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Using reasoned imagination to learn about cascading hazards: A pilot study

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Abstract

Purpose – This article presents the results of a pilot study involving high school teachers in natural sciences. The aim was to foster critical thinking about cascading hazards via the use of reasoned imagination. Cascading phenomena can lead to extreme catastrophes and are thus a challenge for disaster prevention and management.

Design/methodology/approach – Following a presentation listing some known cascading phenomena, the participants completed a questionnaire consisting of a blank hazard correlation matrix (HCM) and some open-ended questions. The HCM qualitatively described possible interactions between 16 different perils selected from a large spectrum of natural, technological and socio-economic hazards.

Findings – Most participants were able to describe cascading phenomena within the HCM by reducing them into sets of 1-to-1 interactions. Based on their experience and imagination, the participants foresaw additional interactions that were not discussed, never observed but are scientifically plausible. The majority of the respondents reported that they learnt something new and wanted to learn more about cascading hazards.

Originality/value – The HCM is especially effective in translating complex hazard scenarios into basic interactions and *vice versa*. Being imaginative (here via the use of reasoned imagination) and accessible, the HCM could be used as basis for transformative learning in the education of the public and of practitioners on the role of cascading hazards in catastrophes.

Keywords Cascading hazards, hazard correlation matrix, critical thinking, questionnaire, reasoned imagination, transformative learning

Paper type Research paper

1. Introduction

Our complex socio-economic system is subjected to both internal (anthropogenic/technological) and external (natural) hazards, whose combined effects may be difficult to anticipate. Recent major catastrophes have often resulted from such interactions. Some of the best known examples are the 2005 hurricane Katrina, USA, which produced a surge large enough to breach levees, ultimately triggering the wide-scale flooding of the city of New Orleans (Comfort, 2006) and the 2011 Tohoku, Japan, earthquake, whose unexpected high magnitude triggered a tsunami larger than planned in the protection of the Fukushima nuclear power plant, leading to a major nuclear accident with radioactive material released, along with other industrial accidents (Norio et al., 2011; Krausmann and Cruz, 2013). Both disasters and their consequences triggered in turn a partial collapse of several production sectors (Hallegate, 2008; Norio et al., 2011). Gill and Malamud (2014) performed a review of almost one hundred potential interactions between various natural hazards, illustrating the richness of cascading hazard phenomena. Challenges in multi-hazard assessment and multi-risk governance are reviewed in Kappes et al. (2012) and Mignan et al. (2016), respectively.

Occurrences of extreme catastrophes - where losses are amplified due to the cumulated effects of cascading events - often appear as surprises, cascading scenarios being rarely considered in preparedness and mitigation plans (Komendantova et al., 2014). In the case when cascading scenarios are considered (e.g., de Dianous and Fiévez, 2006), failure to correctly describe only one critical element or interaction may have severe consequences (Perrow, 2001; Norio et al., 2011). This issue is being extensively re-investigated post-Fukushima and a proposed solution has been to consider “scientific” or “reasoned” imagination (Kameda, 2012; Paté-Cornell, 2012) in risk management. It means considering phenomena, which have not been observed but are scientifically plausible. Indeed, in view of the richness of cascading phenomena, it is evident that most possible combinations have not yet been observed.

Gill and Malamud (2014) already showed how the high variety of hazard interactions could be represented in matrix form with triggering events listed in rows and triggered events in columns. Mignan et al. (2014) developed a quantitative multi-risk framework where interactions are defined by conditional probabilities in an n-square matrix composed of n possible hazardous events. The hazard correlation matrix (HCM) approach is central to the description of cascading hazards over the entire $n \times n$ space of possible interactions. The main challenge then consists in filling the matrix with the proper hazards and interactions.

In this article, the suitability of the HCM method to learn about cascading hazards using reasoned imagination is explored. As a pilot study, a critical thinking exercise is developed using the HCM as basis. It is then tested upon a group of high school teachers in natural sciences. Involving teachers instead of disaster risk reduction practitioners in a first step was done for the following practical reasons: (*i*) by definition, these users have a critical approach to pedagogic tools and no preconception on multi-hazard assessment; (*ii*) being part of the general public, the targeted audience is in agreement with the concept of extended peer community, which includes those affected by the issue (Rosa, 1998), here the issue being extreme cascading disasters; (*iii*) there is a widespread agreement that education is crucial to increase public risk awareness and preparedness (e.g., Ronan et al., 2010; Kuhlicke et al., 2011; Sharpe and Kelman, 2011; Wachinger et al., 2013; Lutz et al., 2014); (*iv*) if the complexity of hazard interactions can be understood by non-experts, it would suggest the applicability of the method to a wide range of user groups.

2. Method

2.1. Critical Thinking Exercise on Multi-Hazard

An exercise was designed with the aim of learning about cascading hazards via the use of reasoned imagination. The exercise took place during the NERA *Seismology@School* (NERAS@S) workshop, organized by co-author A. Sauron and which took place on 23 October 2014 in Sion, Switzerland. Participants to the exercise were 38 high school teachers in natural sciences coming from twelve countries (Australia, France, Germany, Great Britain, Israel, Italy, Palestine, Portugal, Romania, Switzerland, Turkey, United States).

