Infrastructural Aspects of Rain-Related Cascading Disasters: A Systematic Literature Review

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Received: 28 May 2020; Accepted: 1 July 2020; Published: 17 July 2020

Abstract: Cascading disasters progress from one hazard event to a range of interconnected events and impacts, with often devastating consequences. Rain-related cascading disasters are a particularly frequent form of cascading disasters in many parts of the world, and they are likely to become even more frequent due to climate change and accelerating coastal development, among other issues. 1) Background: The current literature review extended previous reviews of documented progressions from one natural hazard event to another, by focusing on linkages between rain-related natural hazard triggers and infrastructural impacts. 2) Methods: A wide range of case studies were reviewed using a systematic literature review protocol. The review quality was enhanced by only including case studies that detailed mechanisms that have led to infrastructural impacts, and which had been published in high-quality academic journals. 3) Results: A sum of 71 articles, concerning 99 case studies of rain-related disasters, were fully reviewed. Twenty-five distinct mechanisms were identified, as the foundation for a matrix running between five different natural hazards and eight types of infrastructural impacts. 4) Conclusion: Relatively complex quantitative methods are needed to generate locality-specific, cascading disaster likelihoods and scenarios. Appropriate methods can leverage the current matrix to structure both Delphi-based approaches and network analysis using longitudinal data.

Keywords: cascading disasters; rain; infrastructure; mechanisms; systematic literature review

1. Introduction

The devastating impacts of disasters such as the Odisha Super Typhoon of 1999, Hurricane Katrina in 2005, and the Central European floods of 2013 have highlighted widespread vulnerabilities to extreme weather events. These types of events involve wind speed, rainfall, and other meteorological variables that “exceed a particular threshold and deviate significantly from mean climate conditions” [1] (p. 2). They can also trigger further and even more catastrophic events, such as landslides and storm surge [2].

Progressions from an initial trigger to a range of subsequent disasters are commonly referred to as cascading disasters, which can include much broader and more severe impacts than the initial trigger event [3]. The 2019 Global Assessment Report on Disaster Risk Reduction [4] stated that “Cascading hazard processes refer to a primary impact (trigger) such as heavy rainfall, seismic activity, or unexpectedly rapid snowmelt, followed by a chain of consequences that can cause secondary impacts” (p. 49). For example, Hurricane Katrina triggered a 7.3 to 8.5 m storm surge that was combined with ongoing rainfall to inundate 80 percent of New Orleans’ urban infrastructure footprint [5,6]. Without well-informed interventions, the kinds of cascading impacts experienced during Hurricane
Katrina are only likely to worsen in the face of accelerating climate change [7], increasingly complex interdependencies, environmental degradation [8], and rapid urban development in areas prone to meteorological hazards [5,9]. There is therefore a pressing need to better understand the secondary hazard events triggered by extreme weather, to better mitigate and prepare for a wider scope of relevant impacts.

Many of these secondary hazard events involve major infrastructure, such as power, electricity, and water supplies. As outlined by Pescaroli and Alexander [3], “critical infrastructure and complex adaptive systems may be the drivers that amplify the impacts of the cascade” (p. 2250). This makes infrastructural vulnerabilities and resilience a very important aspect of analyzing and managing cascading risks, alongside other complexities [3]. Focusing on infrastructural aspects of cascading disasters also helps address the risk of Natech events, where natural hazards trigger severe technological hazards, such as chemical spills [6] and cascading system failures [4]. These types of events can cause major disruptions to affected populations and to emergency response agencies, even when they do not amount to a disaster. Definitively disastrous Natech events, like those associated with the 2008 Wenchuan and the 2011 Great East Japan earthquakes, have had even more severe impacts on human health and economies, in addition to environmental damage [4].

When relevant links between natural and infrastructural hazard events are specified, damage assessments and predictions can reflect a broader and more accurate set of disaster impacts. As highlighted by Hillier, Macdonald, Leckebusch, and Stavrinides [10], the sum of these impacts extends well beyond standard measures of direct property damage and fatalities. Their analysis of weather-related hazard linkages was based on 124 years of meteorological and insurance-related data from the United Kingdom. Hillier et al. [10] found that estimates for direct economic impacts increased by 26 percent, when including statistically weighted linkages between hazard types rather than calculating the impacts associated with a single trigger.

This approach to analysis also permits emergency management agencies to better address relevant linkages, to prevent or mitigate downstream hazard events well before they occur. This reflects the generally substantial cost-effectiveness of hazard mitigation outlined by Kelman [11], for complementing more reactive aspects of emergency management such as emergency response. For example, sandbags are stored close to elevators prone to subterranean flooding in Shenzhen, China. These sandbags are deployed in front of elevators during heavy rainfall, rather than waiting for the shafts to flood, and for many thousands of elevators throughout the city to fail.

The current paper contributes to cascading disaster risk assessment by determining: 1. Known infrastructural impacts triggered by rain-related natural hazards, and 2. The mechanisms explaining linkages between each identified impact and trigger. This was achieved by systematically reviewing case studies of rainfall-related triggers, infrastructural impacts and mechanisms, before adding the results to a preceding review of natural hazard linkages by Gill and Malamud [2]. The combined matrix resulting from the current review provides a robust set of parameters for further analyses of cascading rain-related disaster risk by highlighting a broader, but nonetheless defined range, of known scenario elements.

