at the margin of the Umbria territory, which is mostly served by local- and regional-level services.

The interaction between structural defenses and the transportation networks is still of high significance: because of the regional geomorphological pattern, roads and local railways depend, to a great extent, on a myriad of works that protect

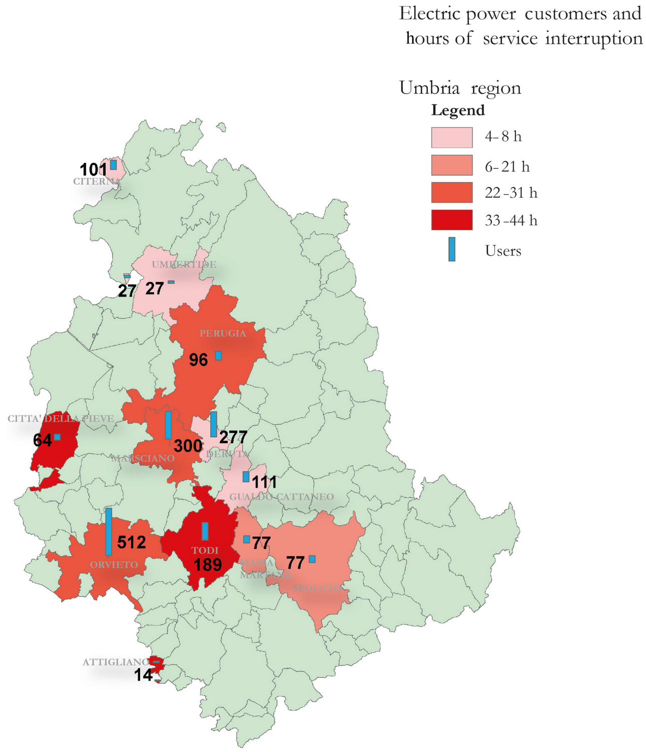

Figure 5. Overview of electricity disruption at regional level: affected users and duration of the disruption per municipality.

them from erosion, active and quiescent landslides that are reactivated at each severe storm.

4.4 Analysis by timescale

The importance of considering the timescale is certainly evident in the industrial and commercial sectors. In fact, industrial activities that we surveyed directly at certain times (10 days and 1 year after the flood) reported damage due to humidity 7 months after the event. In particular, humidity that had infiltrated into the electrical equipment damaged engines in a weighing station for construction debris; several settings reported health problems for workers staying all day in very humid rooms affected by mold. As for the functional damage, all entrepreneurs interviewed reported that full activity was only back in March, which is 5 months after the disaster. In this period they had to ask for unemployment support for their workers.

In the case of the power system mentioned in the previous section, the timescale also mattered. In fact, at least in the city of Orvieto, damage to the electrical network was severe and required a whole year to be repaired. Figure 6 shows the damaged industrial area of Orvieto, including the electrical components that were flooded. Cabins and pylons had to be reconstructed and relocated from the areas more exposed to flood hazard, which also required time spent for getting permission for the new locations and redesigning that part

Table 3. Customers without electricity during the 2012 flood in Umbria: temporal evolution per municipality.

Municipality	Time of the day									
	12 November				13 November					14 November
	14:00	18:00	20:00	22:00	07:30	11:30	16:00	19:00	21:00	10:00
Attigliano	14	2	2	2	2	2	2	2	2	2
Orvieto	512	425	188	188	131	131	131	–	–	–
Deruta	277	2	113	–	–	–	–	–	–	–
Umbertide	27	27	–	–	–	–	–	–	–	–
S. Venanzo	93	–	–	–	–	–	–	–	–	–
Città della Pieve	64	–	–	64	64	64	64	64	40	20
Ponte S. Giovanni	15	–	–	–	–	–	–	–	–	–
Marsciano	–	300	–	172	16	16	16	–	–	–
Gualdo cattaneo	–	111	111	–	–	–	–	–	–	–
Perugia	–	96	–	–	79	79	79	–	–	–
Todi	–	–	–	44	189	189	189	189	189	189
Citerna	–	–	–	101	–	–	–	–	–	–
Perugia	–	–	–	–	79	–	–	11	6	–
Spoleto	–	–	–	–	77	77	–	–	–	–
Massa Martana	–	–	–	–	77	–	–	–	–	–

