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Exploring the Space of Possibilities in Cascading Disasters with Catastrophe Dynamics

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Abstract: Some of the most devastating natural events on Earth, such as earthquakes and tropical cyclones, are prone to trigger other natural events, critical infrastructure failures, and socioeconomic disruptions. Man-made disasters may have similar effects, although to a lesser degree. We investigate the space of possible interactions between 19 types of loss-generating events, first by encoding possible one-to-one interactions into an adjacency matrix A , and second by calculating the interaction matrix M of emergent chains-of-events. We first present the impact of 24 topologies of A on M to illustrate the non-trivial patterns of cascading processes, in terms of the space of possibilities covered and of interaction amplification by feedback loops. We then encode A from 29 historical cases of cascading disasters and compute the matching matrix M . We observe, subject to data incompleteness, emergent cascading behaviors in the technological and socioeconomic systems, across all possible triggers (natural or man-made); disease is also a systematic emergent phenomenon. We find interactions being mostly amplified via two events: network failure and business interruption, the two events with the highest in-degree and betweenness centralities. This analysis demonstrates how cascading disasters grow in and cross over natural, technological, and socioeconomic systems.

Keywords: catastrophe dynamics; absorbing Markov chain; topology; natural hazard; anthropogenic hazard; network failure; business interruption; disease; critical infrastructure; social unrest

1. Introduction

As humans increase their impact on the planet, the risk associated with natural and man-made hazards can be amplified by emerging chains-of-events [1–8]. With rapid urbanization and lifeline connectivity growth, secondary, tertiary, quaternary, and further consequences of initial triggers are likely to occur more often, and more severely. Despite being among the highest-impact threats that society faces, the range of possible domino effects remains mostly unforeseen and unmodelled, due to the interacting process being highly complex, inter-systematic, and only partially experienced. This issue has been recognized recently as a barrier to proper multi-risk governance [9–11].

Some of the most devastating initial triggers include earthquakes and tropical cyclones, due to the tremendous energy they release and their wide spatial footprints [12]. Common secondary effects include other natural events, such as landslides and tsunamis [13], as well as critical infrastructure failures, such as industrial accidents and network breakdowns [14]. All those events and their consequences may further lead to socioeconomic disruptions, such as business interruption, social

unrest, healthcare degradation, and economic crisis. The most recent infamous example of such consequences is the COVID-19 pandemic [15].

Although the ultimate goal of catastrophe risk assessment should be the probabilistic quantification of all physically imaginable interactions between the natural, built and cyber environments, and this at a global scale, the scope is so vast that a brick-by-brick approach should be favored at the present time. Directions being currently investigated include: (i) site-specific multi-risk engineering modelling at the local level [7,16]; (ii) detailed exploration of a given interaction system, e.g., a natural system [2] or a natural–technological interface (i.e., Natech) [6]; (iii) detailed exploration of the full chain-of-events cross-system for a given trigger, e.g., an earthquake [5,13,17]; and (iv) general rules of catastrophe dynamics based on theory and on simplified, generic perils and interactions [4,18,19]. We will here follow the latter approach. In particular, we are interested in exploring the space of possible cascading effects by learning from concepts of system dynamics, interaction-graph topology, and empirical analysis.

2. Materials and Methods

2.1. Catastrophe Dynamics

We employ the term “catastrophe dynamics” as it is used in [18], which describes an approach to understand and quantify all direct and indirect interactions between events during the temporal development of a catastrophe via system dynamics. It is only loosely related to “catastrophe theory”, which studies specific potential functions [20]. With catastrophes here defined as the accumulation of individual, loss-generating events that interact with each other, we assume that the dynamic process is described by the following linear differential Equation:

$$\frac{d\vec{X}(t)}{dt} = \mathbf{Q}\vec{X}(t) \quad (1)$$

In which the dynamics of the vector $\vec{X}$ of events is fully described by the transition rate matrix $\mathbf{Q}$ that encodes all possible one-to-one direct/infinitesimal interactions. The propagator for $\vec{X}(t) \rightarrow \vec{X}(t + \tau)$ can be written as $\mathbf{P}(\tau) = \exp(\mathbf{Q}\tau)$, with the entries $p_{ij}(\tau)$ interpreted as the conditional probability of event j being triggered by event i for a period of τ . This study presumes that we have a direct estimate on the adjacency matrix, defined as $\mathbf{A} := \mathbf{P}(\tau = 1) = \exp(\mathbf{Q})$, i.e., the matrix exponential of $\mathbf{Q}$ [21]. This presumption indicates that the probabilities for events $i \rightarrow j$ within a unit amount of time can be estimated, a construction that does not influence the generality of this study. It also assumes that $\mathbf{Q}$ is constant (i.e., stationary one-to-one interactions) and that probabilities are conserved with $\sum_{j=1}^n p_{ij}(\tau) = 1$, or equivalently, $\sum_{j=1}^n q_{ij} = 0$, where q_{ij} denotes entries of the rate matrix $\mathbf{Q}$.

This study aims at investigating emergent cascading patterns as the catastrophe’s dynamics evolve, given the specification of a $(n_{\text{perils}} + 1) \times (n_{\text{perils}} + 1)$ adjacency matrix $\mathbf{A}$. As the individual one-to-one interactions between the events generated by n_{perils} perils are a priori independent, we define an outflow event as a last matrix entry for conservation of probabilities with conditional probability $1 - \sum_{j=1}^{n_{\text{perils}}} p_{ij}$. We also fix the last row of $\mathbf{A}$, $p_{n_{\text{perils}}+1} = (0, \dots, 0, 1)$, i.e., the outflow event does not trigger any real event but itself. This means that a catastrophe will naturally die off, with the outflow event representing an absorbing state in Markov chain jargon. For convenience, we also define the reduced $n_{\text{perils}} \times n_{\text{perils}}$ adjacency matrix $\bar{\mathbf{A}}$ without the outflow event (absorbing state).

The event interactions, which are encoded in $\mathbf{A}$, can be represented by a graph G with a vertex set V of events and an edge set E of one-to-one interactions. Figure 1 shows an example of an interaction network encoded in $\mathbf{A}$ and displayed as G , in the case of a hydro-dam catastrophe system that includes both natural and technological hazards [4,22]. Each event can lead to dam failure along the chain

of interactions. In the present study, we will use a wider event “grain” with all the elements of a hydro-dam concatenated within a so-called critical infrastructure failure (see Section 2.2). We will also solely consider loss-generating, triggering events and no event that could inhibit another event (naturally or via a mitigation measure).

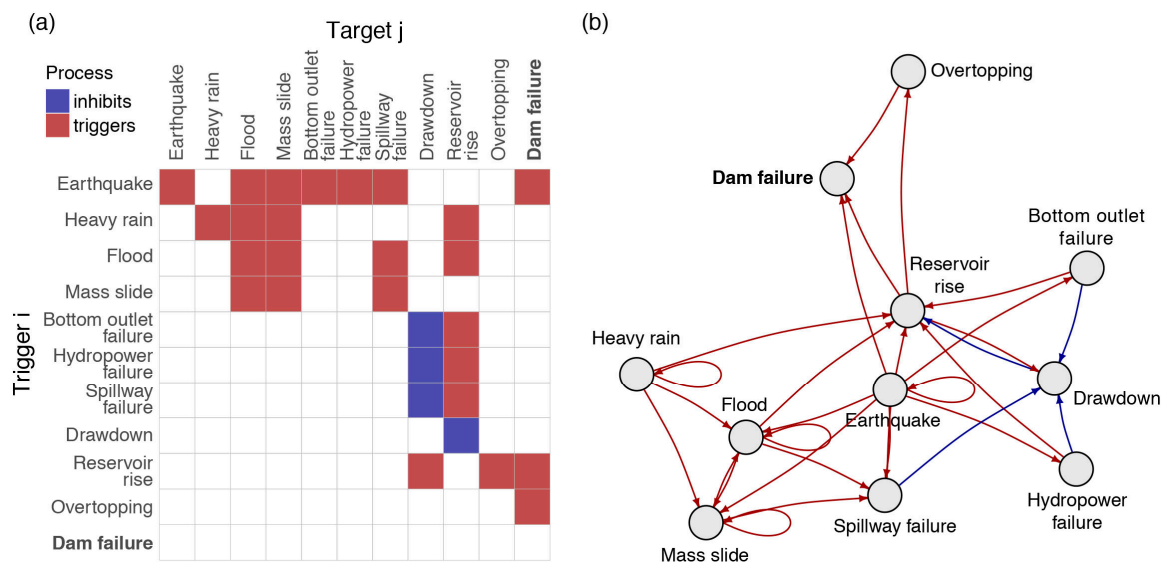


Figure 1. Illustration of how event interactions can lead to the catastrophic failure of a hydro-dam: (a) Interactions encoded in an adjacency matrix A following [4,22]; (b) Interactions described in a graph G .