The exercise lasted one hour and proceeded as follows:

1. A questionnaire including an empty HCM and some open-ended questions was provided to each participant (Fig. 1).
2. A presentation made by lead author A. Mignan on "Extreme consequences of earthquakes" introduced the concepts of cascading event, HCM and reasoned imagination. It also explained how to fill the HCM taking as example the 2011 Tohoku earthquake case – This presentation is referred hereafter as the *exercise guidelines*;
3. In the first part of the exercise, the participants had to fill the HCM based on the examples of past catastrophes described in the guidelines. The examples focused on, but were not limited to, earthquake triggers;
4. In the second part of the HCM exercise, the participants had to continue filling the HCM based on their own knowledge and reasoned imagination. A discussion was facilitated by the lead author;
5. The final part of the survey included a set of open-ended questions about the respondents' learning experience and the usefulness of the HCM method for teaching purposes.

After the questionnaire collection, the data coding and analysis was performed.

The proposed exercise employs critical thinking by giving examples of hazard interactions to guide the participants into discovering by themselves more cascading phenomena (e.g., Bruner, 1961). While the use of reasoned imagination is promoted to better understand cascading hazards, it has the second advantage of making the learning experience more stimulating (e.g., Loewy, 1998; Sharpe and Kelman, 2011).

2.2. Hazard Correlation Matrix (HCM) Method

The hazard correlation matrix (HCM) is the main input to the recently proposed generic multi-risk (GenMR) framework (Mignan et al., 2014), Each cell of this matrix gives the probability of a target event conditional on the occurrence of a trigger event. The HCM (input for hazard correlations) is combined in GenMR to a *risk migration matrix* or RMM (output for multi-risk analysis), whose suitability for multi-risk decision-making has been tested in a previous multi-hazard exercise involving risk practitioners (Komendantova et al., 2014). The present analysis is therefore complementary to that previous study, but with a different user group target (i.e., education professionals).

The HCM here uses qualitative measures with hazard interactions represented by the following symbols: “+” (positive interaction, i.e. cascading), “-” (negative interaction, i.e. inhibiting), “±” (both interactions possible) and “Ø” (no direct interaction possible). Such a qualitative approach makes the simplified HCM similar in concept to hazard matrices used by other authors (Gill and Malamud (2014) and references therein).

The selected events (or perils) are related to high-impact hazards, i.e. hydrological, geological, meteorological and extra-terrestrial hazards, technological hazards including various types of critical infrastructures, and finally socio-economic hazards. More precisely the matrix includes 16 perils:

asteroid impact (AI), disease (Di), earthquake (EQ), fire (Fi), flood (Fl), mass slide (MS), volcanic eruption (VE), wind (Wi), dam and network failures (DF, NF), industrial accident (IA), business and health care interruptions (BI, HI), economic slowdown (ES), social unrest (SU) and war (Fig. 1).

2.3. Exercise Guidelines

The exercise guidelines first explained how to fill the HCM using as example the 2011 Tohoku earthquake case. The cascade was defined as follows: earthquake → tsunami → industrial accident. It was explained that cascades emerge naturally in the HCM from the combination of several 1-to-1 direct interactions. The cascade presented above is thus described in the HCM by noting “+” in the cells (EQ, Fl) and (Fl, IA), respectively, with cells of indices (trigger, target). It was emphasized during the exercise that the Tohoku earthquake did not directly trigger the Fukushima nuclear accident, such that the cell (EQ, IA) should remain empty for that particular catastrophe (a simplification from reality but used in the exercise for sake of illustration; Norio et al., 2011).

The guidelines presented 14 historical catastrophes known for their cascading phenomena. Emphasis was made on earthquakes as triggers but examples were not limited to this initiator. The examples were chosen in order to show the diversity of possible cascades and included well-known catastrophic cascades as well as some more obscure ones. Table I lists all the catastrophes and interactions illustrated in the exercise guidelines, most of which obtained from the scientific literature (see references in Table I). The interactions were described in image and text form and not directly in form of cell indices. There was therefore an interpretation to be made by the participants to translate the provided information into the HCM. The direct interaction couples given in Table I represent the correct results of the exercise compared to which the participants are scored (see section 3.1.2).

The guidelines finally gave two examples of reasoned imagination. The first example showed that asteroid impact scenarios on large cities, although never observed in reality, are imaginable (Harris, 2008) and can therefore be modelled (Mignan et al., 2011). The second example showed that new ideas, such as geomythology, could help in the understanding and quantification of extremely rare events (Piccardi and Masse, 2007). The goal was to clarify the concept of reasoned imagination to promote its use during the exercise.

3. Results

3.1. HCM Quality Evaluation

3.1.1. Basic observations

Before starting the data analysis, it was necessary to select the criteria to evaluate reliable data. We consider unreliable any HCM in which the cascading effect: earthquake → tsunami → industrial accident (i.e., 2011 Tohoku earthquake case) was not properly described, although the answer was explicitly given in the exercise guidelines. Of the 38 HCMs shown in Figure 2, 9 are thus considered unreliable (shown in lighter colours). The rest of the HCM analysis only considers the 29 remaining HCMs. The validity of this filtering approach is confirmed in section 3.1.2.