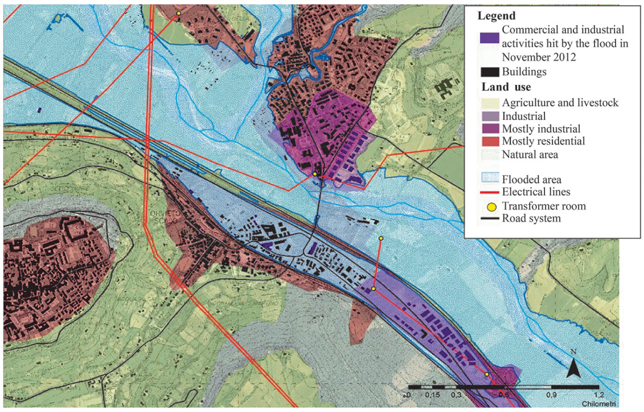

Figure 6. Electrical lines and transformation rooms, economic and industrial activities hit by the November 2012 flood in Orvieto.

of the network. In the meantime, powerful generators and temporary repairs were put in place to serve residential and industrial customers in order to guarantee the continuity of service.

4.5 Examples of forensic analysis carried out to trace the root causes of observed damage

An analysis of damage to and loss in multiple sectors across timescales and spatial scales is also important to understand where priorities lie in addressing future research and application needs. Figure 2 highlights that the reported damage for the residential sector is less relevant than is usually thought of. Instead, damage functions currently used in risk assessments to estimate potential damage in order to support future mitigation choices are biased towards the residential sector, for which studies are more refined and data are available in a large quantity (see Merz et al., 2010; Jongman et al., 2012; Meyer et al., 2013 for a full review). In contrast, damage functions for the industrial and infrastructural sectors (which play a major role in our case study) are much less developed, and their use is subject to higher levels of uncertainty with respect to the residential sector (see, e.g., Merz et al., 2010; Meyer et al., 2013). Our experience suggests that, in certain contexts, damage estimates based on current typical practice are biased towards those sectors for which modeling capacity exists. In the case that we have considered, damage to the industrial sector and infrastructures including defense works is crucial. This is because of the physical damage to machinery, raw and finished materials and products, and also because of the indirect consequences of physical damage when it hampers the continuation of activities. In the latter case, the business interruption duration is an important factor in also determining longer term consequences on the economy of an impacted region.

The analysis of the different types of damage suffered by a variety of sectors across temporal and spatial scales also allows functional and systemic vulnerabilities often discounted by present damage assessment (especially when they are conducted ex ante) to be accounted for, which are important to consider both in the emergency and in the recovery phases.

Information on functional damage to the electricity supply system can be used, for example, during the emergency by both utility owners/managers and Civil Protection, to prioritize interventions and to support disconnected users. Systemic damage were also significant, leading to the disruption of several public services (see Supplement).

On the other hand, information on functional and systemic damage can be used by risk managers in the recovery to assess the viability and the effectiveness of mitigation measures that were in place at the time of the event.

Such an analysis proved to be useful in the 2012 flood as it revealed deficiencies of (i) existing flood hazard maps and risk maps, especially for what concerns the identification of likely flooded areas, (ii) emergency plans, particularly with regard to the actual response to flood early warnings, and (iii) land use planning, particularly regarding the location of industries in the most hazardous areas.

i. Deficiencies of available hazard maps were particular evident in the case of the city of Orvieto, as the area in the floodplain called "Orvieto Scalo", located along the Paglia river, at a level that is lower than the highway and the railway, had been excluded from the flood with a 50-year return period. Somehow the mistake was known by the regional authorities but time was required to change official maps, until, unfortunately the 2012 event forced them to revise them. The exclusion of the Orvieto Scalo zone from the most hazardous areas facilitated the industrial zonation that was decided in the year 2000 master plan, which is still valid, after a number of revisions and amendments. In this specific case it can be said, according to the interpretation of forensic investigation provided by Oliver-Smith et al. (2016), that this decision was actually the one that initiated a chain of individual locational decisions that led to the rather high amount of damage and loss observed in 2012, and was the consequence of a double underestimation of risk. On the one hand, there was the wrong hazard map, and on the other, the lack of awareness of spatial planners of natural hazards (Wamsler, 2006).

ii. As for emergency plans, the same case of Orvieto is emblematic as its analysis showed that the large parking lot that is just close to the railway station and where many workers left their car on the early morning before the flood peak was indicated as the stationing area for rescue vehicles and ambulances in case of emergency (Fig. 6). The Civil Protection plan was revised immediately after the 2012 event in this regard. As for the alerting procedures, these proved to be very effective in some municipalities like Marsciano, and less in others, depending on the degree of preparedness of local actors and the strength of volunteering associations. In the case of Orvieto, the first alert issued on Saturday night was left almost ignored, until the level of the water started to rise early on Monday morning when the decision was made to close the bridge for precautionary reasons. Had the alert been given to the population on Sunday, some hours after it was officially issued, perhaps some damage could have been avoided in the industrial zones, as the owners and workers might have saved at least some movable materials, products and vehicles. The very rapid development of the flood in the city of Orvieto suggests that the emergency plan should be very well constructed, shared among the largest possible number of stakeholders including the potential victims, and designed to help actual reduction of damage by taking some actions before the flood peak without putting people's lives at risk.

