Bollettino di Geofisica Teorica ed Applicata Vol. 62, n. 2, pp. 319-334; June 2021
DOI 10.4430/bgta0317

Domino and cascading effects in complex events and territorial contexts

M.P. Boni[1], S. Menoni[2] and F. Pergalani[1]

[1] *Dipartimento di Ingegneria Civile e Ambientale, Politecnico di Milano, Italy*

[2] *Dipartimento di Architettura, Ingegneria delle Costruzioni e Ambiente Costruito, Politecnico di Milano, Italy*

(Received: 17 July 2019; accepted: 14 January 2020)

ABSTRACT In the paper, a discussion about domino and cascading effects due to triggering hazards is presented. The importance of considering secondary or concurrent events and the complexity of the affected territorial systems, is actually a key topic in scenario and risk studies. This kind of approach actually increases the difficulties in obtaining detailed results, but permits to have a more complete view on the effects of dangerous events, not only in the directly affected areas, but also in wide and sometimes unexpected, times and spaces. A framework representing the logic sequence of the effects (direct, secondary, etc.) due to different hazards (single or cascading, or concurrent), considering the characteristics of the affected territory, in terms of systemic vulnerabilities, response capacity and interdependencies among of the involved sectors, to obtain a scenario of high order, is proposed. The framework is applied to two real cases occurred during central Italy seismic swarm 2016-2017: the landslides triggered by earthquakes on the road system and, the snowstorm and the power outages in January 2017.

Key words: multi-hazard, cascading effects, domino effects, scenario, systemic vulnerability.

1. The increasing complexity of disasters

As a scientific community, we are witnessing an increasing complexity of disasters worldwide. Such complexity can be attributed to the actual development of the impact of natural hazards on an increasingly interconnected environment and/or as a consequence of a different approach to the analysis of events. In both cases, new aspects are emerging as relevant in our discussion, and require, therefore, partly new interpretation partly a renewed attention to factors that were perhaps neglected or less investigated until recently. On one hand there is the change in urban and regional patterns from a social and economic point of view with important repercussions on how infrastructures are built, developed, and how they function. In fact, as discussed by Sassen (2018), in the last twenty years or so, a radical change has occurred in urbanisation. Not only and not simply the urban population has increased to levels unthinkable in the past, but such growth has occurred in a differential way both quantitatively and qualitatively, creating new centralities and new marginalities. The fast and rapid transformation of the patterns of networks and relationships along which resources and people are moving, producing concentration or abandonment effects, are not easy to cope with for administrations and governments. Such new geography creates different risk environments where not only central areas, large cities and metropolitan ones are experiencing increasing vulnerabilities due to large exposure of assets and population and to the interconnection among the latter, services, and production facilities, but also more remote places do.

By being at the periphery of the largest commercial and financial trajectories, the latter experience increased vulnerabilities due to their remoteness, to declining population and rarefying businesses. Even though the reasons and the modalities of vulnerability and risk creation are different in large metropolitan areas and in peripheral semi-rural, mountain areas or islands, still the interconnectedness of services, functions, and places is acting in both, even though at different levels and with different outcomes.

1.1. A changing understanding of multiple hazards

The way in which disasters are tackled has changed as well, under the pressure of funding organisations that have called for more interdisciplinary work and for the inclusion of diverse stakeholders in research projects so as to address real needs and knowledge demand coming from the so called end-users of scientific studies and technical applications. This has led towards the recognition that barriers between disciplines and expertise tackling different hazards are not useful in areas that are exposed to multiple threats at the same time and to develop policies and risk mitigation strategies that, in order to be effective and efficient, need to combine the investment in risk reduction with an increased level of safety for all existing hazards. This development is reflected in two subchapters of the Disaster Science Report issued in 2017 by the Joint Research Centre (JRC) (Poljanšek *et al*., 2017) and collecting the state of the art according to a rather large and diverse group of experts active in various fields of hazard and risk analysis both natural and man-made. The 2.1 subchapter proposing an innovative perspective on quantitative and qualitative risk assessment and the 2.5 one discussing the more recent advancement in multi-hazard/multi-risk perspectives are of particular relevance. As for the former, rather clarifying exposition of the advantages and disadvantages of deterministic and probabilistic methods is provided, pointing at the need of identifying the purposes for which one or the other is selected for a given analysis. Considering deterministic scenarios, the authors open the floor for using the wide range of tools available in industrial risk analysis also in other contexts, such as natural hazards: the Failure Mode and Effect Analysis (FMEA) or the "What if" methods can be reasonably used also in developing scenarios where the triggering event is an earthquake or a flood instead of a mechanical failure. Also, the authors call for a less restrictive understanding of rigour in risk analysis, complementing quantitative and qualitative approaches in order to grasp the widest possible range of consequences and linkages that cannot always be fully included in purely quantitative analyses. Menoni (2006) had already discussed how difficult it is to include cascading and enchained effects in probabilistic risk assessments and how deterministic scenarios, if adequately selected, could provide fundamental understanding on how interlinked and related events could unfold in a given disaster occurrence. Certainly, the use of the event that has actually happened as a relevant "stress test" for previous both probabilistic and deterministic assessments is beneficial for both improving risk modelling capacity and for improving our overall understanding of real disaster occurrences.

The title of the 2.5 subchapter "where are we with multi-hazard, multi-risk assessment capacities" suggests already that definite and concluding solutions are not available. Zschau

(2017) quotes the classification provided by Gill and Malamud (2014), according to which different types of interconnections can be identified between hazards that co-exist in the same area. Following their arguments, a slightly different categorisation is proposed here. First, it is important to distinguish between interdependent and independent events that may still either occur within a short time delay or still threaten the same geographic area. Under the interdependent hazards, the "triggering relationship", such as a landslide triggered by an earthquake, and the "increased probability relationship", such as landslides increased frequency after wildfires, can be grouped. As for independent hazards, one may consider an earthquake and a storm occurring at the same time, even though not physically related, they significantly hamper rescue operations if they happen simultaneously in the same area. There are some hazards that are intrinsically multi-hazards. Volcanic eruptions entail a wide range of phenomena occurring simultaneously or within a short time delay (tephra, ballistics, pyroclastic flows, lava flows, gas emission) and may be preceded by seismic events connected to magma activity and followed by events triggered by the previous ones, such as lahars, landslides, and tsunami. A first level of complexity is due to the interaction among different hazards that may occur during the same event sequence, triggered by one another or independently. Scholars point at the difficulties in assessing quantitatively the probability of occurrence of such interconnected or co-occurring events. Whilst such assessment is certainly relevant for enhancing our knowledge on multiple events, it is not equally necessary for choosing the best mitigation and defense options. In this regard, selected significant scenarios exploring different combinations of events over time and space can better serve the purpose of comprehending the involved challenges and designing alternative strategies.