Figure 3a shows the number of answers *n* per HCM cell. The minimum and average number of answers per cell are 7 and 16, respectively. With only four different answers possible per cell, it indicates a reasonable sample size for the problem at hand. Figure 4a shows the number of answers per row, i.e. per trigger event. The most answered row corresponds to earthquake as a trigger with $\sum n(\mathrm{EQ},\{\mathrm{AI}, \ldots, \mathrm{War}\}) = 377$, which is in agreement with the number of examples given with an earthquake trigger (Table I). The second most answered row corresponds to asteroid impact as a trigger with $\sum n(\mathrm{AI},\{\mathrm{AI}, \ldots, \mathrm{War}\}) = 350$. Mention of asteroid impact hazard (without cascade) during the exercise may have pushed the participants to focus more on this potential trigger. Another reason could be that it is the first row of the HCM and that most participants started there. The main pattern that emerges from the graph of Figure 4a is the higher number of answers for natural hazard triggers compared to anthropogenic hazard triggers. This could be explained by the higher number of examples given in the first category (Fig. 3b), by its upper position in the HCM and/or by the fact that natural and anthropogenic hazards are often considered primary and secondary hazards, respectively (see e.g. the concept of NaTech event; Krausmann et al., 2011). Figure 4b shows the number of answers per column, i.e. per target event. The variations are lower than the ones observed in the case of trigger events, with no clear pattern emerging.

3.1.2. Score per HCM

Cells shown with thick dashed contour in Figure 3 correspond to the interactions described in the guidelines (Table I; Fig. 3b). Figure 3c shows that there is a good agreement between the most common answer given for each HCM cell (by the participants considered reliable) and the expected

HCM result (Fig. 3b). The agreement becomes perfect once non-answered cells are removed (Fig. 3d), which indicates a good overall understanding of the exercise and of the HCM method.

To estimate the quality of each one of the 29 HCMs previously considered reliable, we determine their score as the number of correct answers, assuming that the expected HCM result represents a perfect score $S = 32$. Figure 4c shows the score per HCM (represented by black dots; unreliable HMCs by grey dots). We first remark that the HCMs originally considered unreliable perform indeed badly with scores in the range $5 \leq S \leq 14$, which validates our decision to eliminate them from the analysis. However we also find that 8 HCMs defined as reliable have a score $S < 16$, meaning that they fail to describe more than half of the interactions presented in the exercise guidelines. 72% of the HCMs considered reliable manage to describe at least half of the given examples on the HCM, and 14% more than 90% of the given examples. The score distribution of the reliable HCMs is shown in Figure 4d. These results confirm the good understanding of the exercise and of the HCM method.

3.2. Identifying Reasoned Imagination in the HCM

3.2.1. Main emerging patterns

We now only consider the HCM cells, which were not described in the exercise guidelines (i.e., all grey cells in Fig. 3b). Three rows (AI, Di and War) and one column (AI) are of particular interest since they are almost entirely filled in Figure 3c although no example was given during the exercise.

The participants stated that an asteroid impact is likely to trigger all other events considered in the HCM, except war. It is likely that asteroid impacts depicted in fictional films have shaped the participants' perception on the potential consequences of this hazard (Kirby, 2003). Let us note that a fictional film "*has to be sufficiently credible to be possible in terms of what constitutes a rational possibility of the unknown*" (Hallam and Marshment, 2000), which is by definition reasoned imagination (Kameda, 2012; Paté-Cornell, 2012). How fictional films may be useful in the process of reasoned imagination in the case of cascading hazards has yet to be fully addressed.

The participants also specified that no (earthly) event could trigger an asteroid impact, which is trivial. They also stated that a disease could obviously not trigger other natural hazards. This shows a clear distinction of the relative independence of extra-terrestrial and biological hazards from the geological, hydrological and meteorological hazards, the latter being more intertwined.

Results for war as a trigger are certainly based on the general knowledge of the participants. Most agreed that a war could trigger a disease (biological warfare) and fires (standard warfare). A general result is that most anthropogenic hazards were identified as potentially triggered by any other event, which is particularly clear on Figure 2d. As discussed previously, these hazards are often known to be secondary hazards.

3.2.2. Dubious cases

Only a very limited number of imagined interactions appear dubious. One direct interaction proposed by most participants and subject to discussion is the case of an earthquake triggering a disease. In the strict meaning of "direct", the rupture of a fault is doubtfully able to trigger a disease. Examples described in the exercise guidelines included earthquake → health care interruption → disease and earthquake → mass slide (+ wind) → disease (Table I). One could however imagine earthquake → disease in fact implying earthquake → {lack of hygienic practices; crowded conditions; population displacement} → disease, since this set of potential intermediary events, while imaginable (Shultz et al., 2005), was not considered in the definition of the exercise's HCM. We here see that apparent anomalies in the HCM may in fact inform us about events possibly missing in the matrix. Those missing events could be added in an updated version of the HCM.

3.2.3. From 1-to-1 interactions to complex cascading chains

Although the participants were only asked to describe possible 1-to-1 interactions in the HCM, the combination of these different interactions led to the multiplication of potential chains of cascading events. This emphasizes the power of the method in generating complex, possibly unforeseen cascades, from simple interactions.