iii. As for land use plans, apart from what has been already said with respect to the case of Orvieto Scalo, another example is of relevance. The industrial zone located in the suburb of Ponticelli, downhill of the historic town of Città della Pieve, remained flooded for some days following the break of a levee. Even though in absolute terms the damage to the industrial and commercial sector in Ponticelli was orders of magnitude less than in Orvieto, amounting to EUR 250 000 with respect to EUR 4 million and 300 000, an important ceramic factory that exports within Italy and worldwide was still severely affected. Here the land use plan in force establishes a further development of the industrial zone in what is labeled as the high hazard zone (this time correctly) in the hazard map. At the time when the decision was made, the hazard map did not imply mandatory restrictions for spatial planning. A note in the zoning rules warns that the area is subject to hydrogeological risks though leaving the decision whether or not to build and how to build to developers. In this case the plan is more recent than the Orvieto case; the limitation in the capacity of planners to include risk mitigation as part of their ordinary work (Wamsler, 2006) is still evident and can be considered as a root cause of the damage itself. Understanding the relevance of the land use plan in shaping the recorded damage in the municipality of Città della Pive should lead to the assessment of costs and benefits of limiting further industrial development there. A comparison could be made then with the expected costs and benefits of constructing new structural measures, for which maintenance costs should be accounted for as well, and/or of mitigation at the building level (including, for example, elevation, use of factories only for some kinds of productive activities for which relocation of materials, products and machinery is not a major issue).

5 Conditions for the viability of the proposed damage model

The proposed model overcomes limits of existing reports focusing on a certain time span (like in the case of PDNA reports), on a specific scale (like "return of experience" reports), on the only "damage" variable (like reports presently produced by Italian authorities) or on a specific sector (like reports by insurance companies). The model supports the production of complete event scenarios that can be used for different types of analyses, including forensic investigation. Even though the damage model does not constitute a forensic investigation by itself, it does provide a fundamental pillar on which such an investigation can be performed. Furthermore, it can be stated that a model such as the one proposed in this paper offers an important basis for a shared understanding of the event, from which each stakeholder may benefit in his/her own activity and mandate. In fact, while individual stakeholders generally collect and analyze information on damage to assets or components they are directly responsible for, a comprehensive model permits them to locate the damage suffered by their specific assets into a larger context so as to evaluate how and to what extent they depend on other sectors.

On the condition that the same damage model is followed in assessing post-flood consequences at each event, comparison among cases will be much easier across geographic regions and time. It will then be easier to recognize similarities among cases and aspects that are specific to each case. Furthermore, data collected and processed in the same way for key variables will also permit statistical evidence to be obtained in the long run for some variables that are only accounted for in a qualitative way at present. Here the reference is certainly to systemic effects and to indirect damage and loss: quantitative values can be found with respect to such variables in literature and case studies; however they mostly derive from modeling and are hard to verify and validate with real numbers coming from the field (Carrera et al., 2015).

Consistency among different flood disaster cases will be achieved once all event scenarios in the future supply damage information according to the same logical structures (e.g., distinguishing among sectors, types of damage, drivers – i.e., explicative variables), and at the spatial and temporal scales that are relevant to assess the different types of damage.

5.1 Procedural aspects implied by the proposed damage model and by its implementation in real situations

In order to implement the damage model in Sect. 3, and as the field case study has shown rather clearly, lots of data are required, from different sources and characterized by different levels of detail and accuracy, sometimes including sensitive information. Considering the present (un)availability of flood-related data (see, e.g., Merz et al., 2010; Meyer et al., 2013), it is likely that most knowledge required by the analysis is lacking or that available data are not comparable. For this reason, a procedure for data collection should be shared among all possible stakeholders (i.e., data owners, data collectors and data users). An important advantage of such a procedure is to "produce" data that are compatible with their use for defining multipurpose scenarios. Such multiple purposes also include, besides forensic investigation, compensation, identification of needs for recovery and return to normalcy, feeding ex ante risk and scenario assessments with evidence from real event scenarios and accounting at national and international scales for program investments in mitigation and prevention.