Graphs can be described by various centrality measures, the most important ones being in-degree, out-degree, closeness, and betweenness [23]. Degree centrality of a vertex is the number of edges incident on the node; closeness centrality of a vertex is the average of the shortest path lengths from the vertex to all other vertices in the network; betweenness centrality of a vertex is the number of the shortest paths that pass through that vertex. In catastrophe dynamics, the main triggering events (or sources) are represented by high out-degree and closeness centralities; the main triggered events (or sinks) by a high in-degree centrality, and the main catalysts that promote cascading by a high betweenness centrality [16].

Applications in which catastrophic interactions are encoded in an adjacency matrix are as varied as in disease spread forecasting and risk mitigation [18,24], tramway infrastructure risk assessment [25], hydro-dam failure analysis [22], volcanic eruption post-crisis assessment [7], modeling of road network disruption by floods [26], or ecological disaster modeling [27]. The system’s dynamics is usually simulated, although an analytical solution to the final state can also be estimated [21]. While the analysis of the matrix power A^τ (or $\bar{A}^\tau$) for $\tau \rightarrow \infty$ (i.e., discrete case, see [18] for the continuous case) suffices to explore the full space of possible interactions in a topological sense, we are here also interested in evaluating how a catastrophe can be amplified [19] in terms of chain-of-events length. This can be computed via the concept of fundamental matrix [21], which captures the frequency/intensity of each transition event before resting at the absorbing state.

With G finite, we can define the fundamental matrix

$$N := (I - A)^{-1} = I + \sum_{\tau=1}^{\infty} A^\tau = I + A + A^2 + \dots = I + M \quad (2)$$

With the entry n_{ij} , the expected number of times the chain-of-events reaches event j given that the catastrophe starts with event i and I the identity matrix. All events here represent transient states prior to the absorbing state being entered [21]. We then introduce the “interaction matrix” M , which excludes the step $\tau = 0$ that is independent of the topology of interactions. If A encodes $1 \rightarrow 2$ and

$2 \rightarrow 3$, $\mathbf{M}$ additionally describes the chain $1 \rightarrow 2 \rightarrow 3$. As τ increases, non-trivial patterns may emerge in $\mathbf{M}$ depending on the topology of $\mathbf{A}$. This will be investigated in Section 3.1. Note that the reduced $n_{\text{perils}} \times n_{\text{perils}}$ interaction matrix $\bar{\mathbf{M}}$, without the outflow event (absorbing state), will be displayed alongside $\bar{\mathbf{A}}$ in the next two figures.

2.2. Historical Data Encoding

A wide variety of perils exist, which follow different processes and scales. Various taxonomies have been proposed [2,7] and we here adapt and extend the one described in [4]. The list of perils, 19 in total with short descriptors and identifiers, is given in Table 1. Natural events have a geological, geomorphological, hydrological, meteorological, biophysical, ecological, or extraterrestrial origin; anthropogenic events have a technological, economical, or social origin (no distinction is made between accidental and malicious).

Table 1. A generic taxonomy of perils.

ID	Peril	Including
NATURAL		
Geological and Geomorphological		
EQ	Earthquake	Shaking, fault rupture, ground displacement, subsidence
VE	Volcanic eruption	Explosive or effusive
MS	Mass slide	Landslide, rockfall, avalanche, mudslide, liquefaction
Hydrological		
FL	Flood	River flooding, tsunami, storm surge, flash flood
Meteorological		
WS	Windstorm	Tropical cyclone, extratropical windstorm, winter storm, tornado
OS	Other storm	Rainstorm, hailstorm, thunderstorm (lightning), ice storm, snowstorm, sandstorm, haze
EW	Extreme weather	Drought, heat wave, frost, extreme temperature gradient
Biophysical and Ecological		
WF	Wildfire	Bushfire, forest fire
DI	Disease	Outbreak, epidemic, pandemic
Extraterrestrial		
AI	Asteroid impact	Asteroid or comet, impact or air blast
GS	Geomagnetic storm	N/A
ANTHROPOGENIC (Accidental or Malicious)		
Technological		
FI	Fire	N/A
CF	Critical infrastructure failure	Explosion, toxic release (chemical, radioactive), water release (dam/levee break, overtopping)
NF	Critical network failure	In transportation, water and gas, electricity blackout, cyber-attack
Economical		
BI	Business interruption	In industry, agriculture, tourism, etc.
EC	Economic crisis	Recession, depression, financial crisis, hyperinflation
Social		
SU	Social unrest	Riot, strike, vandalism, looting
HD	Healthcare degradation	No rescue, security or access to hospital, unsanitary conditions, starvation (famine)
CO	Conflict	War, revolt, revolution, terrorism

Any taxonomy, by construction, is subjective. We attempted to limit possible discrepancies by keeping event classes as generic as possible, discriminated by different physical processes, and as close as possible as proposed classes in the literature [2,4,7]. We also narrowed the study to events which have an impact from the scale of a city to that of a continent, are relatively sudden and not excessively rare. Hence, we did not consider common or freak accidents (road, domestic, workplace events), long-term trends related to climate change [28] and ecological disasters [27], or speculative and existential risks [29]. As the focus of our work is on hazard and risk interactions, we also defined events so that there can be a clear, explicit one-to-one interaction between two events. All events, direct or indirect, also lead to direct losses defined in terms of casualties and/or economic losses.

Historical cases of catastrophes amplified by cascading effect abound. Table 2 lists some of the most infamous but also other, less known cases that provide some evidence for other potential interactions. Our aim is to explore the space of possibilities for cascading disasters on Earth, first by determining which cells of A are non-zero and second by calculating M . Note that quantifying such interactions in terms of explicit conditional probabilities p_{ij} would require large databases, which are usually only limited to secondary effects, e.g., landslides and tsunamis triggered by earthquakes [5,13]. We follow a binary approach instead, with p_{ij} either 0 or non-zero (see Section 4.1 on a discussion of such a limitation). The literature sources that led to Table 2 are given in Appendix A.

Table 2. List of infamous catastrophes with rich and/or peculiar chains-of-events.

Catastrophe ¹	Observed Cascading Effects ²	Proposed Encoding ³
NATURAL TRIGGER		
Earthquake (EQ) as initial trigger		
2011 Tohoku, JP	EQ → great tsunami → nuclear disaster → blackouts, global nuclear energy turn-around ⇒ decline in global automobile production ⇒ significant fluctuations in global financial markets	(EQ, FL); (FL, CF); (CF, NF); (CF, BI)
2008 Wenchuan, CN	EQ → landslides → landslide lakes → downstream flooding EQ → energy networks outage → industrial production interrupted EQ → derailments → tanks collapse → fire EQ → landslides → roads damaged → rescues delayed EQ → chemical plant failure (toxic release) → health issues EQ → many businesses damaged	(EQ, MS); (MS, FL); (FL, FL); (EQ, NF); (NF, BI); (NF, CF); (CF, FI); (MS, NF); (NF, HD); (EQ, CF); (CF, DI); (EQ, BI)
2004 Sumatra, ID	EQ → tsunami → poor sanitation, lifelines ↓, tourism, fishing and farming ↓ EQ → great aftershocks EQ → volcanic eruption	(EQ, FL); (FL, NF); (FL, HD); (FL, BI); (EQ, EQ); (EQ, VE)
1994 Northridge, US	EQ → landslide → Valley Fever outbreak	(EQ, MS); (MS, DI)
1923 Kanto, JP	EQ → water network ↓ → fires → social unrest (Koreans attacked on false rumors) EQ → water network ↓ → unsanitary conditions → typhoid and dysentery ⇒ ideological, political and societal reforms ⇒ World War II	(EQ, NF); (NF, FI); (FI, SU); (NF, HD); (HD, DI)
1906 San Francisco, US	EQ → water and gas network ↓ → fires ⇒ 1907 Financial Panic	(EQ, NF); (NF, FI)
Volcanic eruption (VE) as initial trigger		
2010 Eyjafjallajökull, IS	VE → air travel disruption → airline bankruptcies	(VE, NF); (NF, BI)
2002 Stromboli, IT	VE → collapse of volcano side → tsunami → island closed to tourism	(VE, MS); (MS, FL); (FL, BI)
1783 Laki, IS	VE → extreme weather fluctuations → agriculture ↓ VE → poisonous cloud → sickness VE → poisonous cloud → agriculture ↓ (cattle mass death, scorched vegetation) → famine ⇒ climate change, 1789 French Revolution	(VE, EW); (EW, BI); (VE, OS); (OS, DI); (OS, BI); (BI, HD)
Mass slide (MS) as initial trigger		
1963 Vajont, IT	MS → tsunami on artificial lake → dam overtopping	(MS, FL); (FL, CF)

Table 2. Cont.