Based on the HCM shown in Figure 3c, one can for example stipulate that the following cascade is plausible: Earthquake → earthquake → dam failure → flood → mass slide → network failure → fire → industrial accident → business interruption → economic slowdown → social unrest or in a narrative form: "*A large aftershock triggered a dike breach, which led to flooding. When receding, the flood in turn provoked a landslide on an unstable slope, which cut vital sections of the infrastructure networks of the area. With no water* *available, multiple gas leaks and roadblocks limiting access to first responders, fires quickly propagated. It led to a major industrial accident, the interruption of its business activities, and in consequence to a general slow down of the regional economy, which is highly dependent on this industry. In this situation, riots and lootings followed.*" This is one example of a multitude of complex chains-of-events described from simple 1-to-1 interactions in the HCM built by the participants.

3.2.4. Open-ended questions

Results from the open-ended questions are represented in Figure 4e. Different categories have been created in order to identify trends in the qualitative data analysis.

Q1: Which cascading effect (see matrix) do you fear most? Why? led to answers where each respondent listed one or more perils. In most cases, the proposed events were considered as the most frightening trigger events (e.g., asteroid impacts, earthquakes, disease or war), which were noted to have broad consequences. In other cases, the proposed events were clearly considered as the most frightening consequences (e.g., health care interruption, fire, social unrest, radioactive release). A less misleading question could have been: *what event do you fear most (taking into account cascading effects)?* Of the 16 perils in the HCM, six were found particularly worrisome, in order: earthquake (10), disease (9), war (8), flood (6), asteroid impact (5) and health care interruption (3). During the exercise the participants often mentioned the 2014 West Africa Ebola epidemics, which had its pick of activity in October 2014 (Pandey et al., 2014) when the workshop took place. This may explain why disease ranked at the second place of the most frightening perils and why health care interruption was also part of the top-six list. However these results remain ambiguous due to the responses not exactly answering Q1.

For *Q2: If you were a decision-maker, what would you do first to reduce the risk of cascading effects?,* the participants' answers were categorised as follows: Improve risk assessment (7), improve resilience (13), improve communication (7), increase funding (2) and not clear on which action to take (2). For example the risk assessment should be improved by investigating the links between different events, by implementing the HCM method and by simulating cascade scenarios. Other proposed actions, such as fast response to crisis, restoration of critical infrastructures, redundancy of health care, better preparedness, avoidance of cascades and other mitigation measures, are all part of the concept of resilience. Improving communication meant in particular improving awareness, educating, informing first responders and the public of plans of actions, *etc.* The issue of funding was also raised, for both research and mitigation.

For *Q3: Did you learn something new today? What? Are you planning to use this new information in your teaching?*, a positive answer was given by 84% of the respondents. They answered that they learned first about cascades (9) and how complex they are, and second about the *modus operandi* (5) or how complex cascades can be simply defined from direct links in the HCM. In rare cases (3), it was indicated that the learning experience was negative. The main reason was that the exercise was considered too short to clearly understand the concepts. Overall, a number of participants indicated their will to use the HCM approach in their class because of its simplicity and of the link between physical and societal aspects (statements in post-exercise discussions).

Only about one third of the participants answered to *Q4: Do you want to learn something more about cascading effects? If yes, what?* Twelve respondents answered affirmatively (86%) and two negatively. The respondents were especially interested in learning more about how to teach about hazardous cascading phenomena in high schools and how to prevent cascades and mitigate their consequences.

4. Conclusions

The results on the present pilot study revealed that the HCM is a simple tool to describe known cascading phenomena (e.g., Fig. 4d) and that it could also be used to integrate reasoned imagination into the description of additional – often unforeseen – cascades (section 3.2). The participants, high school teachers in natural sciences, clearly stated that they learned about the complexity of cascading hazards and this especially thanks to the *modus operandi*, which is the HCM method. This suggests that the HCM method could be labelled as a cognitive and teaching tool (Jonassen, 1992), since it engages thinking processes on cascading hazard processes. More precisely, once the idea that complex cascades can be deconstructed into simple 1-to-1 interactions is assimilated, new knowledge can be inferred.

More work has yet to be done to confirm the usefulness of the HCM method in describing cascading hazards, (1) for learning purposes and (2) for disaster risk reduction. Only point (1) was tackled in the present paper. Future studies will need to define a more robust approach, including pre-post knowledge testing, a control group and potentially some modifications to the HCM (e.g., adding additional perils, changing the order of perils). It was also noted by some participants that the exercise might have been too complex, which makes the addition of more perils in the HCM challenging. Immediate solutions include longer exercises (e.g. half-day) and a better guidance through the exercises (also to avoid the HCM being seen as a mere box ticking exercise by some participants).

Although the results shown in Figure 3 are overall reliable, one can note that some interactions are missing, for instance geothermal power plants triggering earthquakes (or IA → EQ) (e.g., Mignan et al., 2015). An in-depth analysis of imaginable cascades for multi-risk management will require the participation of risk experts and the definition of site-specific HCMs where more specific interactions are considered. As a first step in this direction, the HCM was recently used as a discussion interface to assess the range of potential cascades at dams prior to any probabilistic multi-risk analysis (Matos et al., 2016). Figure 5 shows this dam-specific HCM where perils include reservoir rise and dam element failures.