The remainder of this Section 1 outlines challenges for the numerical analysis of cascading disaster risk, before explaining how case study reviews can help address those challenges. This is followed by Section 2 detailing the systematic literature review process used by the current research, to review a wide range of rain-related disaster case studies. Section 3 outlines how literature review results were used to develop a conceptual matrix of documented linkages between natural hazards and infrastructural impacts during cascading disasters, together with a list of associated mechanisms. Section 4 then compares these results and their limitations with prior research. This is followed by Section 5 that summarizes all the preceding sections before outlining how the current analysis could be used to structure localized analyses of expert knowledge and longitudinal data.
1.1. Challenges for Analysing Cascading Disaster Linkages

Huggins et al. [12] highlighted the potential for using localized, longitudinal data to study transitions from one disaster state to another. However, large and well-structured sets of relevant data are often not available for analysis. Kar-Purkayastha, Clarke, and Murray [13], and Huggins et al. [12] have outlined how open-access disaster impact databases typically lack important chronological, geographic, and other details. Associated challenges can be worsened by government agencies who are reluctant to allow researchers to access more detailed disaster impact data at a national scale [14]. Even where data is available, standardized impact assessment protocols often do not address the infrastructural impacts of meteorological hazards [15]. Other protocols require detailed analysis that is not usually feasible within many disaster-affected contexts [16].

All these challenges are exacerbated by rapidly changing urban development. Atta-ur-Rahman, Nawaz Khan, Collins, and Qazi [14] outlined how hazardous urban development in landslide-prone areas of Pakistan has been accelerating over time. Many other disaster-prone areas are also developing so rapidly that larger sets of longitudinal data do not apply to current urban footprints. The rapidly developing city of Shenzhen provides one example from within China’s Pearl River Delta. According to Swiss Re [17], this Delta is more heavily prone to storms, storm surge, and riverine flooding than any other metropolitan area in the world. It appears that the situation was not always so problematic because Shenzhen was formerly limited to the scale of a fishing town, prior to rapid development starting in the 1980s. Its urban footprint and potentially exposed population have since grown to a resident population of over 13 million people.

Issues concerning the structure, detail, and relevance of statistical hazard data mean it is often impossible to determine the base rate frequencies required for analysis such as the Bayesian Event Tree methods developed by Marzocchi, Sandri, and Selva [18]. However, these frequencies are not strictly required for predictive models based on the opinions of experienced and suitably qualified experts [19]. Relevant approaches to developing numerical models of potentially cascading disasters are exemplified by the combination of Cross Impact Analysis with Interpretive Structural Modelling (CIA-ISM), by Ramirez de la Huerga, Bafuls Silvera and Turoff [19]. Their method produces structural models of cascading disaster progressions by gathering, iterating, and then combining expert likelihood ratings, without using base rate frequency data.

Of course, no one analytical approach provides a panacea for the challenges of analyzing cascading disaster risk. Despite the many types of events that could be involved, Ramirez de la Huerga et al. [19] caution against adding too many triggers and impact parameters to the CIA-ISM process. This is because each parameter has a substantial effect on the number of expert ratings required. The importance of selecting the right set of initial rating parameters was demonstrated by Ramirez de la Huerga et al. [19] by reminding readers that the number of pathways requiring ratings is equivalent to $N \times 2^{n-1}$. This exponential relationship between parameters (N) and ratings required constrains the number of triggers and impacts that could be thoroughly considered by busy experts with limited time available.

1.2. Cascading Disaster Models Derived from Literature Reviews

Where appropriate data and expertise are available, wide-ranging literature reviews can help to constrain large sets of numerical parameters. Rather than providing an exhaustive list of possible triggers and impacts, they can refine analysis towards a more compact set of initial parameters that are well known to trigger one another. As outlined above, this is particularly important for expert-rating methods such as CIA-ISM [19]. Following the rationale and example provided by Mignan et al. [20], parameters could then be added or eliminated by experts, to reflect their professional knowledge of a particular context, or of a more generic set of mechanisms.

Among other examples, previous reviews of cascading disaster literature have resulted in a generalized model of freezing rain consequences by Schauwecker et al. [21], and a multi-hazard model constructed by Kumasaki, King, Arai, & Yang [22]. Schauwecker et al. [21] generalized from the basis of a single, freezing rain event in Slovenia. This meant that, although they also referred to a broader range
of relevant cases, the context and particulars of their initial case resulted in a relatively deterministic pathway model, i.e., one that largely flowed from one determined consequence to another. Although this model included 17 different types of hazard events, only five of those event types could trigger two or more additional cascading pathways.

Kumasaki et al. [22] reviewed a much wider range of cases. They used their review of relevant documents to produce a much more exhaustive model of cascading pathways between documented natural hazard events that had occurred in Japan. The resulting model was also strengthened through specifying mechanisms for each of the cascading linkages. However, only 7 of 23 hazard types specified by Kumasaki et al. [22] branched into two or more further consequences. The specificity of these linkages may have been due to the particular geographic context of Japan, and relevant constraints on documenting the cases in question.