In fact, once the probability of multi-hazard or multi-event scenario is identified, one needs to establish the risk associated to them, not only in terms of number of deaths or overall economic damage, but also in terms of sequence of different order failures and damages. In fact, especially economists (Cochrane, 1997; Rose, 2004; Meyer *et al.*, 2014) have shown that damage is not only the direct physical impact due to the stress of the extreme phenomena on a number of exposed assets, but also important is the so called "indirect" damage that actually comprises a number of different types of negative consequences that deserve to be appraised. The latter are key as in some cases second order and long term damage can be larger than the cost associated with rebuilding and repairing what has been physically harmed (excluding of course the consideration of the victims). In this respect, it is important to account for the unserviceability and malfunctioning of systems, activities, and sectors that may be crucial for a community and its economy. In a comprehensive risk assessment, therefore, not only the direct physical impact and its equivalent in repair or substitution costs must be considered, but also the larger set of indirect and even long term effects (duPont IV and Noy, 2015).

1.2. Complexities unfold across multiple spatial and temporal scales

The complexity of events is due to the fact that combined and enchained effects of what may be perceived as an initial triggering event gain relevance across both spatial and temporal scales. Cascading and domino effects are not necessarily occurring right after the initial triggering event but often manifest along time (days, weeks, months to years) and may be felt in areas that have not been physically harmed. Definitions of cascading and domino are missing in literature and often, especially in the field of industrial risk analysis, the two terms are used interchangeably or one is used to explain the other. For example, Delvosalle (1996) defined domino events as "a cascade of events in which the consequences of a previous accident are increased by following one(s), as well spatially as temporally, leading to a major accident". According to the Centre for Chemical Process Safety, as quoted by Kadri *et al*. (2013), domino may be referred "to an accident in which a primary event propagates to nearby equipment (units), triggering one or more secondary events resulting in overall consequences more severe than those of the primary event". Berg (2016) suggests that whilst the term domino is more widely used in the industrial risk literature, cascading is more often adopted in natural disaster studies. Pescaroli and Alexander (2015) grounding on the results of an extensive review conducted in the context of the EU funded project Fortress proposed the following definition: "Cascading effects are the dynamics present in disasters, in which the impact of a physical event or the development of an initial technological or human failure generates a sequence of events in human subsystems that result in physical, social or economic disruption. Thus, an initial impact can trigger other phenomena that lead to consequences with significant magnitudes". The term cascading is also extensively used in the domain of critical infrastructures: it has been defined by Rinaldi *et al*. (2001) in an authoritative article as effects that occur "when a disruption in one infrastructure causes the failure of a component in a second infrastructure, which subsequently causes a disruption in the second infrastructure"; note that such eventuality does not require that the infrastructures are proximal to one another as it may result from functional interrelationships among complex networks.

As an example of cascading, typically one may think of power or water outages that are the consequence of the combined effect of physical damage to elements of the network, to the hierarchical relevance of the latter, and to the lack of redundancy of the grid. As an example of domino effect, one may think about the impact that the relocation of services and key businesses may have on the abandonment ratio of a region after a disaster occurrence. In both cases the quality and the timing of response and allocation of resources can modify a damage pattern or sequence. As indirect and longer term damage is hard to measure even after a disaster, there has been a general tendency to underestimate or leave out such considerations certainly from quantitative analyses but often also in qualitative accounts. More recently, improved statistical databases, an improved software and hardware capabilities have permitted to dig more even on longer term damage, being able, albeit with some degree of uncertainty, to clearly detect the impact of disasters on economic activities over longer time frames (duPont IV and Noy, 2015).

Fig. 1 summarises the framework that is proposed for including in the same scenario assessment the different linkages due to the interaction or co-occurrence of multiple phenomena, the differential sequence of impacts due to the latter and to the ripple effects created by systemic vulnerabilities, response and coping capacity (or lack of) and resilience. The framework is organised so as to show the logic sequence of effects across the time scale from one level to the following one. The stressing factors (hazards and physical damage) are always reported on the upper part of the sequence line, whilst the vulnerability and resilience factors are always represented in the lower part.

The first order damage is the physical impact resulting from the stress produced by an initial hazard occurrence, triggered or co-occuring hazards and the physical vulnerability to the latter of exposed assets and people. Second order damage results from the combination of the first order physical damage and the systemic vulnerability of complex systems that can be counterbalanced by effective coping capacity of responding organisations and community (or instead magnifying the effect of systemic vulnerabilities). Higher order damage can be identified in larger systems and