In a broader context, the HCM method has yet to be treated in both Normal Accident Theory (Perrow, 2001) and High Reliability Theory (La Porte, 1996) to situate its role in the risk management of complex interacting systems. A priori, use of the HCM could improve organizational learning and decentralized decision-making by more knowledgeable operators (Rijpma, 1997). One important challenge in future uses of the HCM will be how to move from qualitative measures obtained from reasoned imagination to quantitative measures. A transitional multi-level framework could be used to make a clear distinction between qualitative and quantitative levels (Liu et al., 2015) prior to being able to model cascading hazards in all their richness.

While the HCM has yet to be tested with risk practitioners in a systematic way, working with members of the public was shown to be beneficial for the improvement of the method in future exercises, in agreement with the idea of extended peer community, which "*makes use of not only available scientific evidence, but also extended facts – lay, anecdotal, and other information* […] *held by this larger community*" (Rosa, 1998). The improvement of public preparedness to cascading hazards by reasoned imagination (via the HCM method) has yet to be demonstrated. However the exercise presented in this paper showed an "*accessible, imaginative and innovative teaching resource* [that] *could excite teachers*" and students alike into changing their behavior toward disasters (Sharpe and Kelman, 2011). In view of the limited practice of multi-risk in general (Komendantova et al., 2014), such teaching would also likely be beneficial to practitioners. It could potentially act as a transformative learning process (e.g., Mezirow, 1997), to shift from the actual single-risk reference frame to a much-needed multi-risk reference frame in the field of disaster risk reduction.

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Tables

Table I. List of catastrophes (in reverse chronological order) and their cascades, as illustrated in the exercise guidelines.

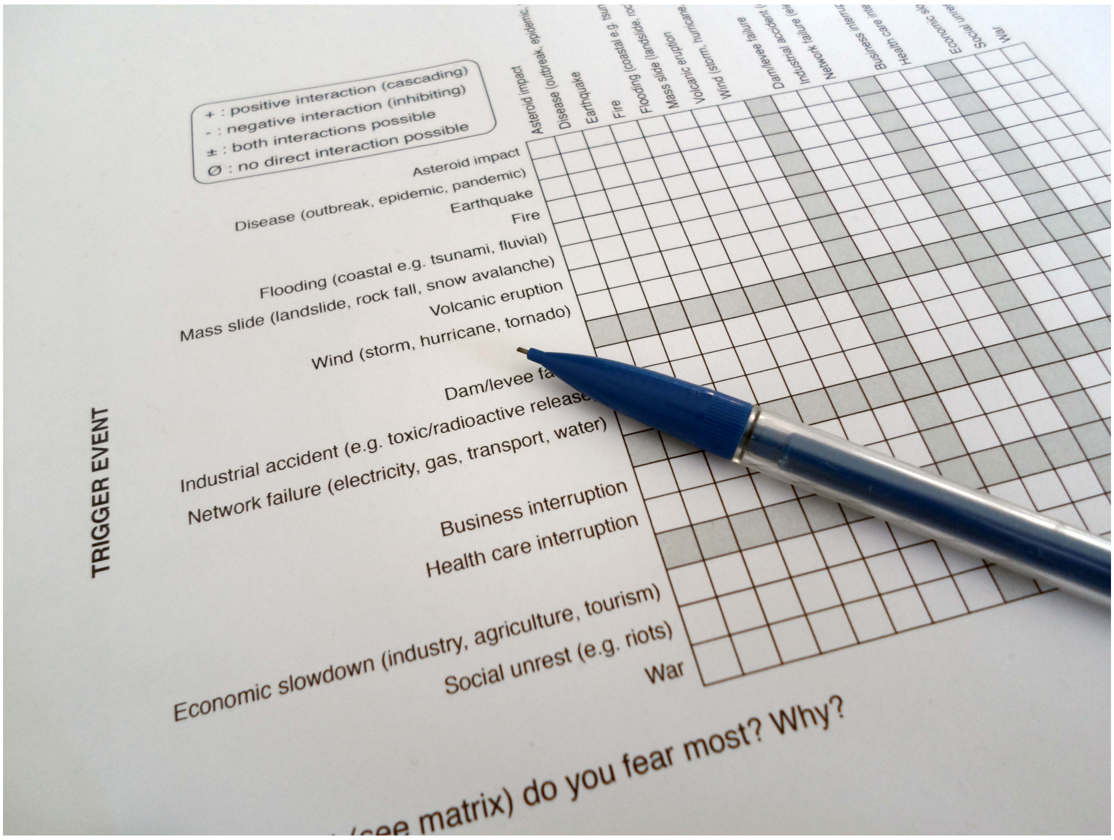
Catastrophe	Cascades, as illustrated in the exercise guidelines	Likely interpretation
2011 Tohoku earthquake (Japan)	Earthquake → Tsunami → Fukushima nuclear disaster [Norio et al., 2011] → Switzerland energy turnaround	EQ → Fl (*) Fl → IA (*) IA → BI
2010 Eyjafjallajökull volcanic eruption (Iceland)	Volcanic eruption → Air travel disruption → Impact on economy & cultural events across Europe [Lund and Benediktsson, 2011]	VE → NF NF → ES
2008 Sichuan earthquake (China)	Earthquake → Cargo train carrying petrol tanks derailed → Fires → Damaged highways, telecommunications cut → Rescue efforts delayed [Krausmann et al., 2010] → Collapse of chemical plants → Release of toxic materials [Krausmann et al., 2010] → Landslides → Rivers blocked → Unstable “quake lakes” → Landslides & downstream flooding [Cui et al., 2009] → (?) Stock exchange fluctuations (copper price rose, oil price dropped)	EQ → IA IA → Fi EQ → NF NF → HI EQ → MS MS → Fl Fl → MS
2005 hurricane Katrina (United States)	Hurricane → Storm surge → Levee failure → New Orleans flooding [Comfort, 2006] → business interruptions → Slow down in various	Wi → Fl Fl → DF DF → Fl Fl → BI