The specific scopes of Kumasaki et al. [22] and Schauwecker et al. [21] have nonetheless led to coherent and easily interpreted models of cascading disaster linkages. Their research outcomes could be compared to highly coherent scenario trees generated by Marzocchi et al. [18] and by Neri, Le Cozannet, Thierry, Bignami, and Ruch [23]. The main practical difficulty is that the compact coherence of these models is not so readily generalizable to a fuller range of geographical contexts and cascading hazards.

Matrix models, like the one shown in Figure 1, provide a much less deterministic approach to the difficulties of predicting potentially cascading disasters because they highlight how several secondary hazards can be triggered by each event type.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Identification of hazard interactions. Reproduced from “Reviewing and visualizing the interactions of natural hazards” by J. C. Gill and B. D. Malamud, 2014, Reviews of Geophysics, 52, p. 14. Copyright 2014 by the authors. Reproduced under the Creative Commons Attribution license 4.0.

This approach to defining multi-hazard linkages was exemplified by the Gill and Malamud [2], the authors of Figure 1, who systematically reviewed a wide range of case studies published in white and grey literature. Their review was summarized by this matrix of linkages from a set of 21 primary
natural hazard triggers, listed vertically, and 21 types of secondary hazard events, listed horizontally. Grey triangles indicate a triggering or amplifying effect from a primary to a secondary hazard, resulting in a fairly exhaustive summary of which natural hazard types have historically triggered and/or worsened each other. Comparable matrices of inter-hazard linkages have also been produced by Tarvainen, Jarva, and Greiving [24], Kappes, Keiler, von Elverfeldt, and Glade [25], and by Mignan et al. [20].

2. Methods

As also exemplified by Gill and Malamud [2], the current methods were designed to fit the systematic literature review criteria from Boaz, Ashby, and Young [26]. These criteria require that a review: 1. Uses protocols to guide the process, 2. Is focused on a particular question, 3. Appraises the quality of the research, 4. Identifies as much of the relevant research as possible, 5. Synthesizes the research findings, 6. Aims to be as objective as possible, and 7. Is updated in order to remain relevant. The methods used to meet each one of these criteria are outlined in Table 1.

Table 1. Review criteria applied to the current research.

| Criteria | Application |
|----------|-------------|
| Follows a Protocol | Followed steps outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol [27]: Identification, Screening, Eligibility, Inclusion. |
| Answers a Research Question | Answered: 1. What are the infrastructural impacts resulting from rain-related hazards? 2. What are the mechanisms explaining how each impact was caused? |
| Appraises Research Quality | Reviewed academic journal articles, subject to relatively standardized peer review processes. All identified mechanisms subject to review from a disaster resilience and civil engineering expert. |
| Addresses as Much Research as Possible | Drew on more than 22,800 publications covered by Scopus and 21,177 covered by the Web of Science Core Collection. |
| Synthesizes Research Findings | Findings synthesized into a selective extension of a pre-existing matrix from Gill and Malamud [2]. |
| As Objective as Possible | Key parts of coding framework subject to inter-rater reliability testing. |
| Update in Order to Remain Relevant | All database searches updated within two weeks of initial review. |

Figure 2 summarizes the overall process used to conduct the current literature review. Identification, screening, eligibility, and inclusion processes were incorporated from the standard PRISMA [27] protocol. Search results were generated by searching journal article texts for the natural hazards listed above, their common synonyms, and the terms “infrastructure” and “case study”.

Initial screening excluded all titles and abstracts that did not indicate at least one ground collapse, flood, landslide, storm, storm surge, or tornado case study. Titles and abstracts that did not indicate infrastructure impacts were also excluded. Eligible article texts outlined at least one relevant natural hazard event, and at least one infrastructural impact triggered by those events. Eligible texts also specified mechanisms explaining how each infrastructural impact was triggered.

Subsequent, qualitative synthesis used a set of established definitions, as outlined below, to categorize the rain-related triggers documented by each case study. A set of more generic terms were used to define the infrastructural impacts of these triggering events, as also outlined below. Trigger and impact categorizations were tested for inter-rater reliability, using a random sample of case study literature. Mechanisms linking triggers to secondary impacts were also categorized at this stage. Mechanism categories initially matched the original case study literature as closely as possible. They were then subjected to expert review, before being refined and included as part of the current results.

All reliable trigger-impact results matched with a valid mechanism were added to a selective, and slightly modified, version of the Gill and Malamud [2] matrix which is shown in Section 3 of the current paper. Impact magnitudes, scales, and durations were also recorded during this process. However, as shown in Table A1 (Appendix A), these data were not consistent enough for a more quantitative synthesis.
Definitions

For consistency with the original Gill and Malamud matrix [2] (p. 11) of triggers and impacts, the same definitions were used to categorize rain-related natural hazard triggers:

**Avalanche**: The downslope displacement of surface materials (predominantly ice and snow) under gravitational forces.

**Ground Collapse**: Rapid, downward vertical movement of the ground surface into a void.

**Ground Heave**: The sudden or gradual, upward vertical movement of the ground surface.

**Landslide**: The downslope displacement of surface materials (predominantly rock and soil) under gravitational forces.

**Flood**: The inundation of typically dry land with water.

**Storm**: A significant perturbation of the atmospheric system, often involving heavy precipitation and violent winds.

**Tornado**: A violently rotating column of air pendant (normally) from a cumulonimbus cloud and in contact with the surface of the Earth.