Catastrophe ¹	Observed Cascading Effects ²	Proposed Encoding ³
Flood (FL) as initial trigger		
2011 Thailand	FL → manufacturing sector ↓ → GDP ↓ FL → manufacturing sector ↓ → supply chain ↓ → international import sector ↓ → GDP ↓	(FL, BI); (BI, ES); (BI, NF); (NF, BI)
Windstorm (WS) as initial trigger		
2017 Hurricane Harvey, US	WS → rainfall event → fluvial inundation → transportation network ↓ → emergency response service ↓	(WS, OS); (OS, FL); (FL, NF); (NF, HD)
2012 Hurricane Sandy, US	WS → storm surge → electric network ↓ → health care facility evacuated WS → storm surge → power plants ↓ → electric network ↓ → other lifelines and supply chains ↓	(WS, FL); (FL, NF); (NF, HD); (FL, BI); (BI, NF); (NF, NF)
2005 Hurricane Katrina, US	WS → storm surge → levee failure → business interruptions WS → storm surge → levee failure → electrical cell phone stations ↓ → rescue, medical care, security scarce → violence and looting	(WS, FL); (FL, CF); (CF, BI); (CF, NF); (NF, HD); (HD, SU)
Other storm (OS) as initial trigger		
2008 southern China ice storm, CN	OS → roads, trains and flights ↓ → supply chains of energy and food ↓ → power plants shut down, food shortage ⇒ consumer price index ↑ nationwide	(OS, NF); (NF, NF); (NF, BI); (NF, HD)
1977 New York City thunderstorm, USA	OS → blackout → airports closed, rescue units and hospital operations hampered OS → blackout → looting and arson → fires → businesses damaged	(OS, NF); (NF, NF); (NF, HD); (NF, SU); (SU, FI); (FI, BI)
Extreme weather (EW) as initial trigger		
2006–2010 Syrian drought, SY	EW → crop failure → malnutrition → diseases EW → crop failure → food price ↑ → violence ⇒ 2011-present Syrian civil war	(EW, BI); (BI, HD); (HD, DI); (BI, ES); (ES, SU)
Wildfire (WF) as initial trigger		
2019–2020 bushfires, AU	WF → further bushfires WF → transportation and production ↓ → logistics, tourism ↓ WF → smoke-related diseases	(WF, WF); (WF, NF); (WF, BI); (NF, BI); (BI, BI); (WF, DI)
Disease (DI) as initial trigger		
2020 COVID-19	DI → healthcare system ↓ DI → travel restriction → tourism, energy, manufacturing sectors ↓ → GDP ↓, financial crisis DI → travel restriction → tourism ↓ → agriculture sector ↓ DI → travel restriction → domestic violence DI → secondary diseases	(DI, HD); (DI, NF); (NF, BI); (BI, ES); (BI, BI); (NF, SU); (DI, DI)
Asteroid impact (AI) as initial trigger		
1908 Tunguska, RU	AI → large fires ignited near ground zero AI → hurricane-force winds	(AI, WF); (AI, WS)
Geomagnetic storm (GS) as initial trigger		
1989 Québec, CA	GS → power blackouts → loss of sales → GDP loss	(GS, NF); (NF, BI); (BI, ES)

Table 2. Cont.

Catastrophe ¹	Observed Cascading Effects ²	Proposed Encoding ³
ANTHROPOGENIC TRIGGER		
Fire (FI) as initial trigger		
1986 Basel, CH	FI → chemicals released → water supply suspended	(FI, CF); (CF, NF)
Critical infrastructure failure (CF) as initial trigger		
1986 Chernobyl, UA	CF → radiation-related diseases, agricultural crops ↓ CF → nuclear fire	(CF, DI); (CF, BI); (CF, FI)
1984 Bhopal, IN	CF → gas-related diseases → workforce incapable of work, food supply shortages → food price ↑, transportation ↓ CF → vegetable crops affected, protests and violence	(CF, DI); (DI, BI); (BI, ES); (BI, NF); (CF, BI); (CF, SU)
1976 Seveso, IT	CF → chemical lesions, contaminated crops	(CF, DI); (CF, BI)
Network failure (NF) as initial trigger		
2003 blackout, IT	NF → Internet network ↓ → further power stations breakdown	(NF, NF); (NF, NF)
2003 blackout, US	NF → subway and water systems ↓, perishable food lost at restaurants and stores	(NF, NF); (NF, BI)
Social unrest (SU) as initial trigger		
1992 Los Angeles riot, US	SU → Fires → number of businesses lost SU → “mini-malls” destroyed, burglaries and vigilantes, health and fire service hampered	(SU, FI); (FI, BI); (SU, BI); (SU, SU); (SU, HD)
Conflict (CO) as initial trigger		
11 September 2001 terrorist attack, US	CO → business (World Trade Center, airlines, tourism) ↓ → slight decrease in GDP CO → “War on Terror”, 2003 US/Iraq war	(CO, BI); (BI, ES); (CO, CO)

¹ Catastrophe date, location and country ISO code; ² one-to-one interactions (→) used for encoding while other multi-variate consequences (⇒) only mentioned—Symbols ↑ and ↓ mean rise and fall/shutdown, respectively;

³ subject to interpretation, here kept as generic as possible.

3. Results

We apply the rules of catastrophe dynamics to better understand the range of possible cascading effects. We first explore how different one-to-one interaction topologies yield emergent cascading behaviors based on Equation (2) (Section 3.1). Once understood at a general level, we investigate the topology of one-to-one interactions derived from historical data (Table 2) to identify in a semi-quantitative way how the space of possibilities expands in realistic conditions and in which cases feedback loops leading to risk amplification can be expected (Section 3.2).

3.1. Topological Characteristics of Cascading Effects

We test 24 different topologies of one-to-one interactions in a 10×10 square matrix $\bar{A}$ with constant conditional probability $p_{ij} = p$ fixed for all non-zero entries (the matching matrix A with outflow event for conservation of probabilities is thus of dimensions 11×11). The selected topologies, shown in Figure 2, represent a wide range of possible configurations with different (no-trivial) emergent properties in the interaction matrix M (or $\bar{M}$ on the figure). The topological configurations were defined with the following logic: the patterns increase in complexity per descending row in Figure 2, starting with events triggering themselves (diagonal $\bar{A}_{ii}$, 1-to-1 interactions), followed by cases of only one trigger or of only one triggered event (1-to- n or n -to-1 interactions), and then by cases of two triggers or two triggered events (2-to- n or n -to-2 interactions). Starting with row 3 of Figure 2, any event can be a

trigger and/or be triggered, with the number of possibilities increasing on average in subsequent plots (n -to- n interactions). We also included gaps in the patterns of each configuration in order to investigate the role of specific indices of A . No automated rule was applied with the role of Figure 2 solely to illustrate how M can derive from A geometrically. We used $\max \tau = 10$ at which time step most emergent cascades (i.e., matrix M) have stabilized (although cases 1–20 were already stable at $\tau = 3$). The graphs G of the various matrices $\bar{A}$ can be found in Appendix B for different centrality measures (Appendix B: Figures A1–A4). We observe two cascading phenomena, an increase of the space of possibilities and an amplification of some interactions. Although these results simply derive from the matrix power and summation operators Equation (2), some of the emerging patterns are non-trivial:

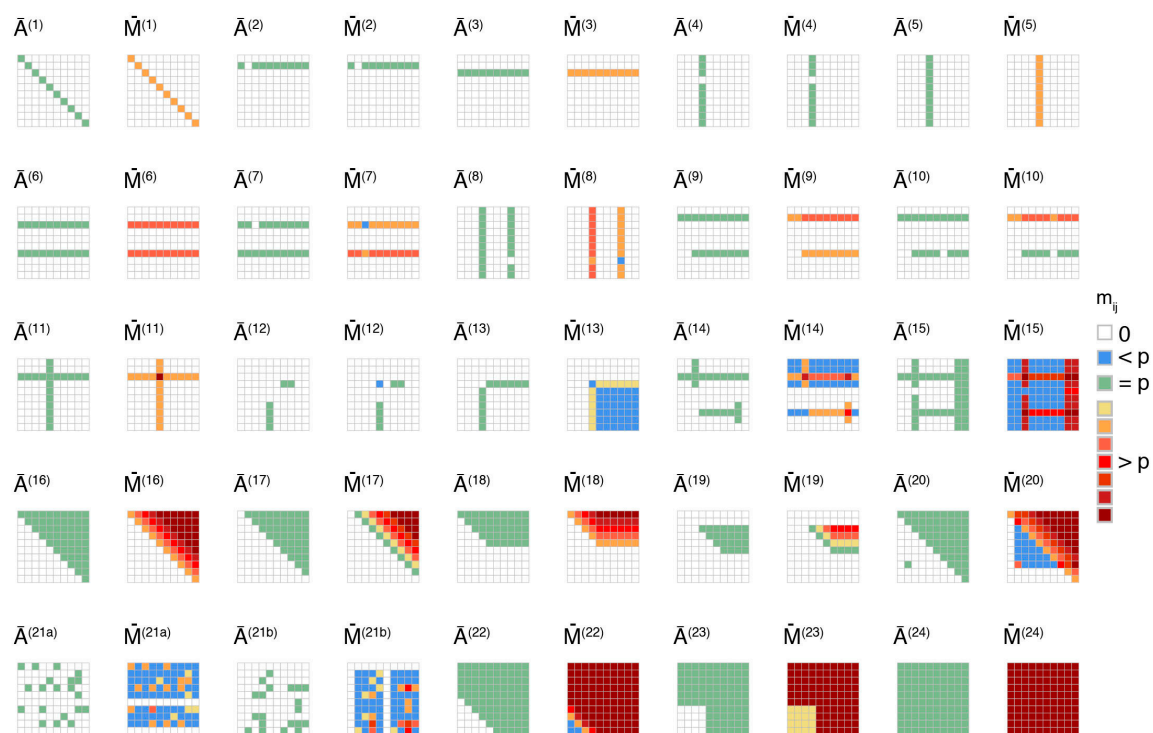


Figure 2. Different topologies l of one-to-one interactions in a reduced adjacency matrix $\bar{A}^{(l)}$ and matching reduced interaction matrix $\bar{M}^{(l)}$ ($\max \tau = 10$). Warmer colors are proportional to the ad-hoc probability, here fixed to $p = 0.1$.