	production sectors [Hallegatte, 2008]	BI → ES
2004 Sumatra earthquake (Indonesia)	Earthquake → Aftershocks, tsunami → Fishing & tourism affected [Levy and Gopalakrishnan, 2005] → (?) Volcanic eruption several months later [Walter and Amelung, 2007]	EQ → EQ EQ → Fl Fl → BI EQ → VE (?)
1994 Northridge earthquake (United States)	Earthquake → Landslide (+wind) → Outbreak of Valley Fever [Harp and Jibson, 1996]	EQ → MS MS → Di (†) Wi → Di (†)
1963 Vajont landslide (Italy)	Landslide → Tsunami on artificial lake → dam overtopping [Kilburn and Petley, 2003]	MS → Fl Fl → DF DF → Fl
1946 Sierre earthquake (Switzerland)	Earthquake → Aftershocks, rockfalls, landslides, avalanches [Fritsche et al., 2012]	EQ → EQ EQ → MS
1923 Kantô earthquake (Japan)	Earthquake → Fires, landslides, tsunami, aftershocks → Water mains broken (+wind) → More fires [Borland, 2006] → Unsanitary conditions → Jump in typhoid fever morbidity [Nagashima, 2004] → Toxic well water +fires → Rumors of Koreans poisoning wells & arson acts → Violence against Koreans [Borland, 2006] (?) Typhoon → Storm surge → earthquake [*unverified Wikipedia source*] (?) "*Yokohama Burning: The Deadly 1923 Earthquake and Fire that Helped Forge the Path to World War II*"	EQ → Fi EQ → MS EQ → Fl EQ → EQ EQ → NF NF → Fi Wi → Fi (†) EQ → HI HI → Di EQ → SU Fi → SU

	[Hammer, 2011]	
1906 San Francisco earthquake (United States)	Earthquake → Gas leaks & water supply failure → extreme fires → (?) 1907 Panic & creation of the Federal Reserve System [Odell and Weidenmier, 2001]	EQ → NF NF → Fi Fi → ES (?)
1868 Hawai earthquake (United States)	Earthquake → Coastal subsidence → Tsunami → Mudslide → (?) Reduced magma volumes in nearby volcanoes	EQ → Fl EQ → MS EQ → no VE (?)
1783 Laki volcanic eruption (Iceland)	Volcanic eruption → Severe weather across Europe (poisonous cloud) → Crops & cattle destroyed → Poverty & famine [Thordarson and Self, 2003] → (?) French Revolution	VE → Wi Wi → ES
1755 Lisbon earthquake (Portugal)	Earthquake → Tsunami & Fires → (?) Long-term effects on society, politics, philosophy [Marques, 2005]	EQ → Fl EQ → Fi Fl → ES (?) Fi → ES (?)
1584 Aigle earthquake (Switzerland)	Earthquake → Rockslide → Subaquatic slide → Tsunami → Aftershock (+rainfall +snow) → Rockslide [Fritsche et al., 2012]	EQ → MS MS → Fl EQ → EQ

[No reference indicates a Wikipedia source; (*) Answer given during the exercise; (†) Participates to the interaction; (?) (Direct) interaction described in the guidelines as unverified indicating that different interpretations are possible. Note that only one example of negative interaction (inhibition) is shown (1868 Hawaii earthquake case).]

Figures



\+ : positive interaction (cascading)
\- : negative interaction (inhibiting)
± : both interactions possible
Ø : no direct interaction possible

TRIGGER EVENT

Asteroid impact
Disease (outbreak, epidemic, pandemic)
Earthquake
Fire
Flooding (coastal e.g. tsunami, fluvial)
Mass slide (landslide, rock fall, snow avalanche)
Volcanic eruption
Wind (storm, hurricane, tornado)
Dam/levee fa
Industrial accident (e.g. toxic/radioactive release
Network failure (electricity, gas, transport, water)
Business interruption
Health care interruption
Economic slowdown (industry, agriculture, tourism)
Social unrest (e.g. riots)
War

Asteroid impact
Disease (outbreak, epidemic,
Earthquake
Fire
Flooding (coastal e.g. tsun
Mass slide (landslide, roc
Volcanic eruption
Wind (storm, hurricane
Dam/levee failure
Industrial accident (
Network failure (ele
Business interru
Health care inte
Economic slo
Social unre
War

see matrix) do you fear most? Why?

Figure 1. Exercise sheet (questionnaire) with the empty hazard correlation matrix (HCM) and list of open-ended questions.

Figure 2. HCMs defined by the 38 participants. HCMs considered unreliable are shown in lighter colours. The HCM row/column indices (i.e. events) are the same as in Figure 1.