Gill and Malamud [2] originally included **storm surge**, the landward movement of seawater resulting from a combination of heavy ocean-bound rainfall and tidal undulations, as a type of flood. This hazard was given its own category for the current research, to recognize the grave impacts of this increasingly common hazard. Frozen rain events, including hail, were excluded from the current analysis due to substantial differences between these types of hazards and more generic (liquid) rain-related triggers outlined by Schauwecker et al. [21]. Furthermore, and as shown in Figure 1, frozen rain events are not commonly triggered by liquid rainfall, being the focus of the current research.

Infrastructural impacts were not so difficult to define. This is because most people in the modern world are reliant on a broad range of infrastructures, as they go about their daily lives. Most people
are also familiar with the failure of these infrastructure types. The following, relatively simplistic, definitions were therefore used to categorize impacted infrastructure:

Agriculture: Land developed for farming crops or livestock. Effectively critical for subsidence communities or settings characterized by low food security.

Buildings: Any private or public building that does not form part of other infrastructure categories.

Electricity: Stationary structures built for the generation and supply of electricity.

Oil & Gas: Stationary structures developed for the collection, refinement, and supply of oil or gas.

Railway: Stationary structures built for the transit of trains across the land, and bridges built for the transit of trains.

Roads: Stationary structures built for the transit of motor vehicles across the land, and bridges built for motor vehicle transit.

Telecommunications: Stationary structures built for the transmission of communications, including wired and mobile telephones.

Water Supply: Stationary structures developed to supply potable water for consumption.

3. Results

Figure 3 provides a standard PRISMA-based summary of how literature identification, screening, eligibility, and inclusion progressed from an initial set of 934 search results from the Web of Science Core Collection and 415 from the Scopus database. Once duplicates had been removed, a very large number of case study articles were excluded due to plainly irrelevant titles and abstracts. One hundred and five article texts were then excluded for failing to meet all criteria outlined in Section 2. Table 2 lists events and locations addressed by the 71 case study articles that were retained for synthesis.

Figure 3. Progression through the systematic literature review protocol.
Table 2. Events and Locations Addressed by Eligible Case Studies.

| Year       | Event                  | Location             | Country           |
|------------|------------------------|----------------------|-------------------|
| Not dated  | Not named              | Flanders             | Belgium           |
| n.d.       | Not named              | Northeast Area       | USA               |
| 1831       | Not named              | Avarua               | Cook Islands      |
| 1871       | Cartago Floods         | Cartago City         | Costa Rica        |
| 1935       | Not named              | Avarua               | Cook Islands      |
| 1946       | Not named              | Ngatangiia           | Cook Islands      |
| 1962       | Not named              | Mid-Atlantic Coast   | USA               |
| 1967       | Not named              | Avarua               | Cook Islands      |
| 1974       | Not named              | Itmündener Wand      | Germany           |
| 1985       | Not named              | Tibet                | China             |
| 1987       | Cyclone Sally          | Avarua               | Cook Islands      |
| 1987       | Not named              | Martell Valley       | Italy             |
| 1988       | Not named              | Midui                | China             |
| 1993       | Not named              | Zêzere Valley        | Portugal           |
| 1994       | Phojal Nalla Flood     | Kullu District       | India             |
| 1995       | Not named              | Vorarlberg           | Austria           |
| 1997       | Bugobero Village Landslide | Bugobero            | Uganda            |
| 1999       | Not named              | New York City        | USA               |
| 2001       | Tropical Storm Allison | Texas                | USA               |
| 2002       | Not named              | Eilenberg            | Germany           |
| 2003       | Not named              | New York City        | USA               |
| 2004       | Cyclone Heta           | Avarua               | Cook Islands      |
| 2004       | Not named              | Hua-Qing Highway     | China             |
| 2004       | Not named              | Northern Apennines   | Italy             |
| 2005       | Cyclone Meena          | Avarua               | Cook Islands      |
| 2005       | Cyclone Nancy          | Matavera             | Cook Islands      |
| 2005       | Hurricane Katrina      | Gulf Coast           | USA               |
| 2005       | Not named              | New Orleans          | USA               |
| 2005       | Not named              | Apulia               | Italy             |
| 2005       | Not named              | Zêzere Valley        | Portugal           |
| 2005       | Not named              | Carlisle             | UK                |
| 2006       | March River Flood      | March River          | Austria           |
| 2007       | Cyclone Sidr           | Sarankhola Upazi     | Bangladesh        |
| 2008       | Not named              | Altay                | China             |
| 2008       | Not named              | Solent               | UK                |
| 2009       | Sextas Landslide       | Tena Valley          | Spain             |
| 2009       | La Selva Landslide     | Tena Valley          | Spain             |
| 2009       | Not named              | Tianmo               | China             |
| 2009 to 2011| Not named              | Calabria             | Italy             |
| 2010       | Central Indus Basin    | Muzaffargarh         | Pakistan          |
| 2011       | Not named              | Calabria             | Italy             |
| 2011       | Not named              | Gimigliano           | Italy             |
| 2011       | Not named              | San Fratello         | Italy             |
| 2011       | Not named              | Chia                 | Colombia          |
| 2011       | Not named              | Syracuse             | USA               |
| 2011       | Typhoon Roke           | Tokai, Japan         |                  |
Table 2. Cont.