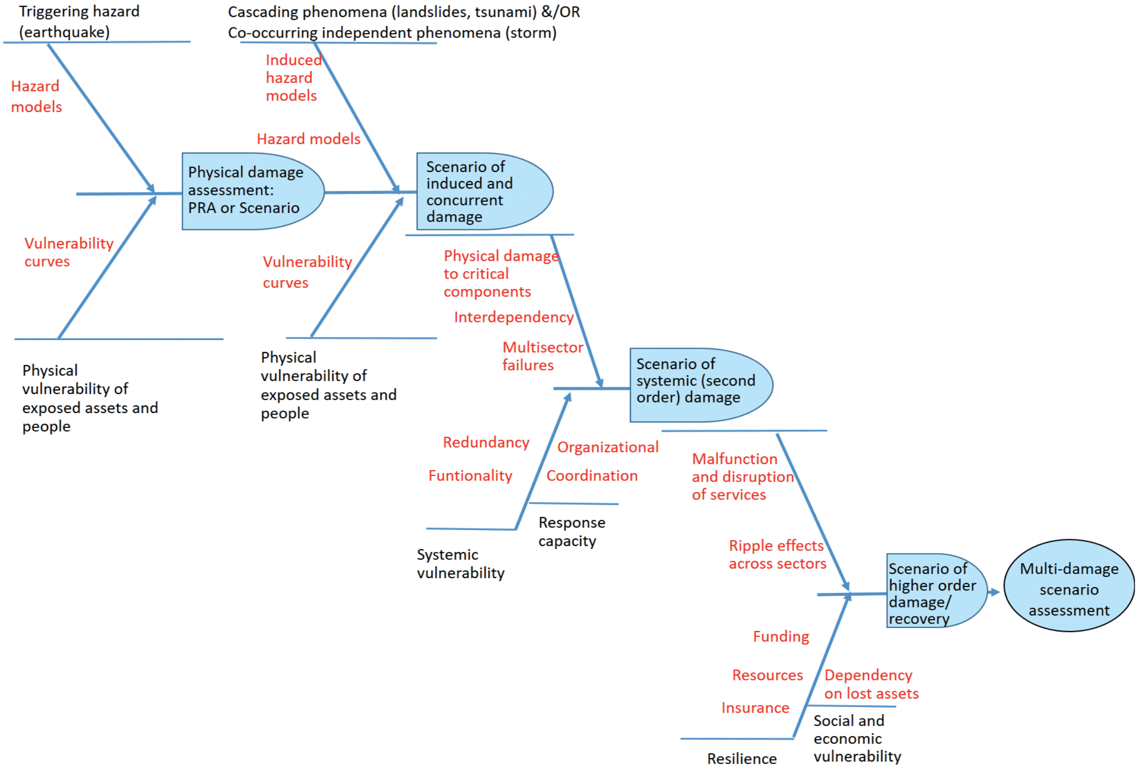


Fig. 1 - Sequence of multiple hazards and consequences.

sectors that depend to different degrees on systems such as lifelines, supply chains, and services and that are in their turn interconnected to each other (like for example economic activities that pertain to the same production chain).

2. Examples of multi-hazards events and damage in the central Italy seismic swarm 2016-2017

The central Italy swarm constitutes an interesting example of event that defeat the traditional understanding of the phases following a disaster due to fast onset natural hazards such as earthquake. Such a traditional sequence implies an impact, a first emergency, an early recovery, reconstruction, and advanced reconstruction. A swarm, however, is bringing back the system to the emergency phase even when recovery and even first reconstruction is ongoing, creating a significant stress on the population and also on intervening agencies and governments (regional and national). Also in terms of spatial scales the event was not limited to the villages that were particularly devastated, but created significant functional and systemic damage in a large territorial system comprising four regions, non-redundant road connections between the Adriatic and the Tyrrhenian coasts, displacing and reconfiguring the life of communities displaced from the mountain areas to the shoreline. In the article we will provide as examples two cases of multi-hazard events, one triggered by another, i.e. the landslides triggered by the numerous ground shakes that cut many roads, and two co-occurring independent events such as the 5.5 magnitude shake that occurred on the 18 January 2017 and the snowstorm that affected the central - eastern part of Italy in the days comprised between 16 and 22 January.

2.1. The effects of the landslides triggered by earthquakes on the road system

The evolution of the seismic crisis in the months between August 2016 and January 2017 caused a continuous evolution of the landsides activations and displacements. After the 24 August event, the triggered landslides were very numerous and spread in the territory, but, in most of the cases, characterised by limited dimensions, with the exception of the well-known case of Pescara del Tronto. The situation though worsened significantly after the October events both in terms of number and dimension (Stewart *et al*., 2017).

Phenomena such as rockfalls, debris falls on the roads, or cracks/failures of the roadways impacted severely the road system interrupting and/or reducing its functionality over a large area. These criticalities had to be added to the numerous direct damage caused by the earthquakes (e.g. to bridges and retaining walls).

Due to the complexity of the problem, the national government decided to design national autonomous roads corporation (ANAS), as the unique subject in charge of analysing, coordinating, and managing the damage and the consequent interventions in collaboration with the local administrations and Civil Protection (D.L. n. 205/2016). In order to define a program of prioritised interventions, specific criteria were applied, balancing the relevance of the various roads for the emergency phase (e.g. to guarantee the access to the temporary sheltering areas or the accessibility to the debris storage areas) and the level of importance of each road for territorial accessibility (e.g. a main road connecting two regions is more important than a local road). The program signed in 2017 is still undergoing and its specific realisation can be followed through a devoted website (http://www.anas-sisma2016.it).

To understand the dimension of the problem and the weight of the landslides effects in the total amount of criticalities, it is possible to download the data from the interactive map published in the website (updated to 3 May 2018, Fig. 2): overall 541 interventions are reported, 65% of which regard landslides.

The functional second order damage, in terms of interruptions or limited accessibility before and during the interventions, varied depending on the type and relevance of roads. As an example, intervening on a series of rockfall threatening a road, required several subsequent interventions to retrofit large portions of slopes. This implied to close and reopen the same road tract more than once to permit the access and the works in safe conditions.

In the following two examples of functional second order damage will be discussed in more detail.

The first case regards the provincial road number 209 (Valnerina), an important connection between Umbria and Marche regions, that, during the 2016 seismic crisis was affected by a large number of landslides, in most of the cases rockfalls. Fig. 3 shows the impressive rockfall provoked by the 30 October 2016 earthquake near Visso (km 65.8) that fall down in the narrow valley where the SP 209 road runs parallel to the Nera River. The road and the river were buried by a large amount of deposits and the riverbed diverted, flooding the road following the sequence represented in the scenario diagram in Fig. 4.

In this case, the road interruption was a concatenation of criticalities: the large rockfall and