(i) The feasible set of interactions expands in the subspace (i, j) (mostly represented in blue in Figure 2) as soon as event i triggers a chain of at least one event (excluding i and j), which finally reaches event j . This yields to all possible permutations of (i, j) being explored, i.e., the cardinality of the set of cascades increases. It follows that emerging cascades (see cases 7–8, 12–13) remain rare when the number of triggers and/or triggered events is low (cases 1–13). As the numbers of potential triggers and triggered events increase, more transitions become feasible (cases 14–15, 20, 22–23). For random configurations of one-to-one interactions (cases 21a–b), the feasible set of transitions can rapidly expand by the merging of several subspaces being explored. In short, as physical couplings increase, cascades become richer, and multi-risk assessment more prone to negative surprises if the underlying models fail to correctly encode the interactions related to intermediary events between i and j . The impact on overall risk may remain limited however due to the exponential decay of triggering probabilities at each step of the stochastic process ($p_{ij} < p$ represented in blue in Figure 2).

(ii) Amplification effects (represented in warm colors in Figure 2) occur as soon as an event can trigger itself (case 1). Such feedback loop $p_{ii} > 0$ further amplifies, via propagation, the other events that it can trigger (compare cases 3–5 to non-amplification cases 2–4, the same rule being observed for more complex topologies, such as cases 6–15). When there is no such feedback loop, amplification also

occurs if event j is triggered by an event i that triggers an intermediary event, which also triggers j , the best examples being cases 17 and 19. Finally, both possibilities can combine their effects for further amplifications (cases 16 and 18, extreme cases 22–24). The less trivial behaviors are observed in cases 14–15 and 20–21. For multi-risk assessment, the amplification can be understood as an increase in the re-occurrence of event j in a catastrophic chain of events starting with event i . As a corollary, losses associated to the said event accumulate as well, leading to catastrophic loss amplification [19].

This semi-quantitative analysis illustrated how both the space of possible cascading effects and overall loss can increase via a small number of linear algebra rules, albeit in a non-trivial way. We will now investigate which is the overall configuration of A in reality and which its expected impact is on cascading disasters on Earth.

3.2. Application to Cascading Disasters Based on Historical Data

We now encode the one-to-one interactions of Table 2 into an adjacency matrix A and compute the matching interaction matrix M . As in Section 3.1, the interactions, here listed in the last column of Table 2, are described in a binary approach, p_{ij} fixed to an ad-hoc p if observed and to zero otherwise. Note that we made the choice to encode interactions based on past observations for the advantage of being relatively objective. This approach could be complemented by including additional plausible interactions via expert judgement [7] and reasoned imagination [4]. Although the encoding is likely incomplete (see Section 4.1), it still represents a reasonable overview of possible interactions across the natural, technological, and socioeconomic systems, which should be further refined in future works. Results are shown in Figure 3.

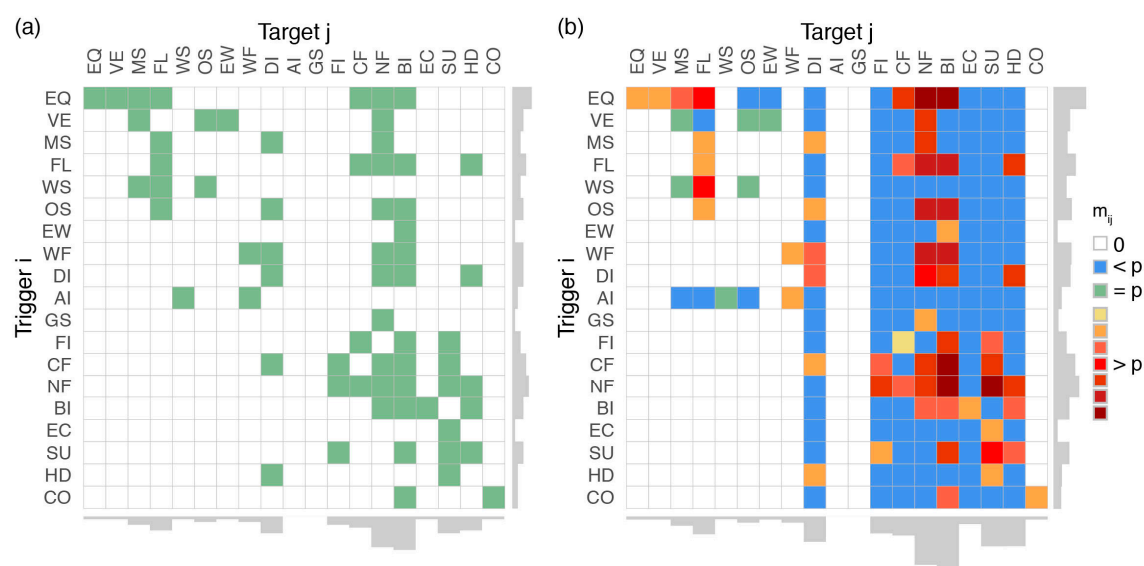


Figure 3. Topology of historical catastrophes constructed from Table 2. (a) Reduced adjacency matrix $\bar{A}$; (b) matching reduced interaction matrix $\bar{M}$ ($\max \tau = 3$) showing both an expansion of the transient interaction set (mostly in blue) and an amplification of certain events for given initial triggers (warm colors). Warmer colors are proportional to the ad-hoc probability, here fixed to $p = 0.1$.

We show that the space of possibilities expands, i.e., is enriched by additional transient events, for the technological and socioeconomic systems for any type of trigger. This is mainly controlled by network failures (NF) and business interruptions (BI) as they can be triggered by most possible events and in turn can trigger many events in the technological and socioeconomic systems. Diseases (DI) also emerge systematically, whichever the initial trigger. The potential of surprising chains-of-events leading to secondary natural perils is very limited in comparison. We also verify the independence of extraterrestrial events.

Amplification effects (i.e., increased number of times a cascade goes through event j given the initial event i) are most pronounced for i an earthquake (EQ) or a network failure (NF). In both cases, feedback loops can occur such as large aftershocks amplifying risk [17] and cascading network failures [30]. Moreover, both great earthquakes and lifelines have wide footprints, which can increase the chance of other feedback effects via various types of intermediary events (see examples in Table 2). For triggered events j , the main amplification effects are observed for network failures (NF) and business interruptions (BI) as they can be triggered by many different perils, which, via various paths, may lead to a repeat of those two events.

Figure 4 finally shows the graph G derived from the empirical adjacency matrix $\bar{A}$, illustrating the complexity and strong coupling of peril interactions. The highest in-degree and betweenness centralities are observed for network failure (NF) and business interruption (BI), which is in agreement with the results obtained above. Both events are important targets and catalysts of further interactions in the catastrophe network, explaining their critical role in cascading. In particular, they both provide an interface between loss-generating events in the natural system on one side and in the technological and socioeconomic systems on the other side.

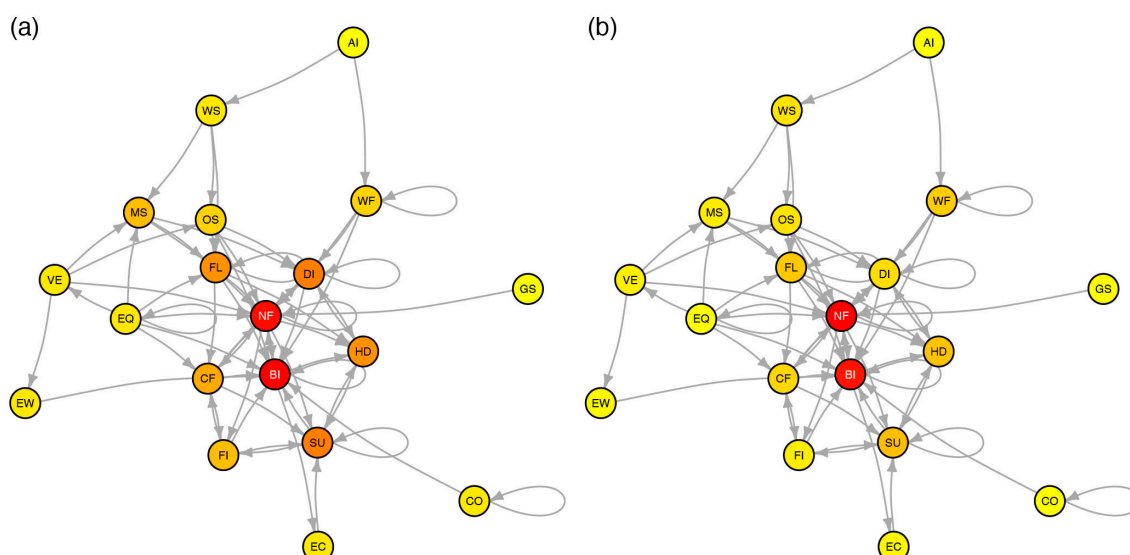


Figure 4. Catastrophe graph G of the reduced adjacency matrix $\bar{A}$ shown in Figure 3. (a) In-degree centrality; (b) betweenness centrality. A warmer color represents a higher centrality value; see Table 1 for peril identifier definition.