As the effort that is required is considerable, stakeholders need to find a good reason to commit. An important reason is inherent in the obligations countries took in signing the Sendai Framework for Disaster Risk Reduction, as the adherence to its principle will be measured through indicators for which damage data will have to be collected in a much more systematic way than has been the case until now. Additionally, a sound basis on which to prove the effectiveness and economic sustainability of mitigation measures is now a condition for accessing many sources of funds (European scale in particular, but also national), and therefore knowing and understanding the damage that occurred in the past and may occur again in the future without appropriate mitigation is key.

It must also be pointed out that the required effort may be overestimated by stakeholders for the reasons stated here below. First, it has to be said that the current way of collecting data by a multiplicity of stakeholders in formats and according to standards that are not compatible with each other is very inefficient. A sort of re-engineering of the whole process is necessary to improve the quality of data in general that are input in databases and also to permit a wider use and reuse of such data. This is already considered as a policy objective by some bodies, both international, such as the European Commission and the United Nation International Strategy for Disaster Risk reduction (UNISDR), and national, such as in Italy. In the Umbria case, a new procedure named RISPOSTA (Reliable InStruments for POST event damage Assessment) has been established to formalize the distribution of tasks between the regional Civil Protection authority, other regional and local administrations and the Politecnico di Milano. The procedure identifies a number of steps and responsibilities to be shared in a transparent and structured way among the involved stakeholders. It is also tailored to optimize time and efforts needed to collect and subsequently produce analytical reports of damage according to the timeline established by national laws, directives and ordinances of the National Department of Civil Protection (Molinari et al., 2014a, b; Ballio et al., 2015).

Second, it is important to say that the majority of stakeholders would be involved in some sort of damage data collection and management in any case so that the extra burden imposed by the procedure, which requires improved and more extended information gathering, is actually outbalanced by the overall rationalization that is introduced. Discussions with lifeline providers are still open, as some of them (specifically water and transportation companies) already refer to the regional Civil Protection authority, while others sometimes do and sometimes refer instead to the national level (like communication and electrical system providers).

The procedure also introduces the figure of a coordinator of damage data collection and analysis, who does not necessarily carry out all the tasks, but guarantees that the procedure is performed as smoothly as possible and acts as a bridge between authorities and organizations. Such a role can be assumed by public administration services with an ad hoc mandate. With respect to this, Civil Protection agencies are well positioned because of their direct involvement in the emergency and recovery phases after a disaster and because of their preferential links with stakeholders (i.e., data owners and users).

In fact, this is coherent with the damage data coordinator and data curator as intended by the last report of the technical group led by the EU Commission JRC (EU Commission, 2015). The debate as to whether the damage data coordinator and curator should be the same person(s) or different is still open; however it must be pointed out that these activities are closely interconnected. A proper data analysis requires in fact a preprocessing of data to fully grasp the meaning and the exact terms of damage data provided in the form of descriptions and costs by different administrations.

5.2 The need to support the damage data collection and management with appropriate IT systems

Parallel work for developing proper IT tools supporting the whole process (i.e., from data collection to analysis) has been ongoing since the first attempts to formalize the damage model and to develop appropriate survey forms. It is not just a matter of facilitating as much as possible the data management from input to output, but also, more importantly, to develop an information system that will support the type of reporting and analysis implied by the model that is described in Sect. 3. Details regarding the tools that have been developed insofar as can be found in Molinari et al. (2014b).

Commonly, damage data are collected and managed using a traditional file-based approach, where each stakeholder manages the data using its own application and separate files to store, modify and access it. The multiplicity of stakeholders that will either collect data or access to them to perform analysis according to the model we propose challenges the file-based approach. Indeed, it is likely that data will need to be shared between stakeholders, and storing them many times and on many devices will be wasteful and will lead to inconsistencies. The opportunities that a database approach rather than a file-based approach offers would solve these issues by storing data in an integrated and coordinated manner, so that various stakeholders can share it. It is for these reasons that we adopted such an approach, by designing a unique shared database where the predefined relationships among data would permit consistency in data collection, storage and analysis, as identified in the paper, to be developed.