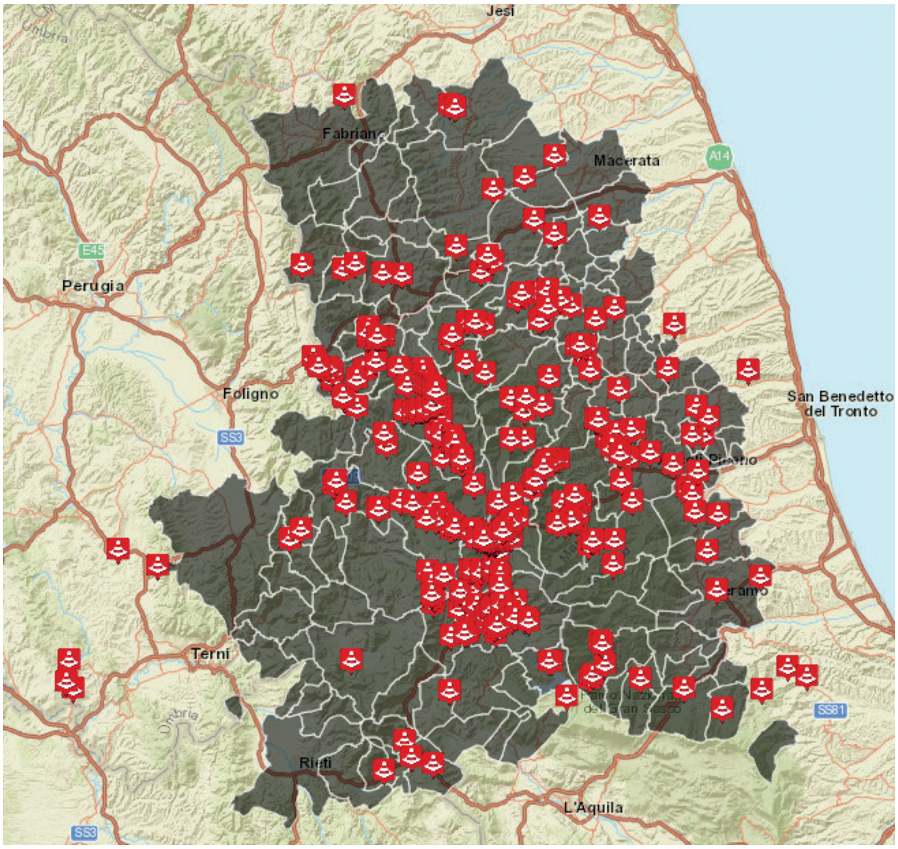


Fig. 2 - ANAS interventions at different work progress updated to 3 May 2018 (http://www.anas-sisma2016.it).

the flood. So, a series of complex interventions were planned by ANAS: to retrofit the slope, to remove the deposits, and the repositioning of the river in the original riverbed, besides the repair of a bridge and of another part of the road near this point damaged by other rockfalls (http://www.

Fig. 3 - The rockfall triggered by the 30 October 2016 earthquake on the SP 209 and Nera River (https://www.perugiatoday.it/foto/cronaca/terremoto-norcia-frane-valnerina/aa644aa1.html#&gid=1&pid=1).

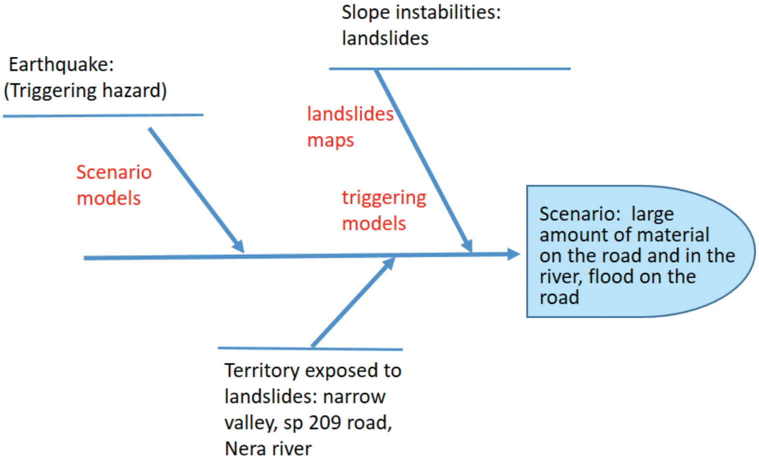


Fig. 4 - Cascading effects concerning the 30 October 2016 earthquake and the SP 209 near Visso.

anas-sisma2016.it). A temporary re-opening with limitations was possible in October 2017 and the road was completely accessible since 1 February 2018 (in Fig. 5 the situation in July 2018, after the interventions).

The described situation put in evidence the many vulnerabilities of the SP 209 road in that site: an intrinsic physical and morphological condition (a narrow valley), the river near the road, the presence of numerous landslides with high possibility to fall down, especially in case of earthquake.

Fig. 5 - The SP 209 near Visso after the interventions (July 2018).

The second case refers to the access roads to the Castelluccio di Norcia Plan. All four roads leading to the Castelluccio Plan were affected by the 30 October 2016 shake. Different causes produced damage and/or obstructions: roads structural failure, landslides, and debris of collapsed buildings (http://www.anas-sisma2016.it). After the event, it was quite impossible to access the plan, with significant repercussions not only in terms of mobility for the inhabitants of the hamlet of Castelluccio, but also for the local economy based on the lentil cultivation (very particular and appreciated variety) and on tourism, especially in summer during the "Plan Flowering", when a carpet of coloured flowers covers the plan and it seems like a paint. The sequence of second and higher order damage is represented in Fig. 6.

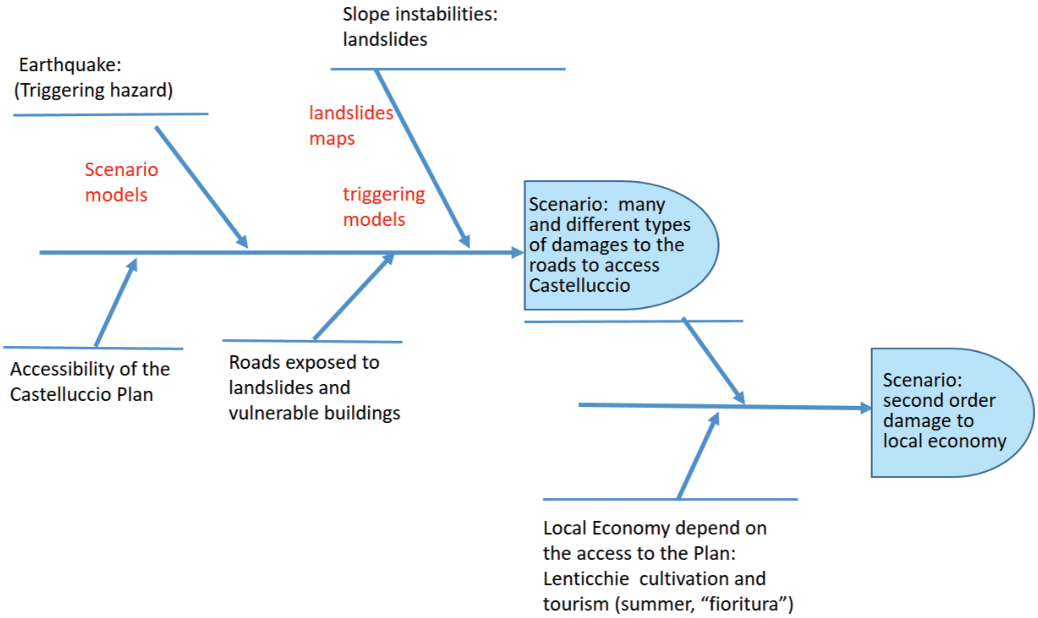


Fig. 6 - Second order damage due to the 30 October 2016 earthquake in Castelluccio di Norcia Plan.