4. Limitations and Future Directions

4.1. Incompleteness Issues in Historical Data

This study is based on the analysis of only 29 historical cases of cascading disasters (Table 2). Although believed to be representative of a relatively large space of physically possible interactions, other potential interactions, but also perils, are necessarily missing. Moreover, any given one-to-one interaction present in Table 2 recurs less than 29 times, none being systematic. This is the reason why we used a binary, semi-quantitative approach by fixing a constant ad-hoc conditional probability p , which led to an unweighted adjacency matrix. With all interactions considered equal, the ones occurring rarely take a preponderant role relative to other, more common, interactions. The best example is the case of a landslide triggering a disease outbreak (1994 Northridge earthquake case, one of the most peculiar chains-of-events listed in Table 2) which is extremely rare and only included here to show the extent of possible interactions. Although it is likely to lead to biases in event amplification in Figure 3, it does not further cascade into M , and hence does not impact on our main conclusions. The other interactions are unlikely to lead to any significant bias in relative amplification measures.

Encoding the adjacency matrix with realistic values of p_{ij} will require extensive data mining in historical records to obtain reliable estimates from a more complete set of data. Such a database has yet to be built, making our approach a pilot study in the promotion of such development in the near future. A further level of incompleteness is related to potential intermediary interactions missing in the encoding of the raw data, as this process is subject to interpretability (the reason why we provide all the raw data in Appendix A). Here again, the development of a large database will help to identify the best event granularity and the general physical rules to consider in the definition of one-to-one interactions.

4.2. Beyond One-to-One Links

The full scope of catastrophe dynamics is not limited to the linear dynamic process represented by Equation (1), which provides only a first-order description. We observed in the literature important consequences that cannot be described by one-to-one links but by multiple variables (represented by $\Rightarrow$ in Table 2). For instance, it is sometimes observed that an independent coinciding event amplifies risk, a textbook example being wind during or just after a non-atmospheric event: wind can amplify fires following an earthquake (firestorm [31]), wildfires (megafires [32]), or disease spread during a landslide (dust-borne spore clouds [33]). Rain can trigger a landslide where the soil has first been destabilized by a wildfire [8] or lahars following a volcanic eruption (e.g., tropical cyclone during the 1991 Mount Pinatubo eruption) [2].

Many one-to-one interactions could be further amplified by underlying conditions. It has, for example, been suggested that a civilization or society can collapse following a natural catastrophe, but only if the economic situation of the civilization or society is very weak [34]. Other long-term drivers such as climate change are also known to amplify those direct interactions by increasing the available energy by temperature rise [28]. Conflicts (e.g., a war), as observed in historical cases (Table 2), can be a direct consequence of another conflict (e.g., terrorism). However, as illustrated in Figure 3, no other chain of one-to-one interactions is likely to lead to conflict. Such an event is more likely to be triggered by the accumulation of many different, sometimes independent, events.

4.3. The Temporal Evolution of Cascading Phenomena

As temporal processes evolve, so do cascading phenomena: earthquakes could directly trigger fires prior to the 20th century when households were lighted by candles that could fall due to ground shaking (e.g., 1755 Lisbon earthquake [35]). Nowadays, direct fires are much less likely, occurring via critical infrastructure and network failures (e.g., gas leak). In other cases, much more interactions would be expected today: The 1859 geomagnetic storm (Carrington Event) did not lead to cascades at the time, but its reoccurring today would cause widespread electrical disruptions and damage, far more than the 1989 Québec event [36]; it is the same with the 1908 Tunguska airburst, which, if it had occurred over an urban area [37], would have led to critical chains-of-events as are observed following other wide-footprint high-energy events.

The limitations described just above and in Section 4.2 show the way to follow in this domain, i.e., adding non-linearity to Equation (1) (which could relate, then, more closely to catastrophe theory [20]), time-dependency in variables and conditional probabilities, as well as developing counterfactuals [38] in multi-risk. Analytical solutions such as Equation (2) would however become rarer with simulation approaches more adapted to model non-Markovian processes [17,19,24,39].

4.4. The Concept of Unit Time in the Current Framework

Finally, it is important to mention that the cascading events studied in this paper occur in a natural physical time scale, and the (physical) time required for each triggering event to happen varies. For example, the time required for an earthquake to trigger a tsunami can be different from that to trigger a critical network failure or a landslide. However, in the proposed discrete Markovian framework, the physical time scale is simplified into the “consecutive trials” in a Markov chain. In consequence of this simplification, only the causal relationship presented within the original physical

time is preserved. For instance, the simplification suggests that both the triggering event “ $A \rightarrow B$ ” and “ $A \rightarrow C$ ” are counted as “a single trial”, with the causal relationship that “ A ” triggers “ B ” or “ C ” being preserved. To further incorporate the time difference into each event triggering, in future studies, one could attempt to recover the rate matrix in the continuous master equation—Equation (1)—without the presumption that adjacency matrix A was directly estimated.

5. Conclusions

We explored the range of potential cascading effects in catastrophes by applying the rules of system dynamics and by defining finite catastrophic chains-of-events as absorbing Markov chains. We first investigated the richness of cascades and amplifying feedback effects by computing the interaction matrix M , i.e., a variant of the fundamental matrix N , for idealized topologies of one-to-one interactions encoded in an adjacency matrix A (Section 3.1). We found that cascade patterns rapidly become non-trivial (Figure 2), which is likely to hamper multi-risk assessment and mitigation when not all possible interactions have been considered. We then encoded 29 historical catastrophes known for their cascading behavior (Table 2, Appendix A) in A and computed the matrix M representative of a general, yet highly simplified, catastrophe dynamical system (Section 3.2). We observed a clear difference between the natural system and man-made systems (technological and socioeconomic) with cascades being enriched and amplified mostly via network failure and business interruption, which bridge the different systems (Figures 3 and 4).

The present analysis should in the future be extended towards a systematic assessment of cascading effects for all types of perils and full chains of events. The key to such an approach would be the combined definition and categorization of both events and event-to-event interactions. The generic perils defined here (Table 1) shall be characterized in physical terms (e.g., energy type, scaling), and the physics of possible interactions made explicit. A physics-based ontology of peril interactions would provide the means to build a database with a proper attribute definition for quantitative multi-risk analysis.

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Appendix A

We here provide the complete data sources on the historical cascading effects summarized in Table 2, consisting of the following literature sources and quotes:

- 2011 Tohoku earthquake, Japan: “the main quake triggered a massive, destructive tsunami [...] The violent shock {led} to subsidence of about 1.2 m [and] potentially more severe flood risk [...] in the future” [40] (p. 35); “Several nuclear power plants and thermal power plants were heavily damaged [...] causing outages”; earthquake and tsunami affected the transportation system, ruined farmland, caused decline in global automobile production, and significant fluctuations in the global financial markets [40] (p. 36); “the cooling system of the first nuclear power plant in Fukushima also stopped working because of the impact of the tsunami [...] the nuclear accident gradually became a level 7 nuclear event” [40] (pp. 37–38).
- 2008 Wenchuan earthquake, China: “Landslides and rock avalanches triggered by the earthquake produced 257 landslide lakes” [41] (p. 209); “Sudden landslide dam failure and resulting outburst floods were common” [41] (p. 210); “landslides and rock falls [...] hampered search and rescue operations due to blocked access routes” [42] (p. 243); “The Wenchuan earthquake caused extensive damage to and outage of

electric-power, gas and water-supply systems, forcing many industrial plants to interrupt production" [42] (p. 246); "fertiliser plants [...] heavily damaged and are reported to have resulted in significant ammonia, sulphuric acid and other releases [as well as] breathing difficulties" [42] (p. 247); "Over 138,000 businesses were damaged during the earthquake, leading to extensive business interruption" [43] (p. 1); "The train, including 13 tank cars filled with gasoline, derailed and burst into flames Monday in Gansu province when the quake cut a major rail line" [44]