| Year | Event              | Location              | Country |
|------|--------------------|-----------------------|---------|
| 2012 | Hurricane Sandy    | Connecticut           | USA     |
|      |                    | New Jersey            | USA     |
|      |                    | New York              | USA     |
| 2012 | Not named          | Beijing               | China   |
|      |                    | Haitong               | China   |
|      |                    | Xiqu                  | China   |
|      |                    | South-West Dieppe     | France  |
|      | Superstorm Sandy   | New York              | USA     |
| 2013 | Central Europe Floods | Not specified      | Germany |
|      | Colorado Floods    | Boulder County        | USA     |
|      | Cyclone Phailin    | Odisha                | India   |
|      | Not named          | Not specified         | Austria |
|      | Not named          | Peace River           | Canada  |
|      | Not named          | Garhwal Himalaya      | India   |
|      | Not named          | Piedmont              | Italy   |
|      | Not named          | Far East Russia       | Russia  |
|      | Not named          | Norrala               | Sweden  |
|      | Typhoon Haiyan     | Tacloban City         | Philippines |
| 2014 | Madeira River Floods | Madeira River       | Brazil  |
|      | Not named          | Acre State            | Brazil  |
|      | Not named          | Outer Carpathian      | Poland  |
|      | Not named          | Loch Insh             | Scotland|
|      | Not named          | Not specified         | Slovenia|
|      | Not named          | Värmland              | Sweden  |
|      | Not named          | Västra Götaland       | Sweden  |
| 2015 | Hurricane Patricia | Colima                | Mexico  |
|      | Not named          | Rest and be Thankful  | Scotland|
|      | Tropical Storm Erika | Not Specified    | Dominica |
| 2016 | Hurricane Matthew  | Princeville           | USA     |
| 2017 | Hurricane Harvey   | Houston               | USA     |
|      | Hurricane Irma     | Florida               | USA     |
|      | Not named          | Jushui Basin          | Japan   |

Labels were assigned to each case of infrastructural failure outlined in retained article texts, using qualitative coding. During coding, it became apparent that ground heave is commonly recorded as a mechanism linking certain events to infrastructure damage, rather than being recorded as a discrete hazard. This helped explain the lack of articles outlining other mechanisms linking this hydro-geological process to infrastructure damage. There was only one article detailing relevant avalanche impacts, so this type of trigger was subsumed within a broadened landslide category. There were no articles clearly outlining applicable tornado hazard events, although relevant dynamics may have been subsumed within case studies of storm events.

Inter-rater reliability testing for natural hazard trigger and infrastructural impact codes was applied to a random stratified sample from the first 30 articles that had been analyzed. This included a total of 10 different articles, concerning 22 different impact occurrences. Coding instructions were improved until the analysis was 86% consistent between the different researchers. The resulting set of 71 articles concerned 99 cases of specific natural hazards triggering infrastructural impacts. These cases had occurred in 37 different countries and had involved a sum of 24 different mechanisms. Table 3 lists each mechanism identified while coding triggers and impacts, and then refined to reflect expert feedback.
### Table 3. Mechanisms by natural hazard trigger and infrastructural impact type.

| Trigger          | Impacted Infrastructure | Mechanisms                                                                                                                                 |
|------------------|-------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|
| **Flood**        | Agriculture             | Blockage, Debris Transport, Erosion, Inundation                                                                                            |
|                  | Buildings               | Erosion, Force, Impact, Incision, Inundation, Scour                                                                                         |
|                  | Telecommunications      | Impact, Scour                                                                                                                              |
|                  | Electricity             | Burying, Debris Transport, Erosion, Force, Inundation                                                                                        |
|                  | Railway                 | Burying, Erosion, Force, Inundation, Subsidence, Undermining                                                                              |
|                  | Roads                   | Burying, Debris Transport, Erosion, Force, Impact, Incision, Subsidence, Sediment Transport, Subsidence, Scour                              |
|                  | Water Supply             | Contamination, Debris Transport, Inundation                                                                                                 |
| **Ground Collapse** | Buildings            | Subsidence                                                                                                                                |
|                  | Roads                   | Subsidence                                                                                                                                |
|                  | Agriculture             | Burying, Erosion, Displacement, Subsidence                                                                                                  |
|                  | Buildings               | Burying, Debris Transport, Erosion, Force, Impact, Settling, Subsidence, Translation                                                       |
| **Landslide**    | Electricity             | Displacement, Erosion, Force, Subsidence                                                                                                   |
|                  | Oil & Gas               | Displacement                                                                                                                               |
|                  | Railway                 | Sediment Transport                                                                                                                         |
|                  | Roads                   | Blockage, Burying, Debris Transport, Displacement, Erosion, Impact, Sediment Transport, Subsidence, Translation                             |
|                  | Water Supply             | Displacement, Erosion, Force, Subsidence, Translation                                                                                      |
|                  | Agriculture             | Inundation                                                                                                                                |
|                  | Buildings               | Inundation, Mold, Wind                                                                                                                     |
|                  | Telecommunications      | Wind                                                                                                                                       |
| **Storm**        | Electricity             | Lightning, Snow Load, Tree Fall, Wind                                                                                                       |
|                  | Oil & Gas               | Wind                                                                                                                                       |
|                  | Railway                 | Wind                                                                                                                                       |
|                  | Roads                   | Erosion, Ice, Inundation, Tree Fall, Wind                                                                                                  |
|                  | Agriculture             | Inundation, Salination                                                                                                                     |
| **Storm Surge**  | Buildings               | Debris Transport, Erosion, Impact, Inundation                                                                                               |
|                  | Roads                   | Debris Transport, Erosion, Inundation, Scour, Undermining                                                                                   |

Figure 4 combines the mechanisms shown in Table 3 with event frequencies, to display the validated linkages documented by eligible case study literature.