Given the multiple causes of the roads damage, several interventions were programmed and realised, setting as a primary goal to permit at least limited access to allow the lentil production and the presence of tourists during summer. On 3 April 2017, it was made possible for the farmers to reach the plan for the lentils sowing with the tractors and other agricultural vehicles. Farmers were guided by Army personnel along two pre-defined itineraries, after some interventions to guarantee a minimal level of safety (Valnerinaoggi, 2017). During the summer, instead, some roads were temporarily reopened in the weekends for touristic activities. Such program of interventions followed a systemic approach considering, beyond physical/technical aspects of road recovery, also social and economic needs. Such an approach required the coordination among many actors: the local administrations, ANAS, the Civil Protection, the population/associations. An unusual and complex way of working together had to be achieved: albeit difficult and imperfect, it permitted to obtain some relevant shared results.

2.2. The snowstorm and the power outages in January 2017

In the days between 5 to 23 January 2017, an exceptional prolonged snowfall associated with strong winds affected central Italy. Two phases can be identified in the series of snow accumulation recording before and after 16 January. The second phase was characterised by significantly higher levels of precipitation with peaks recorded in the days 18 and 19 January. The storm occurred mainly along the Apennines but, to some extent, also along lower areas up to 300 m, affecting the same regions already hit by the August and October shakes but more severely Marche and Abruzzo.

According to the recording that were made available by Terna and Enel (the companies responsible respectively for the network and for the provision of power) in their official website open to the public, after 15 January, two further phases can be distinguished: the first between 15 January in the afternoon and 19 January, when both mountain and plain areas as low as 200 m above sea level were covered by snow; the second phase between 20 and 24 January mainly in the mountain areas. In the first period the two provinces of Pescara and Teramo witnessed a continuous increase in the amount of accumulated snow precipitation, whilst the two other provinces of L'Aquila and Chieti recorded a more constant level. In the second period, and differently from the forecasts of those days, the amount of accumulation increased steadily in all provinces, as can be seen in Fig. 7.

The snow created problems to lifelines, in particular to the road network and to the power system. As for the latter, the accumulation of wet snow sleeves damaged power overheads while trees fell on both high voltage and medium to low lines. A number of transformation rooms in

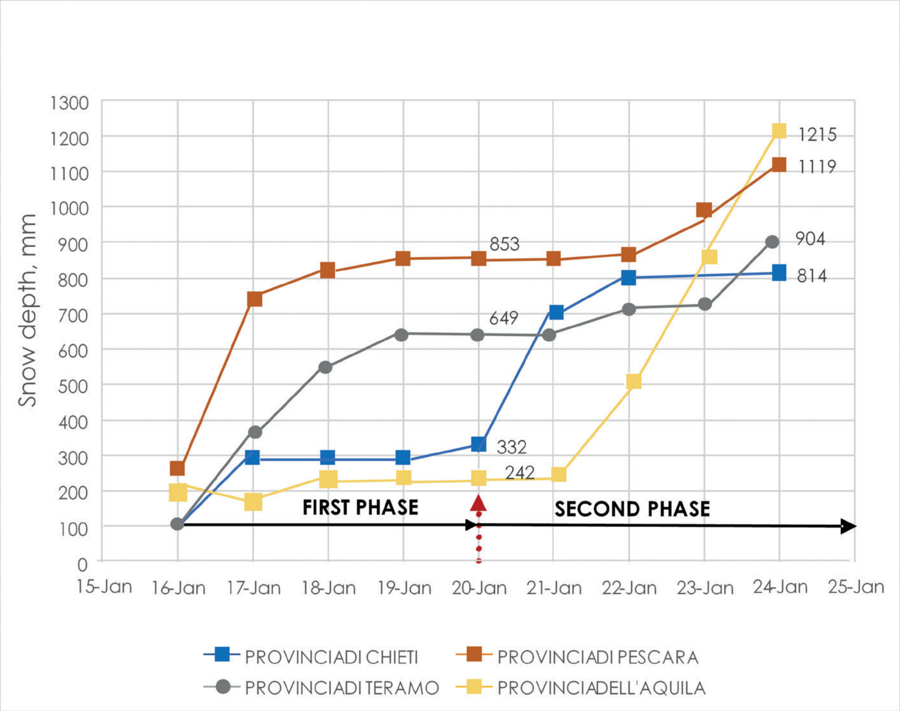


Fig. 7 - Snow depth as recorded by Enel and Terna (Koçoğlu, 2017).

substations were disconnected as a result of disturbances along the lines resulting in a large number of outages across the four provinces of Abruzzo. The long lasting precipitation worsened the operational conditions of the workers of the Enel and Terna companies in charge of repair and of providing mobile generators to restore energy in multiple places. According to the hearings that were held in the Italian Senate, a number as high as 900 generators were dispatched to different areas, drawing on both companies' resources and on external provisions. In Fig. 8 the effectiveness of the restoration operations can be appreciated as the red line shows the peak number of customers suffering power outages in each day, whilst the blue line represents the same parameter at the end of each day. The difference between the two lines is the actual number of customers experiencing recovered service. For example, on 17 January as many as 159,000 customers suffered a blackout; at the end of the same day this number had diminished to 87,000, meaning that energy had been restored for 72,000. A steady decrease of unserved customers can be appreciated in the graph, even though after a week there were still 15,000 customers deprived of energy.