- 2004 Sumatra earthquake, Indonesia: "earthquake generated the most devastating tsunami [...] More deaths are possible due to poor sanitation" [45] (p. 543); "The unstable faultline triggered powerful aftershocks" [45] (p. 544); "The Indian Ocean tsunami severely affected tourism and fishing infrastructure [also] utilities and lifelines; transportation networks; and communication" [45] (p. 551); "salt water contaminated drinking water supplies and farm fields" [45] (p. 553); "Two volcanic eruptions [...] that followed the disastrous M9.3 earthquake [...] raise the question of whether there eruptions were triggered by the earthquake. Here we present new evidence to suggest [so]" [46] (p. 539).
- 1994 Northridge earthquake, USA: "additional effect of the rock falls and rock slides in the Santa Susana Mountains was an outbreak of valley fever (coccidioidomycosis), which can only be contracted by inhaling airborne dust containing the fungal spores that cause the disease" [33] (p. S331).
- 1923 Kanto earthquake, Japan: "the force of the earthquake had broken water pipes, it was impossible for fire fighters to control the outbreak of fires" [31] (p. 880); "rumours alleged that 'Koreans detonated bombs which caused the fires' [...] some vigilantes turned violent and began actively hunting and killing innocent Koreans" [31] (p. 882); "In the wake of the earthquake, [...] the government considered the psychological aspects of reinvigorating not just Tokyo, but the entire nation. In order to reach the nation on an ideological level and 'renew people's minds' [...] for counteracting undesirable social trends" [31] (p. 891); "Public utilities, including running water, and waste removal services were slow to recover [following the earthquake]. As a result sanitary conditions deteriorated rapidly [...] Water-borne infectious diseases spread rapidly [...] (typhoid and dysentery)" [47] (p. 107); Yokohama Burning: The Deadly 1923 Earthquake and Fire that Helped Forge the Path to World War II" [48].
- 1906 San Francisco earthquake, USA: "Most of the damage was not done by the tremor itself [...] but by the fires that followed [...] The combination of close quarters, highly flammable building materials, and earthquake-damaged water mains hampered the efforts of firefighters" [49] (p. 7); "The quake's impact manifested itself in international gold flows [which] threatened the fixed sterling-dollar exchange rate, leading the Bank of England to raise interest rates and discriminate against American finance bills [and] resulting contraction pushed the United States into recession, setting the stage for the 1907 Panic" [49] (p. 1).
- 2010 Eyjafjallajökull volcanic eruption, Iceland: "A substantial proportion of the world's air traffic descended into disorder [...] Airlines suffered heavy losses and some went bankrupt" [50] (p. 7).
- 2002 Stromboli volcanic eruption, Italy: "The 2002 Stromboli tsunami was a tidal wave caused by a volcanic eruption [...] The first landslide was around 13:15 [...] The event also forced the Civil Protection to close the island to the tourists" [51].
- 1783 Laki volcanic eruption, Iceland: "People complained that the haze [triggered by the eruption] caused weakness, shortness of breath, and throbbing of the heart [...] Lethal sickness in the grazing livestock [...] in mass deaths [...] livelihood on farming and fishing, the disastrous effects of the eruption led to a famine [...] sulfur smelling haze caused sickness in humans [...] troublesome headaches, respiratory difficulties, and asthma attacks [...] dramatic temperature changes over a period of several hours" [52] (pp. 13-14); "The cold and harsh summer in 1783 was attributed to the presence of the volcanic haze [...] Severe drought was reported [...] The arrival of spring thaw raised the water of all major rivers in central and south Europe to such a degree that floods caused enormous property damage" [52] (pp. 15-16); "These events contributed significantly to an increase of poverty and famine that may have contributed to the French Revolution in 1789" [53].
- 1963 Vajont landslide, Italy: "The mountainside collapsed [...] Blocking the gorge to depths of as much as 400 m, the landslide traveled to 140 m up the opposite bank [...] Having washed back and forth along both sides of the valley, a wave of water overtopped the dam" [54] (p. 23).

- 2011 Thailand floods: *“In addition to affected farmland, seven industrial parks were inundated [...] Due to the damage to these industrial parks, the manufacturing sector contributed to 8.6% of the decline of the real GDP”* [55] (p. 259); *“The decrease in production impacted the sales for the trade partners to which manufactured cars in Thailand are exported”* [55] (p. 262).
- 2017 Hurricane Harvey, USA: *“The record-breaking rainfall produced by Hurricane Harvey resulted in catastrophic and prolonged impacts on Houston’s transportation infrastructure, inundating entire neighborhoods and rendering them inaccessible to emergency response services”* [26] (p. 1).
- 2012 Hurricane Sandy, USA: *“most damage resulted from storm surge in New York City during Sandy. The indirect damage due to business interruption resulted primarily from interconnected risks within infrastructures [...] caused extensive damage to electric transmission and distribution infrastructures [...] also damaged the region’s petroleum infrastructures [...] The loss of the electricity and fuel sectors propagated to other sectors. Gas stations in New Jersey could not operate because of the outage. Three health care facilities in Manhattan and Brooklyn had to emergently evacuate all patients due to the outage [...] The collapse of power utilities and petroleum infrastructures triggered failures in other infrastructure systems, such as health care facilities, public transportation systems, the supply of necessities and emergency facilities”* [56] (p. 134).
- 2005 Hurricane Katrina, USA: *“Hurricane Katrina makes landfall [...] levee breaches in New Orleans, allowing the waters of Lake Pontchartrain to flood the city. Communications fail completely as electrical stations and cell phone base stations are flooded; radio frequencies are overloaded or incompatible for response agencies [...] Food, water, medical care, security are scarce. Reports of violence, looting break out [...] Lifeline systems - water, communications, transportation, electrical power, sanitary sewers, gas distribution systems - are inoperable”* [57] (p. 506).
- Great 2008 Chinese Ice Storm: *“trains were stranded [...] The disaster damaged 82,000 km of roads across the country. The rain and snowfall lead to the cancelation of 3840 flights across China [...] With all transportation systems frozen, supply chains of energy, food, and other vital goods were broken. Coal reserves reached emergency levels. Power plants had to be shut down. Food shortages occurred [...] The consumer price index nationwide increased by 34%”* [58] (p. 339).
- 1977 New York City lightning: *“looting and arson [...] accounted for almost one half of the total economic costs associated with the blackout [...] The New York airports were ordered closed at 9:57 p.m., only minutes after the power failure [...] Rescue units were hampered by the inability to obtain fuel dispensed by electric pumps [...] Several other important hospital operations were hampered as a result of key activities not supported by emergency power [...] The sequence of events that began with a lightning stroke at 8:37 p.m. on July 13, 1977”* [59] (pp. 44–46).
- Syrian 2006–2010 drought: *“When a severe drought began in 2006/2007, the agricultural system in the northeastern ‘bread basket’ region [...] collapsed [...] between 2007 and 2008, drought was a main factor in the unprecedented rise in Syrian food prices [...] increase in nutrition-related diseases [and] mass migration of rural farming families to urban areas ensued [...] The rapidly growing urban peripheries of Syria, marked by illegal settlements, overcrowding, poor infrastructure, unemployment, and crime, were neglected... We conclude that human influences on the climate change [leading to the drought] are implicated in the current Syrian conflict”* [60] (pp. 3241–3242).
- 2019–2020 Australian bushfires: *“The air quality index [...] hit 2552 or more than 12 times the hazardous level of 200”* [61] *“The severity of the crisis has prompted widespread interruptions such as highway closures, production stoppages, power outages, as well as flight cancellations and delays - all of which inevitably cause significant disruptions to logistics activity”* [62]
- 2020 COVID-19 pandemics: *“A global crash in demand from hotels and restaurants has seen prices of agricultural commodities drop by 20%”* [15] (p. 185); *“Capital market has also been affected. In the US, the S&P 500 [...], the Dow Jones Industrial Average and the Nasdaq fell dramatically [...] The COVID-19 pandemic has caused an unprecedented challenge for healthcare systems worldwide”* [15] (pp. 187–188); *“Lockdown and social distancing measures to prevent spread of COVID-19 have heightened fears of increased levels of domestic violence”* [15] (p. 190); *“Concerns regarding potential neurological complications of*

COVID-19 are being increasingly reported [...] 39 (31%) of 125 patients presented with altered mental status" [63] (p. 1).