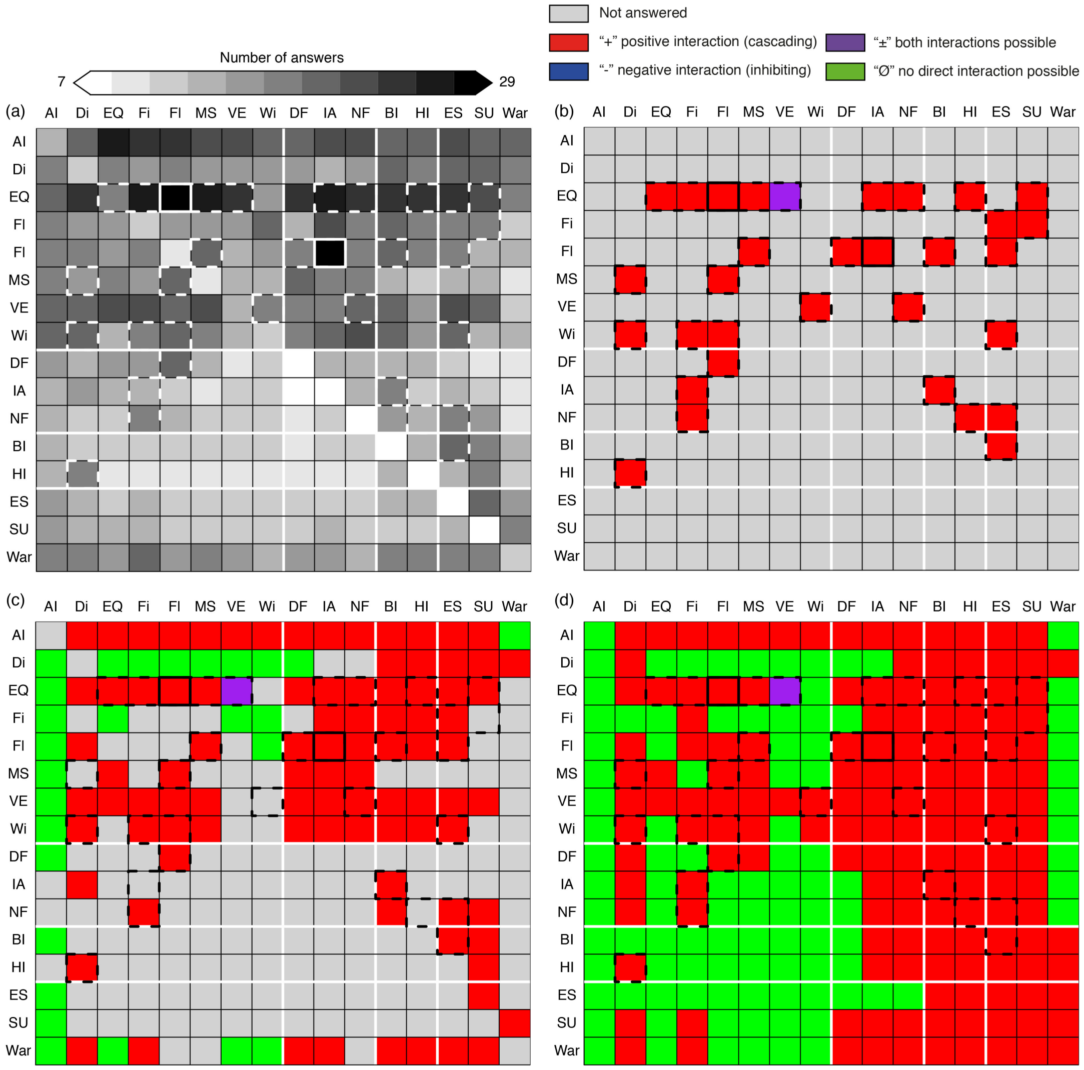


Figure 3. Synthesis of the 29 HCMs considered reliable; (a) Number of answers per HCM cell; (b) Expected HCM result, defined from the examples of past cascades shown during the exercise; (c) Most common result (including "not answered") per HCM cell; (d) Most common answer per HCM cell. Answers for cells with thick solid contour were given at the start of the exercise. Cells with thick dashed contour correspond to interactions shown during the exercise (Table I). The other cells were filled based on reasoned imagination by the participants.