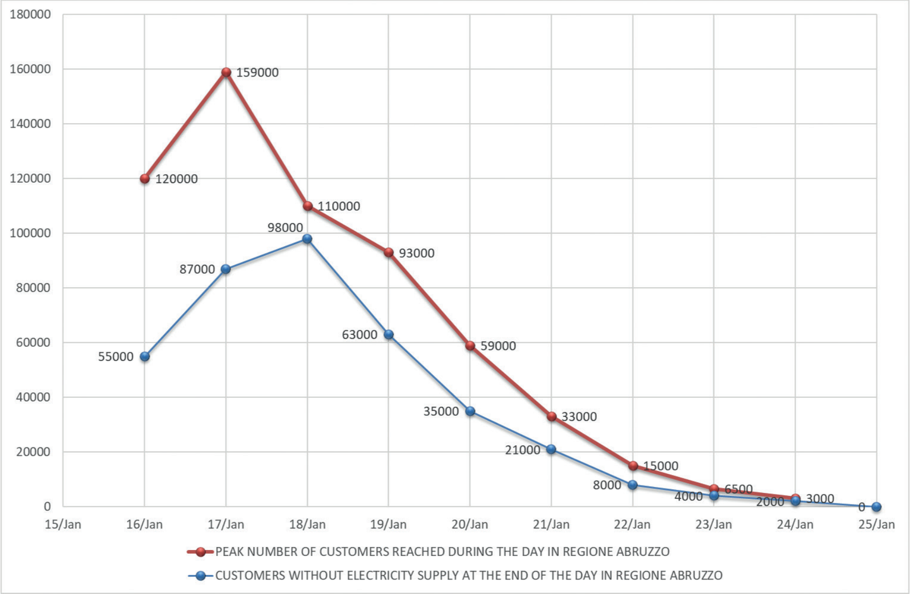


Fig. 8 - Outages (peaks and number of customers at the end of the day) at each day in Abruzzo region (Koçoğlu, 2017).

Fig. 9 provides information regarding the geographic distribution of the outages along the entire disturbance period. The provinces of L'Aquila and Pescara experienced a less severe blackout in terms of unserved customers; the maximum number of outages were felt in the Chieti province, but diminished rather fast in the next days. The province of Teramo is the one that experienced the second highest peak of outages and for a longer period of time compared to the other provinces. A number of factors may explain this result. Some cannot be verified without a more refined and exact information about which are the areas with the most severe physical damage, and also the geographic distribution of customers served by the physically damaged lines and by the disconnected sub-stations. However, some systemic vulnerability factors can

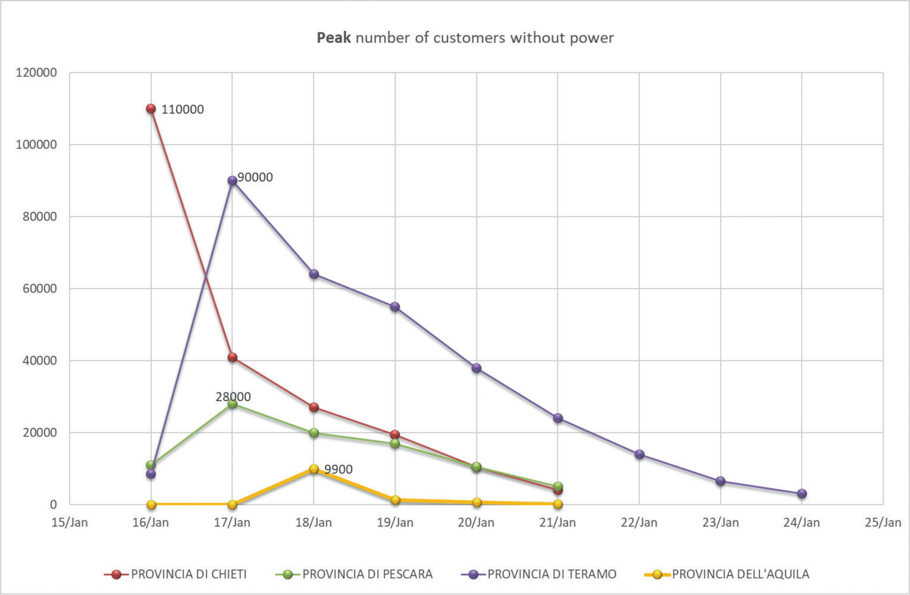
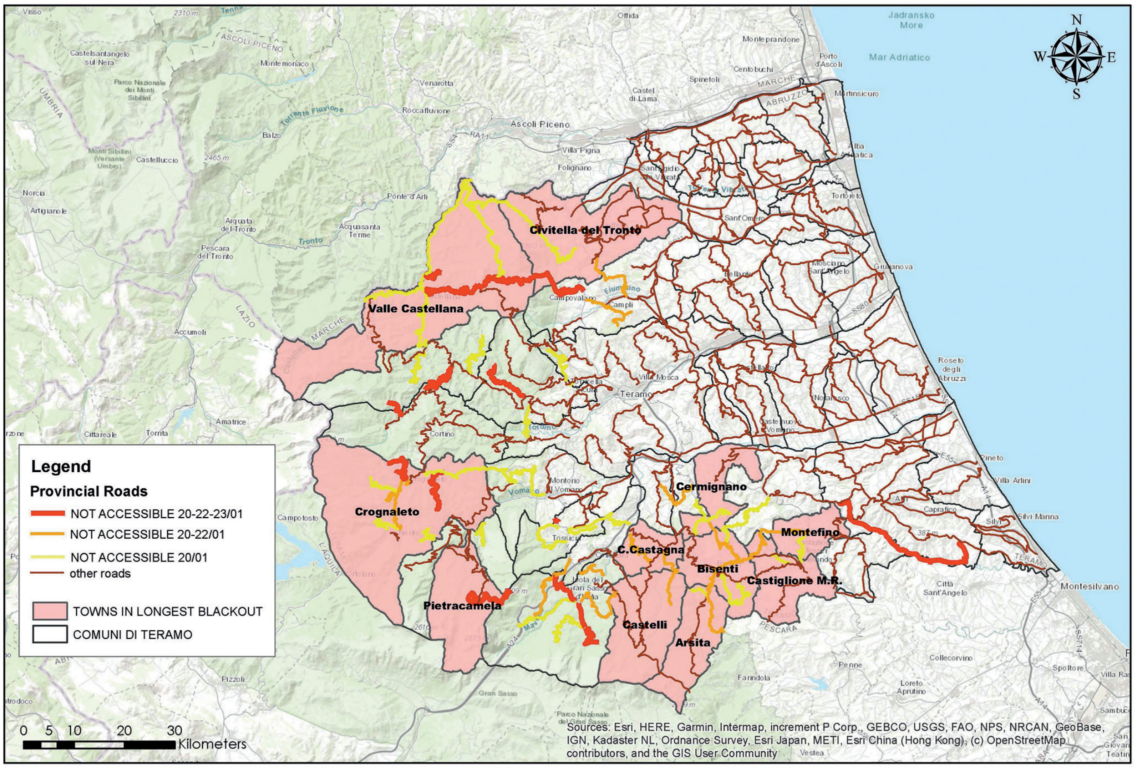


Fig. 9 - Power outages in the four provinces of Abruzzo region (Koçoğlu, 2017).