- 1908 Tunguska airburst, Russia: "large fires were ignited near ground zero [...] and spread outward" [37] (p. 871); "hazard is due to hurricane-force winds [maximum wind speed of 502 mph, 163 mph, and 70 mph for an overpressure of 50, 5, and 2 psi, respectively]" [37] (p. 873)
- 1989 geomagnetic storm, Canada: "The power blackout due to the March 1989 magnetic storm caused direct costs of tens of millions of dollars to Hydro-Québec because of damage to equipment and loss of sales. However, estimates of lost GDP for Québec are many times that" [36] (p. 549).
- 1986 Basel fire, Switzerland: "The majority of the approximately 1250 t of stored chemicals was destroyed in the fire, but large quantities were introduced into the atmosphere, into the Rhine River through runoff of the fire-fighting water, and into the soil and groundwater at the site" [Giger, 2009] (p. S98); "As a precautionary measure, operations at drinking water utilities along the Rhine had to be temporarily suspended" [64] (p. S98).
- 1986 Chernobyl nuclear disaster, Ukraine: "Immediately following the accident at Chernobyl, humans exposed to high-level radiation suffered from acute radiation sickness [...] Most of the long-term consequences of the Chernobyl disaster stem from the inhalation and ingestion of radionuclides generated by the explosion and nuclear fire" [65] (p. 200); "The genetic consequences of radioactive contamination by the fallout to agricultural crops after the accident at the Chernobyl NPP in 1986 has been studied [...] Analysis of genetic variability in three sequential generations of rye and wheat revealed increased cytogenetic damage in plants exposed" [66] (p. 155).
- 1984 Bhopal chemical industrial accident: "The Bhopal Gas Leak, India 1984 is the largest chemical industrial accident ever. 520,000 persons were exposed to the gases, and up to 8000 died during the first weeks" [67] (p. 1); "The gases immediately affected trees [...] vegetable crops all showed signs of being badly affected" [67] (p. 5, sec. 7.3.6); "75 percent of the workforce was incapable of work, mainly because of breathlessness" [67] (p. 1, sec. 8.5.2); "The day after the leakage, several thousand Bhopal residents tried to storm the factory" [67] (p. 1, sec. 8.6.1); "Communications came to a stop. Key-persons for train and public transports were missing [...] With shops and markets closed, the prices of food went up [...] large protests to the withdrawal of free distribution of rations were organised. This resulted in police violence and arrests" [67] (p. 3, sec. 8.6.2).
- 1976 Seveso, Italy: "signs of toxic dermatitis" [68] (p. 329); "measurements showed that 80% or more of the total TCDD traced adhered to the vegetation (foliage, grass, crops)" [68] (p. 358).
- 2003 electrical blackout, Italy: "the electrical blackout that affected much of Italy on 28 September 2003: the shutdown of power stations directly led to the failure of nodes in the Internet communication network, which in turn caused further breakdowns of power stations" [30] (p. 1025).
- 2003 Northeast Blackout, USA: "The blackout caused major disruptions to many facets of life. Commuters stood trapped in subways for hours, restaurants and grocery stores dispensed masses of unprotected perishable food, cars waiting for gas backed up in lines stretching around city blocks, and households had to manage without water service" [69] (p. 184).
- 1992 Los Angeles riots, USA: "The number of fires does not reflect the total number of businesses lost to fire [...] The mini-malls proved to be frequent targets of the disturbance. In addition to injuries and arson damage, the Los Angeles Police Department (LAPD) reported 3330 burglaries [...] A Korean radio station called for Korean vigilantes to patrol the streets [...] Unique to the Los Angeles situation was the manner in which health and fire personnel delivered services during the unrest. Their speed and effectiveness were hampered by their need of police protection" [70] (p. 266).
- 2001 9/11 terrorist attacks, USA: "the direct BI losses were only \$12 billion [...] reduction in air travel and related tourism [...] the impact of 9/11 on growth is significant with approximately a negative 0.5 percentage point impact on GDP per capita growth" [71] (pp. 5–6); "The effective fixing of the meaning of the September 11 attacks in terms of the "War on Terror" substantially circumscribed political debate, and we explain why this discourse became dominant. The Bush administration then capitalized on the

existing portrait of Saddam Hussein to bind Iraq tightly into the War on Terror and thereby silence leading Democrats and legitimate the war” [72] (p. 409).

Appendix B

The following plots show the in-degree, out-degree, closeness and betweenness centralities, respectively, of the graphs $G^{(i)}$ representative of the adjacency matrices $A^{(i)}$ of Figure A2. We hereby verify that all proposed topologies display different network properties. The impact on risk accumulation of a given event (or vertex) having a high centrality is not explored in the present study as all events are weighed the same.

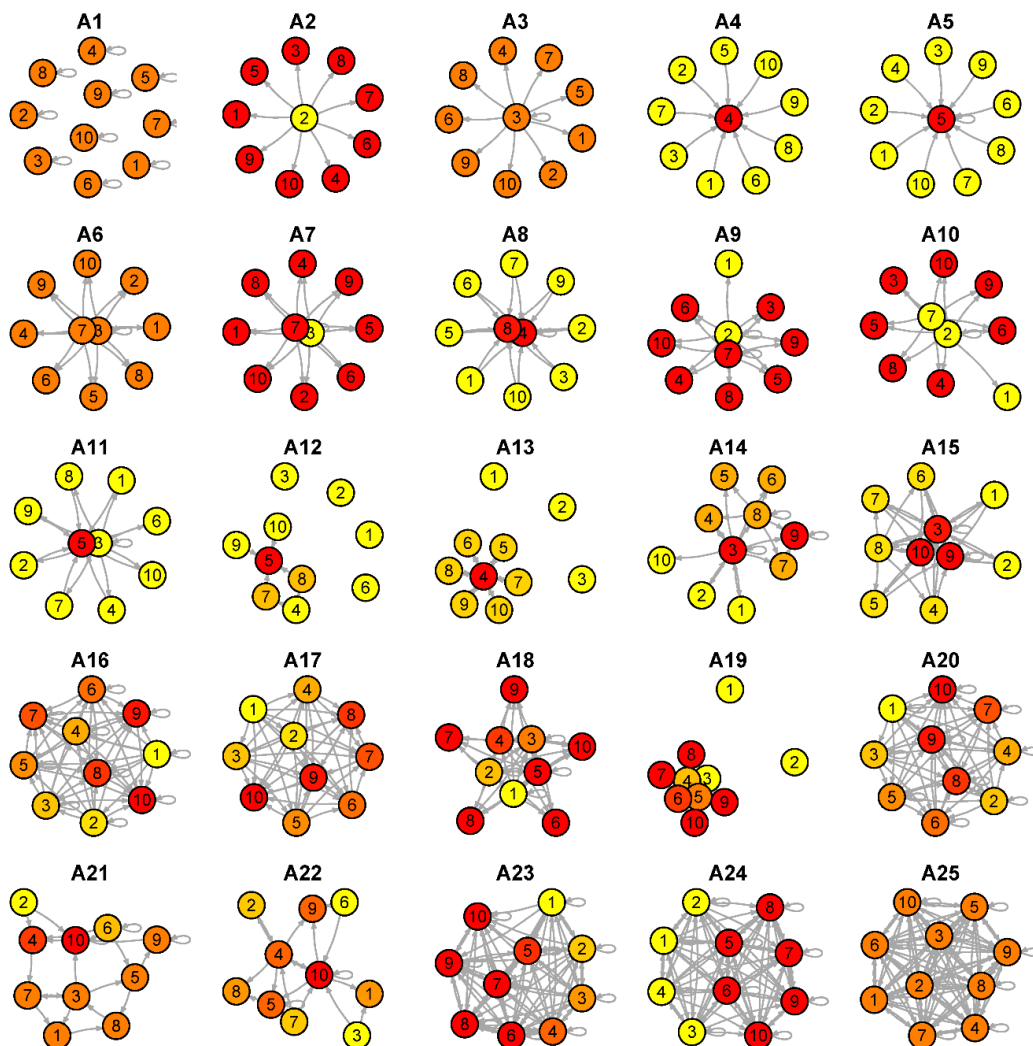


Figure A1. Graphs $G^{(i)}$ with in-degree centralities colored by the yellow-red gradient.

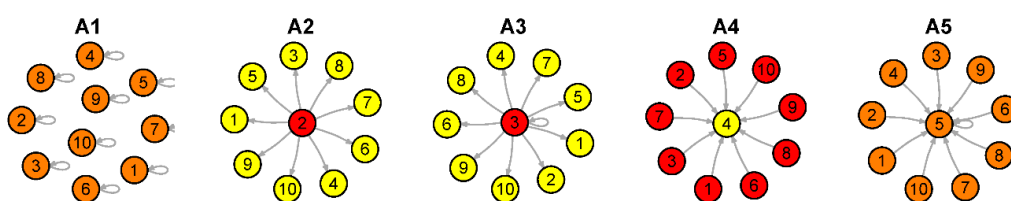


Figure A2. Cont.