![Figure 4](image-url)
The bold numbers in each block indicate the total number of events where this linkage was well-documented by an eligible case study. The number of relevant mechanisms documented by the same literature is shown in brackets and plain type. There was often more than one mechanism involved in each event. This led to mechanism scores that are higher than event scores for some trigger-impact linkages.

The matrix shown in Figure 5 adds linkages from Figure 4 to rain-related triggers and impacts identified by Gill and Malamud [2]. Linkages between the latter set are marked with an asterisk. Linkages from natural hazards to natural hazards are shown in green, and linkages from natural hazards to infrastructural impacts are colored brown. The current matrix also includes infrastructure to infrastructure linkages, which were identified during the current review and have been colored blue.

![Figure 5. Matrix of triggers and impacts showing the number of cases in bold and the number of mechanisms in brackets.](image)

The current literature review also identified 149 infrastructural impact magnitudes or scales, and 55 failure durations. However, substantially variable data formats and measurement units, combined with a very low statistical sample, meant that these more in-depth review data were not suitable for standard meta-analysis methods. There were comparable issues with the way impact magnitudes had been recorded, or not recorded, in the case studies being reviewed. Although this meant that the analysis of impact magnitudes, scales, and duration data was beyond the scope of the current research, a table summarizing raw data is provided in Appendix A.

4. Discussion

A comparable literature review of hurricane-related impacts on health infrastructure and non-communicable diseases by Ryan et al. [28], fully reviewed a sum of 19 relevant articles. The Gill and Malamud [2] review included a much larger total of over 200 cases. However, the latter review included a much wider scope and less restrictive inclusion criteria. The current set of 99 event cases is positioned in between each of these literature review antecedents, as is the current research scope.

The lack of a documented link between storm surge and power outages reflects conclusions from prior research. Tonn et al. [29] compared longitudinal relationships between various hurricane-related hazards and critical infrastructure impacts but found that storm surge did not have a substantial effect on power outages. They concluded that wind and precipitation rates had a much stronger relationship with electrical infrastructure failure. By contrast, flooding impacts account for a substantial proportion...
of the current linkage matrix shown in Figure 5. This echoes findings from other research, which have highlighted the disproportionate frequency and consequences of flooding disasters compared to other types of natural hazard events. According to an overview of the global Emergency Events Database (EM-DAT) by Cuñado and Ferreira [30] (p. 1), “Floods are the most common natural disaster accounting for 40 percent of all natural disasters between 1985 and 2009”. Together with storms, flooding accounted for 67 percent of losses recorded over the same period [30].

As outlined in Sections 1 and 2, the current literature review does not provide a definitive list of all hazard linkages that have constituted cascading disasters. The current research was focused on events triggered by extreme rainfall and limited to case studies published in the English language. Even within these limitations, many relevant linkages would have been triggered by non-disastrous hazard events, outside the scope of generally disaster-focused case studies. Furthermore, the current literature review does not address how infrastructural impacts can amplify the impacts of natural hazard events and obstruct responding agencies [3], leading to highly complex disaster management scenarios. Caution is therefore required, to avoid over-interpreting the significance of the current results, and to remain mindful of how difficult it is to reliably predict the outcomes of complex interactions between diverse hazards, scales, and relevant social dynamics. As outlined in the Global Assessment Report on Disaster Risk Reduction [4], resulting disaster processes and impacts continue to surprise disaster management researchers and practitioners alike.

The type of matrix shown in Figure 5 can nonetheless be used to reduce initial CIA-ISM or other Delphi-type parameters into a more workably compact set of expert rated values. As shown in Figure 6, an expert rating matrix derived from Figure 5 can then be used to efficiently analyze the likelihoods of rain-related disaster linkages. Experts would simply be asked to assign probabilities to each of the blank white rectangles shown in Figure 6. This is how the current extension of the Gill and Malamud [2] matrix could be used to create more detailed scenarios of rain-related disaster cascades, including infrastructural impacts.

Figure 6. Matrix showing values for expert rating as blank white blocks.

Numerical values from Figure 5 can provide approximate base-rate linkage frequencies, between natural hazard triggers and infrastructural impacts. The same applies to approximations from the original matrices produced by Gill and Malamud [2]. Where permitted by an expert rating protocol, experts could be prompted to consider both sets of values. This would help mitigate a perceptual bias
called the base-rate fallacy, where individuals tend to inflate the likelihood of recent disaster linkages, by ensuring that each expert considers how relatively infrequently those linkages occur [12].

The literature review results summarized in Figure 5 can also be used to shape network-orientated analyses based on empirical data. In principle, this would involve assigning values to the type of linkages shown in Figure 7. Given appropriate data, relevant approaches to network analysis could provide a data-driven alternative to the type of scenario model generated by Schauwecker et al. [21]. Even without assigning values to the links shown in Figure 7, the current qualitative synthesis suggests that landslides and floods are particularly central nodes. However, a network analysis of quantitatively consistent data would produce a much more robust conclusion.