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Fig. 10 - Map showing the overlapping road interruption and the towns experiencing the longest power cuts.

be certainly appreciated. As the snowstorm affected severely also the road system, a number of localities became inaccessible to rescue services and to the teams in charge of restoring energy.

The map in Fig. 10 shows the overlapping of the towns that experienced the longest duration of power cuts and the roads that were closed for one day or more in the days between 20 and 23 January. In fact, it can be easily seen that those towns are mainly in mountain areas, and were hardly accesible during those days.

The example illustrated above displays a number of features that characterise a multi-hazard event in a complex setting. The chain of failures and resulting damage scenarios are displayed in the fishbone diagram in Fig. 11. In fact, two independent events, the snowstorm and the rather strong earthquake co-occurring at the same time, created additional challenges to a territory that had been already significantly affected by the seismic swarm of the preceding months. The snow, exceptional both for its duration and intensity in terms of accumulation, provoked damage to physical components of the power system. The mountain setting of the area made some places unreachable for the combined effect of the snow on the road system, made of narrow lanes with many curves and high inclination in some parts; small towns and hamlets dispersed over a wide

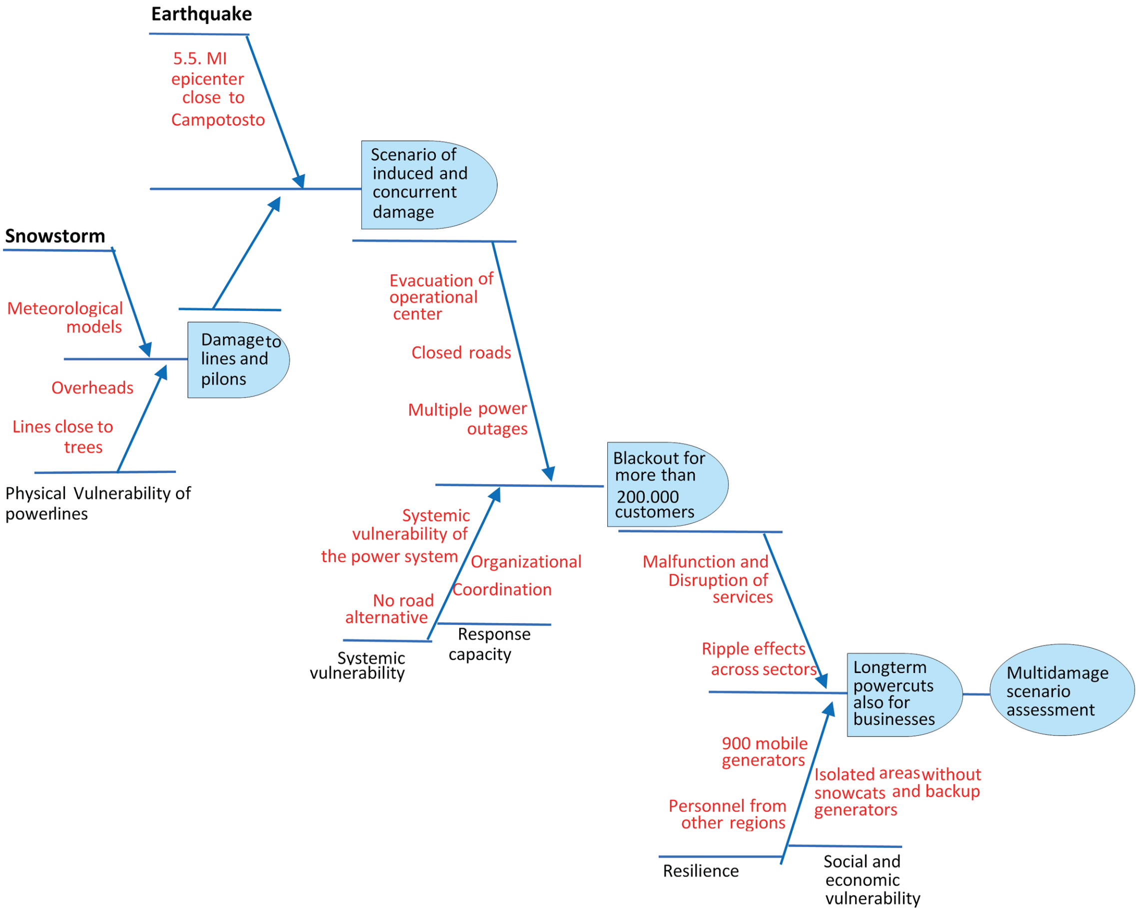


Fig. 11 - Sequence of damage in January 2017 in central Italy due to the combined effect of the snowstorm and the earthquake.

region, partially isolated also in less severe circumstances where a declining old population lives without means and resources such as local generators and snow cats.

Following the fishbone diagram representation, the event has been re-constructed in its main aspects in Fig. 11.

3. Discussion and conclusion

The analysis of the two cases using the conceptual framework that has been provided in section 1 highlights the importance of collecting and appraising damage and failure data in a systematic way, addressing not only the direct impact that is usually recorded but also more systemic effects. It has been shown how the environmental context matters, not only in shaping the potential for multiple, enchained or not, phenomena, but also what we have defined elsewhere as systemic vulnerability (Menoni *et al.*, 2007). The latter refers to those weaknesses and fragilities that arise at systems' level, depending on interconnections and interdependency among systems and systems' components (Rinaldi *et al.*, 2001), and on the lack of redundancy and transferability (Van der Veen and Longtjmejer, 2005) of crucial functions and services. Systemic vulnerability is one important cause of the disruption of services, businesses, and societal sectors often independently from the magnitude and the extent of the physically damaged components, due to amplification effects that derive from lifelines and other critical infrastructure complexity. In the case of central Italy, both the landslides triggered by the shakes and the snowstorm in January 2017 represent a typical multi-site event as defined in Menoni and Margottini (2011) that stressed a rather wide area that was systemically vulnerable due to the dispersed territorial pattern made of small towns and hamlets located in the mountain, often with few alternatives, difficult to drive because of their configuration and sometimes closed due to the lack of organisational and technical resources needed to clean them from the snow.