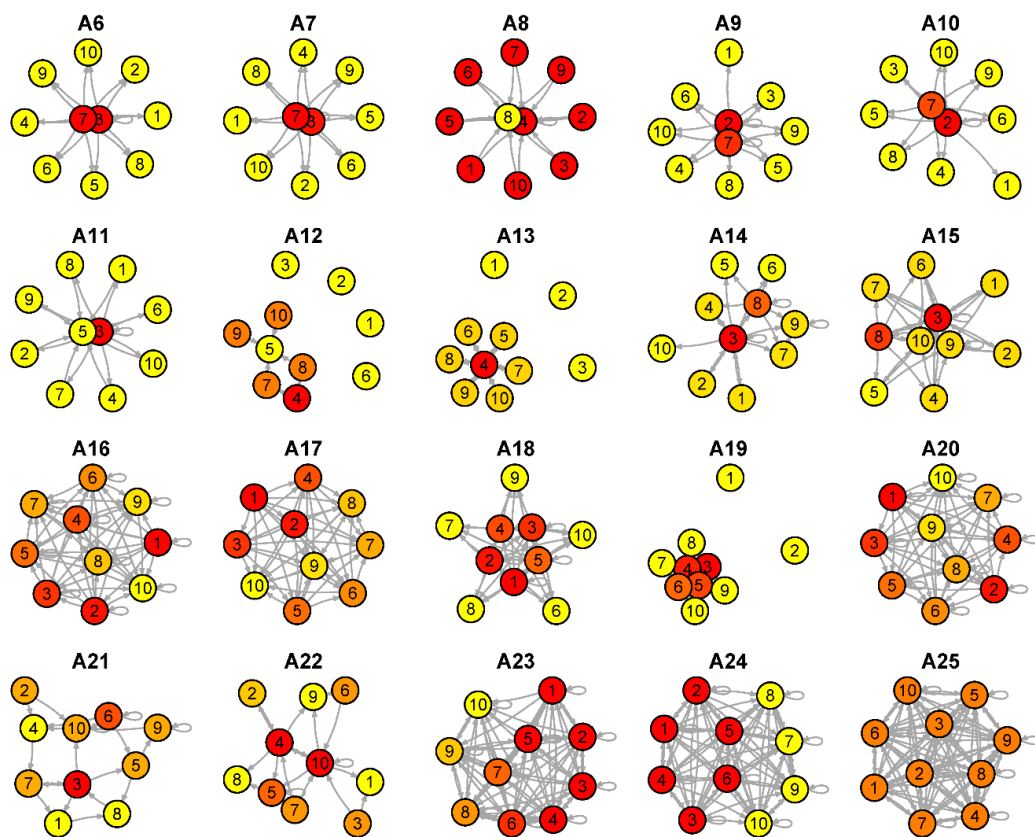


Figure A2. Graphs $G^{(i)}$ with out-degree centralities colored by the yellow-red gradient.

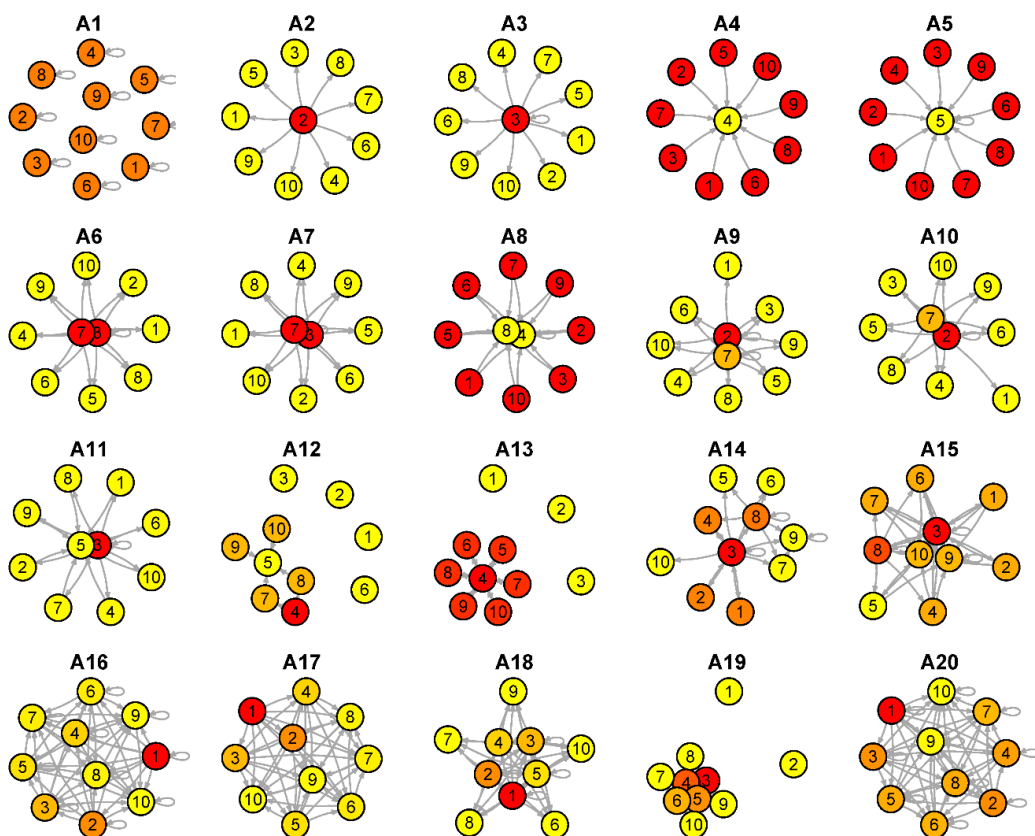


Figure A3. Cont.

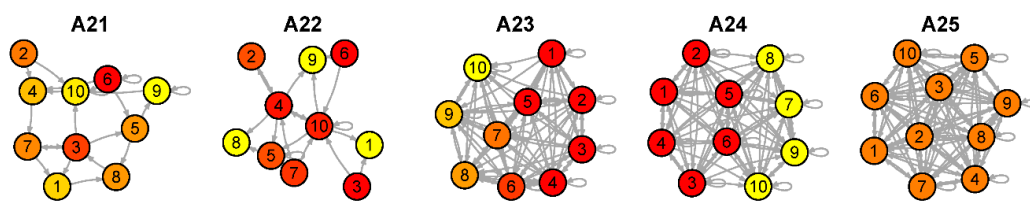


Figure A3. Graphs $G^{(i)}$ with closeness centralities colored by the yellow-red gradient.

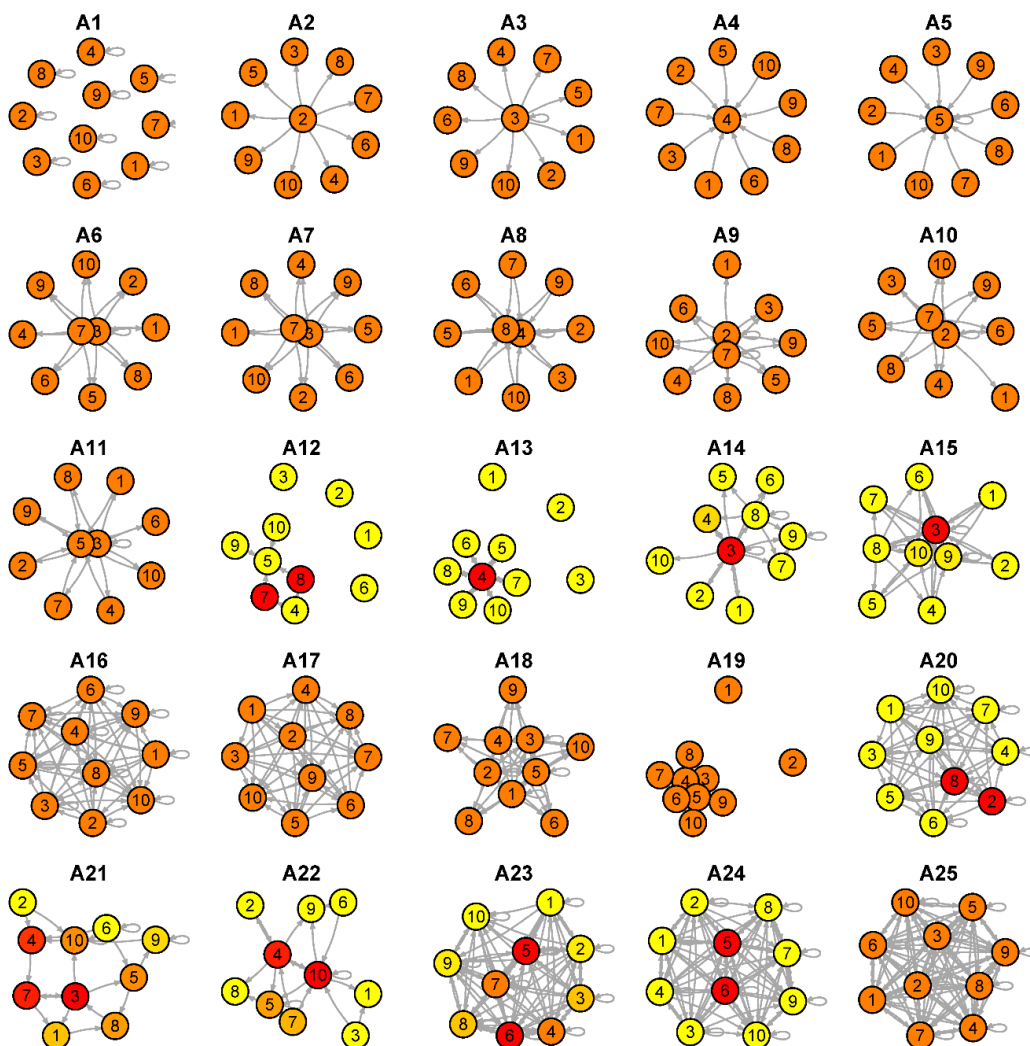


Figure A4. Graphs $G^{(i)}$ with betweenness centralities colored by the yellow-red gradient.

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