Figure 7. Network model framework summarizing literature review results.

Where possible, subsequent expert-rating protocols or network frameworks informed by the current research should still be subject to piloting and adjustment for specific geographic areas. This can include local expert feedback on possible alterations and additions, to avoid excluding salient linkages. The importance of these expert modifications was illustrated by Mignan et al. [20], who developed an expansive set of potential multi-hazard linkages through consulting with high school teachers who were specialized in natural sciences. The participants made several additions to hazard linkages that had been previously documented. Drawing on their own expert knowledge, Mignan et al. [20] concluded that each of these additional linkages was reasonable and that they could realistically occur.

5. Conclusions

Cascading disasters progress from one type of hazard to others, with consequences that are often devastating [3]. Rain-related cascading disasters are particularly frequent in many parts of the world, leading to repeatedly catastrophic impacts. These types of disasters are likely to become even more frequent due to climate change [7], and accelerating development in areas prone to relevant hazards [5,9].

Infrastructural impacts often result from natural hazard triggers. These types of impacts can form a particularly catastrophic and even amplifying aspect of cascading disaster scenarios [6]. However, to the best of the authors’ current knowledge, cascading linkages from rain-related natural hazards to infrastructural impacts have not previously been addressed by systematic case study reviews. To address this gap in scientific knowledge, the current literature review focused on mechanisms leading to infrastructural impacts in particular. This is how the current results have defined much of what is known about linkages between rain-related triggers and infrastructural impacts amounting to cascading disaster risk. A range of mechanisms constituting these linkages have also been identified by the current research.
A sum of 71 articles, concerning 99 case studies of rain-related disasters, were reviewed using a systematic literature review protocol. This was restricted to case studies detailing the mechanisms that have led to infrastructural impacts, and which had been indexed in high-quality academic journal databases. Twenty-five distinct mechanisms were identified as a result. These were combined with linkages previously identified through a systematic case study review by Gill and Malamud [2], to form a matrix running between five different natural hazards and eight types of infrastructural impacts.

The resulting matrix, shown in Figure 6, is principally designed for structuring expert rating analyses of rain-related cascading disaster scenarios. It can be used for Delphi-based, cross-impact analysis [19,31], as an initial set of rating parameters which reduce the time and attention required from expert raters. Base-rate approximations included in this matrix can be added to a range of approximations from Gill and Malamud [2], to mitigate known biases. The same matrix, or the graphic shown in Figure 7, could also be used to identify key parameters in longitudinal analyses of cascading rain-related hazard events. These key parameters could help to collect and structure available data, including social media. This is one way that the current results can be used to transparently structure a range of quantitative analyses, including analyses leveraging artificial intelligence.

Author Contributions: Conceptualization, T.J.H., F.E., K.C., W.G., and L.Y.; methodology, T.J.H.; validation, T.J.H. and F.E.; formal analysis, T.J.H.; investigation, T.J.H.; data curation, T.J.H.; writing—original draft preparation, T.J.H.; writing—review and editing, T.J.H.; visualization, T.J.H.; supervision, L.Y.; funding acquisition, L.Y. All authors have read and agreed to the published version of the manuscript.

Funding: The current research was funded by the National Natural Science Foundation of China, Project No. 71771113, and by the National Key Research and Development Program of China, Projects No. 2018YFC0807000 and No. 2019YFC0810705.

Acknowledgments: The authors gratefully acknowledge guidance from the following experts: Doctor Charlotte Brown of Resilient Organizations, Professor Didier Sornette of ETH Zurich and the Southern University of Science and Technology, Professor Junguo Liu of the Southern University of Science and Technology, and Professor Susan Cutter of the University of South Carolina. Validation assistance from Ms. Paola Yanez, from the Southern University of Science and Technology, is also gratefully acknowledged.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Review criteria applied to the current research.