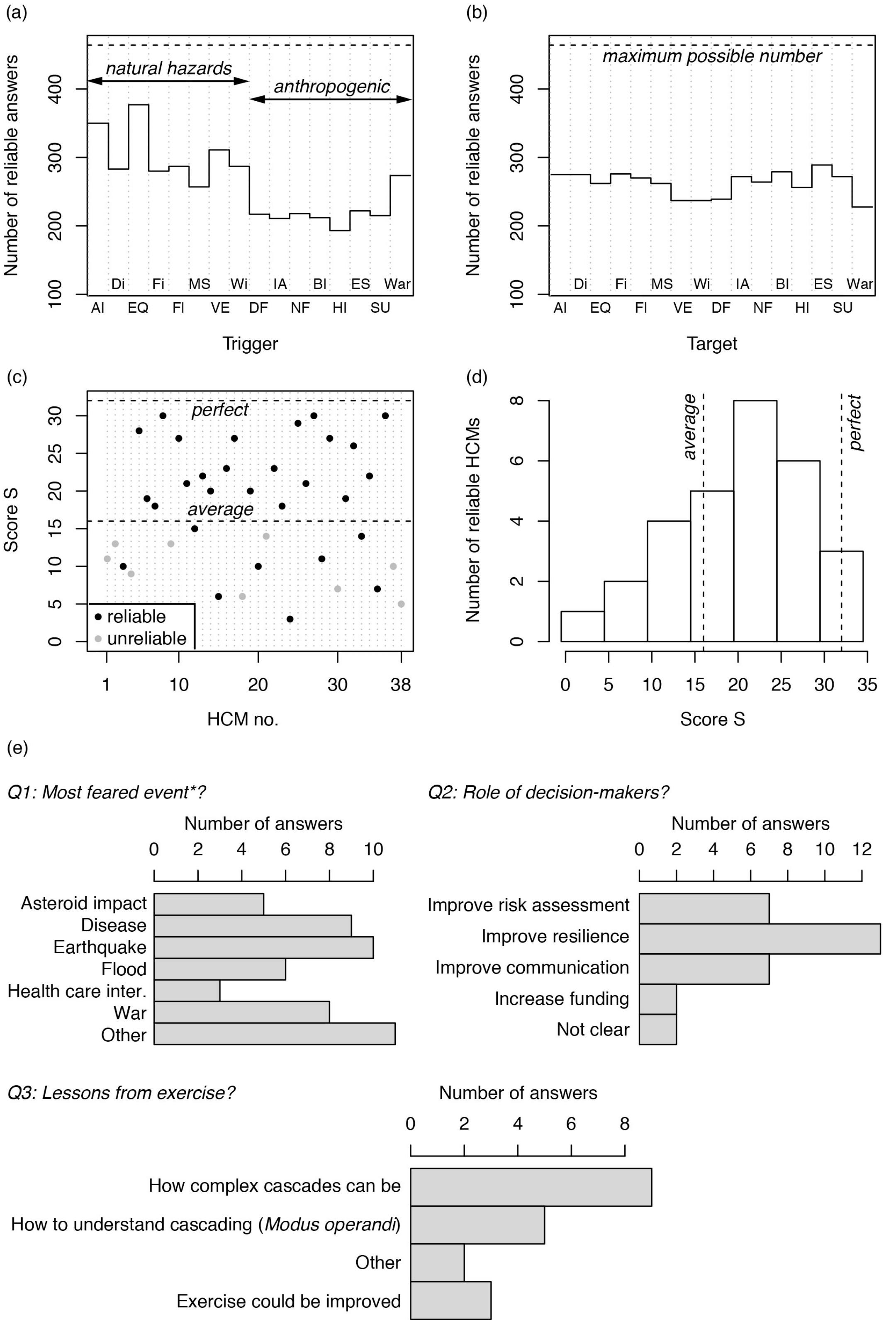


Figure 4. Statistical analysis of the HCMs shown in Figure 2; (a) Number of answers considered reliable per trigger event; (b) Number of answers considered reliable per target event; (c) Score *S* per HCM, a perfect score

corresponding to a perfect match to the expected HCM result (Fig. 3b); (d) Number of HCMs considered reliable as a function of score *S*; (e) Categorization of the answers to the open-ended questions (* Question Q1 changed from “*Which cascading effect (see matrix) do you fear most? Why?*” due to the lack of direct answers, indicating some ambiguity in the responses to Q1).

	EQ	HR	FI	MS	BOF	HPF	SWF	DD	RR	OT	DF
Earthquake (EQ)	±	Ø	+	+	+	+	+	Ø	Ø	Ø	+
Heavy rain (HR)	Ø	±	+	+	Ø	Ø	Ø	Ø	+	Ø	Ø
Flood (FI)	Ø	Ø	+	+	Ø	Ø	+	Ø	+	Ø	Ø
Mass slide (MS)	Ø	Ø	+	±	Ø	Ø	+	Ø	Ø	Ø	Ø
Bottom outlet failure (BOF)	Ø	Ø	Ø	Ø	Ø	Ø	Ø	-	+	Ø	Ø
Hydropower failure (HPF)	Ø	Ø	Ø	Ø	Ø	Ø	Ø	-	+	Ø	Ø
Spillway failure (SWF)	Ø	Ø	Ø	Ø	Ø	Ø	Ø	-	+	Ø	Ø
Drawdown (DD)	Ø	Ø	Ø	Ø	Ø	Ø	Ø	Ø	-	Ø	Ø
Reservoir rise (RR)	Ø	Ø	Ø	Ø	Ø	Ø	Ø	+	Ø	+	+
Overtopping (OT)	Ø	Ø	Ø	Ø	Ø	Ø	Ø	Ø	Ø	Ø	+
Dam failure (DF)	Ø	Ø	Ø	Ø	Ø	Ø	Ø	Ø	Ø	Ø	Ø

Figure 5. Illustrative HCM for a conceptual embankment dam, defined from expert judgement (used for the Matos et al. (2016) analysis). An extreme reservoir rise may lead to overtopping and, eventually, to dam failure. Different events can trigger the reservoir rise or directly dam failure, such as natural hazards and dam element failures. To avoid catastrophic failures, a drawdown of the reservoir can be initiated.