The effort that the European Commission, international organisations such as Irdr, Unisdr, and scientific associations are carrying out to improve the modality of damage data collection and reporting is justified also by the need to enlarge the pool of data from which more robust analysis of second order damage, cascading, and enchained effects can be derived. Recent disasters have unveiled a complexity that was unexpected due to a number of causes: some related to the hazards, other to the characteristics of exposed assets and the vulnerability of the latter and of systems. Being able to comprehend, model, and assess such complexities in order to better prepare and prevent risks, requires a better understanding of the multiple relationships that the diagrams used to represent the conceptual framework suggest. A better understanding can be achieved by continuous comparison and cross-validation of indicators and parameters that have been already identified by past research but need to be empirically verified in real events. Therefore, what has been proposed in this paper is just a first step that opens though a trajectory for future studies in order to substantiate both the conceptual framework and the indicators that have been already propose and to indicate new ones that appear to be relevant in the course of the analysis.

Acknowledgements. Part of this paper was presented at the 37th GNGTS meeting held in Bologna on 19 to 21 November 2018.

REFERENCES

Berg H.P.; 2016: *How to investigate and assess combination of hazards*. J. Pol. Saf. Reliab. Assoc., **7**, 1-12.

Centre for Chemical Process Safety (CCPS); 2000: *Guidelines for chemical process quantitative risk analysis, 2nd ed*. American Institute of Chemical Engineers, New York, NY, USA, 748 pp.

Cochrane H.; 1997: *Indirect economic losses*. In: Development of standardized earthquake loss estimation methodology, National Institute for Building Sciences, Washington, DC, USA, Vol. II.

Delvosalle C.; 1996: *Domino effects phenomena: definition, overview and classification*. In: Proc., First European seminar on domino effects, Leuven, Belgium, pp. 5-15.

duPont IV W. and Noy I.; 2015: *What happened to Kobe? A reassessment of the impact of the 1995 earthquake in Japan*. Econ. Dev. Cult. Change, University of Chicago Press J., **63**, 777-812, doi: 10.1086/681129.

Kadri F., Chatelet E. and Lallement P.; 2013: *The assessment of risk caused by fire and explosion in chemical process industry: a domino effect-based study*. J. Risk Anal. Crisis Response, **3**, 66-76.

Koçoğlu B.; 2017: *Power systemic failures due to a multi-site contingency: an innovative approach to damage data analysis. The blackout crisis in January 2017 in Italy*. PH.D. Thesis in Ingegneria Civile e Ambientale, Politecnico di Milano. Milano, Italy.

Menoni S.; 2006: *Different preventive strategies require diversified risk assessment models*. In: Proc., MorelIgor B. and Linkov I. (eds), NATO Advanced Research Workshop on the role of risk assessment in environmental security and emergency preparedness in the Mediterranean Region, Environmental Security and Environmental Management: the Role of Risk Assessment, Eilat, Israel, pp. 211-221.

Menoni S. and Margottini C. (eds); 2011: *Inside risk: a strategy for sustainable risk mitigation*. Springer-Verlag, Berlin, Germany, 369 pp.

Menoni S., Pergalani F., Boni M.P. and Petrini V.; 2007: *Lifelines earthquake vulnerability assessment: a systemic approach*. In: Linkov I., Wenning R.J. and Kiker G.A. (eds), Managing Critical Infrastructure Risks, NATO Science for Peace and Security Series C: Environmental Security, Springer, Heidelberg, Germany, pp. 111-132.

Meyer V., Schwarze R., Becker N., Markantonis V., van den Bergh J.C.J.M., Bouwer L.M., Bubeck P., Ciavola P., Genovese E., Green C., Hallegatte S., Kreibich H., Lequeux Q., Logar I., Papyrakis E., Pfurtscheller C., Poussin J., Przyluski V., Thieken A. and Viavattene C.; 2014: *Assessing the costs of natural hazards - state of the art and the way forward*. In: Quevauviller P. (ed), Hydrometeorological hazards: interfacing science and policy, Wiley & Sons Ltd, Chichester, UK, pp. 225-290, doi: 10.1002/9781118629567.ch4a.

Pescaroli G. and Alexander D.; 2015: *A definition of cascading disasters and cascading effects: going beyond the "toppling dominos" metaphor*. Planet@Risk, **3**, 58-67.

Poljanšek K., Marin Ferrer M., De Groeve T. and Clark I. (eds); 2017: *Science for disaster risk management 2017: knowing better and losing less*. Publication Office of the European Union, Luxembourg, EUR 28034 EN, 551 pp., doi: 10.2788/842809 JRC102482.

Rinaldi S., Peerenboom J. and Kelly T.; 2001: *Identifying, understanding and analyzing critical infrastructures interdependencies*. IEEE Control Systems, **21**, 11-25, doi: 10.1109/37.969131.

Rose A.; 2004: *Economic principles, issues, and research priorities of natural hazard loss estimation*. In: Okuyama Y. and Chang S. (eds), Modeling of spatial economic impacts of natural hazards, Springer, Heidelberg, Germany, pp. 13-36.

Sassen S.; 2018: *Cities in a world economy, 5th ed*. Sage Publ. Inc., Thousand Oaks, CA, USA, 440 pp.

Stewart J.P., Lanzo G., Ausilio E., Cairo R., Bozzoni F., Capatti M.C., Della Pasqua F., Dezi F., Di Sarno L., Durante M., Simonelli A.L., Foti S., Chiabrando F., Dabove P., Di Pietra V., Maschio P., Passeri F., Sgobio A., Teppati Lose' L., Franke K. and Zimmaro P.; 2017: *Engineering reconnaissance following the October 2016 central Italy earthquakes, Version 2*. In: Zimmaro P. and Stewart J.P. (eds), Geotechnical Earthquake Engineering Reconnaissance GEER Association, GEER-050D report, doi: 10.18118/G6HS39.

Valnerinaoggi: 2017: <https://www.valnerinaoggi.it/norcia/semina-lenticchia-castelluccio-seminatrici-e-trattori-trainati-dai-mezzi-dellesercito-7492/>.

Van der Veen A. and Logtmeijer C.; 2005: *Economic hotspots: visualizing vulnerability to flooding*. Nat. Hazards, **36**, 65-80.

Zschau J.; 2017: *Where are we with multihazards and multirisks assessment capacities?* In: Poljanšek K., Marín Ferrer M., De Groeve T. and Clark I. (eds), Science for disaster risk management 2017: knowing better and losing less, Publications Office of the European Union, Luxembourg, EUR 28034 EN, Subchapter 2.5, pp. 98-115, doi: 10.2788/688605JRC102482.

Corresponding author: Maria Pia Boni
Dipartimento di Ingegneria Civile e Ambientale, Politecnico di Milano
Via G. Colombo 40, 20133 Milano, Italy
Phone: +39 02 23994261; e-mail: mariapia.boni@polimi.it