Moreover, the need to design a complete information system for the management of damage data according to the relations among data defined by the model, emerged during this *learning by doing* process. Information systems (ISs) were initially defined for business processes as systems that manage and process information (Alter, 2002). The idea to adopt an information system approach would enable the model using damage data for the needs of our stakeholders. Moreover, the IS design would be developed so to permit the integration of different databases, not only to access the event-related data but also the historical data present in other databases. In fact, data have to be input and stored in a database first and connected with databases that store information that is available prior to the event, like, for example, census data, hazard and risk maps in force at the time of the flood, land use and emergency plans. Secondly, it will be possible to perform queries to feed subsequent analyses with relevant numbers pertaining to the most important variables that have been identified in the proposed damage model. As we discovered with our own testing, this is far from being an easy task and we are currently developing such a system within the IDEA project funded by DG-ECHO. Furthermore, the relevance of the spatial scale in representing some of the damage and how it has affected and transformed inundated territories also requires such databases to be connected to a mapping platform.

Furthermore, data quality assurance is an unavoidable activity to be included throughout the process of design of the information system. If till now, preprocessing of data has been done "manually" as for the 2012 flood event, this activity will have to be supported by automatic procedures, which means also paying attention to other dimensions of the data, such as granularity, format and density.

The information system is necessary to allow the use of the damage model in different cases and in different geographic regions, in order not only to ease the work of officials inserting the data and the data coordinator and curator in managing and using it for analysis, but also to guarantee comparability across cases.

It is expected that the information system that is under development will significantly ease the effort required to manage post-disaster data that have been identified as an important barrier to improved data collection. The existence of a structured procedure even with an incomplete information system has already proved to be useful to reduce both time and efforts for data collection, as could be observed for the development of the post-flood scenario after the event that hit the Umbria region in November 2013 just 1 year after the one analyzed in Sect. 4 (ongoing activity). So far, the analysis of the 2013 flood event implied a significant reduction of resources compared to those involved in 2012, as analysts were familiar with practices developed for data collection and analysis. In other words, a rationalization of resources in combination with ad hoc developed IT instruments in the long run should save time and effort required for the data collection and analysis with respect to the present situation.

6 Conclusion

This paper responds to the necessity of an integrated interpretation of flood events as the base to address the variety of needs that arise after a disaster, among them, the following, which may be utilized towards more effective risk mitigation strategies: prioritization of interventions, damage accounting and compensation, risk assessment and disaster forensic investigation.

To this aim, a model is supplied to develop multipurpose complete event scenarios. The model organizes information available in the aftermath of floods according to five logical axes. This way, post-flood damage assessments can be developed that (i) are multisectoral, (ii) and (iii) address the spatial scales that are relevant for the event at stake depending on the type of damage that has to be analyzed, i.e., direct, functional and systemic, (iv) consider the temporal evolution of damage that may be suffered or gain relevance as the time passes and finally (v) allow damage mechanisms and root causes to be understood. All these features are key for the multi-usability of resulting flood scenarios.

The possibility offered by the model of producing scenarios that may support different readings of a flood disaster is the main innovative contribution of the research. Existing flood reports typically focus on a certain time span, on a specific scale of analysis, on the analysis of damage without an investigation of root causes or on a specific sector. The model proposed in the paper widens the spectrum of possible interpretations of data and, as a consequence, of resulting actions.

Still, the successful implementation of the model requires the knowledge of a huge amount of data that may not be available. A procedure for data collection and a fully operational IT system to manage the data should then be implemented, and shared among all possible stakeholders, to be applied in case of flood.

Two last points deserve to be discussed: the minimal threshold of an event's severity, below which the application of the model is not useful or even counterproductive, and the possibility of extending the damage model to other risks. As for the former point, it is believed that the damage model that has been designed is applicable on the condition that relevant comparison and linkages between sectors can be found and that consequences across spatial scales and timescales can be identified. For very small events this is not possible, so we think the overall structure of the damage model needs to be reconfigured so as to extract meaning from the data that will be collected. Referring to one individual event at a time as the proposed damage model does is probably not the right solution.

As for the latter point, we consider that the damage model may have a validity beyond the specific case of floods. Actually the model has been partially developed after similar attempts that have been made in the case of earthquakes (Menoni, 2001). However the level of development of the two models is not comparable, as the one for earthquakes is in an embryonic state compared to the one proposed here, and further work and research must be invested in order to understand how and to what extent the experience described in this paper can be actually of use for analyzing post-disaster damage due to other hazards.

7 Data availability

The data implemented in the case study are not publicly accessible. The first reason behind this is that some data come from private sources (i.e., businesses, utilities companies) that agreed on sharing their data only for research objectives. Nonetheless, while they agreed on making public aggregate data and total figures they did not agree on sharing disaggregated and original data. The same can be stated for data coming from public sources. In this case, the main problems of sharing disaggregated data relate to the presence of sensitive information and the still ongoing process of damage compensation by public authorities.

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