| Event Cases                          | Trigger                      | Magnitude                         | CI Type                          | Impacts                          | Impact Scale | Impact Duration |
|--------------------------------------|------------------------------|----------------------------------|---------------------------------|----------------------------------|--------------|-----------------|
| Central Indus Basin Floods, Muzaffargarh, Pakistan, July 2010 | Flood                         | Approx. 1.04 ft/s peak discharge  | Agriculture                      | Cotton, rice and sugarcane crops destroyed | 106 ha       | 3 weeks         |
| Unnamed Event, Garhwal Himalaya, India, June 2013 | Flood                         | River gradient increase to 68 m/km | Agriculture                      | Destroyed                        | 17 ha of farmland | Not specified  |
| Unnamed Event, Garhwal Himalaya, India, June 2013 | Flood                         | River level increase of >30 m    | Agriculture                      | Destroyed                        | 3.3 × 10^6 km of farmland | Not specified  |
| Madeira River Floods, Madeira River, Brazil, April 2014 | Flood                         | 20 m rise in river level, above normal level | Buildings                        | Damaged                          | 0.65 km^2 of urban area, containing 27 public buildings >10 shops, four houses, two hotels, one big temple, one large motor workshop | Not specified  |
| Unnamed Event, Garhwal Himalaya, India, June 2013 | Flood                         | River level increase of approximately 32 m | Buildings                        | Destroyed                        | Not specified  |
| Hurricane Harvey Houston, USA, August 2017 | Flood                         | Not specified                     | Buildings                        | Hospital closed                  | 1 hospital    | 4 days          |
| Event Cases | Trigger | Magnitude | CI Type | Impacts | Impact Scale | Impact Duration |
|-------------|---------|-----------|---------|---------|--------------|----------------|
| Tropical Storm Allison, Texas, USA, June 2001 | Flood | 425 m$^3$/s, 765 m$^3$/s flow rate | Buildings | Damaged | 1 hospital | Not specified |
| Unnamed event, Zêzere Valley, Portugal, 1993 | Flood | Not specified | Buildings | Damaged | 1 hotel | Not specified |
| Unnamed event, Sirwolte, Switzerland, September 1993 | Flood | 150,000 m$^3$ of water from glacier lake breach. 400 m$^3$/s or 320 m$^3$/s peak discharge | Buildings | Destroyed | 1 house | Not specified |
| Unnamed event, New York City, USA, June 2003 | Flood | Not specified | Buildings | Damaged | 1 house | Not specified |
| Unnamed event, Altai, Russia, Autumn 2013 | Flood | 8,000,000 km$^2$ | Buildings | Damaged | 12,643 houses, 402 social facilities | Not specified |
| Unnamed Event, Chia, Colombia, April–May 2011 | Flood | 100-year event | Buildings | Damaged | 1455 urban plots | Not specified |
| Central Indus Basin Floods, Muzzaffargarh, Pakistan, July 2010 | Flood | Approx. 1.04 ft/s peak discharge | Buildings | Damaged | 1491 houses in flooded area, at a cost of USD 586,642 for replacement or repair | Not specified |
| Unnamed Event, Garhwal Himalaya, India, June 2013 | Flood | River gradient increase to 68 m/km | Buildings | Buried | $2.3 \times 10^4$ m$^2$ village | Not specified |
| Unnamed Event, Altay, China, Spring 2007 | Flood | Covering 386.39 km$^2$ | Buildings | Damaged | 2375 households and 6388 rooms | Not specified |
| Unnamed Event, Garhwal Himalaya, India, June 2013 | Flood | River level increase of $>30$ m | Buildings | Destroyed | 3 large hotels | Not specified |
| Unnamed event, New York City, USA, January 1999 | Flood | 76 mm/h of rainfall | Buildings | Damaged | Inundated to within 152.4 mm of ceilings | Not specified |
| Unnamed event, Carlisle, UK, January 2005 | Flood | Average depth of 1.79 m | Buildings | Damaged | 322,950 m$^2$ | Not specified |
| Tropical Storm Allison, Texas, USA, June 2001 | Flood | 425 m$^3$/s, 765 m$^3$/s flow rate | Buildings | Damaged | 4 hospitals | Up to 5 weeks |
| Eilenberg, Germany, August 2002 | Flood | Average depth of 1.91 m | Buildings | Damaged | 529,725 m$^2$ | Not specified |
| Tropical Storm Allison, Texas, USA, June 2001 | Flood | 425 m$^3$/s, 765 m$^3$/s flow rate | Buildings | Damaged | 6 hospitals | Up to 5 weeks |
| Unnamed event, Outer Carpathian, Poland, August 2014 | Flood | 2.5 above floodplain terrace, with flow of between 1.6 and 2.0 m$^3$/s$^{-1}$ | Buildings | Damaged | 70 farm buildings | Not specified |
| Unnamed event, Eilenberg, Germany, August 2002 | Flood | 3 m deep urban inundation | Buildings | Damaged | 765 buildings | Not specified |
| Unnamed Event, Garhwal Himalaya, India, June 2013 | Flood | Not specified | Buildings | Buried | Entire town | Not specified |
| Unnamed Event, Garhwal Himalaya, India, June 2013 | Flood | River gradient increase to 243 m/km | Buildings | Destroyed | Entire village | Not specified |
| Unnamed Event, Garhwal Himalaya, India, June 2013 | Flood | $-2.09 \times 106$ m$^3$ of debris flow | Buildings | Destroyed | Entire village | Not specified |
| Event Cases | Trigger | Magnitude | CI Type | Impacts | Impact Scale | Impact Duration |
|-------------|---------|-----------|---------|---------|--------------|----------------|
| Unnamed Event, Garhwal Himalaya, India, June 2013 | Flood | River level increase of 50 m | Buildings | Destroyed | Entire village | Not specified |
| Unnamed Event, Garhwal Himalaya, India, June 2013 | Flood | River level increase of 30–40 m | Buildings | Destroyed | Lower part of Govindghat village | Not specified |
| Unnamed Event, Garhwal Himalaya, India, June 2013 | Flood | River level increase of >30 m | Buildings | Destroyed | Hydropower plant | Not specified |
| Unnamed Event, Martell Valley, Italy, August 1987 | Flood | 300–500 m$^3$ of water released from reservoir | Buildings | Damaged and destroyed | Mainly affected three villages | Not specified |
| Cartago Floods, Cartago City, Costa Rica, October 1871 | Flood | More than 2 m of debris flow, leaving up to 1 m of mud | Buildings | Damage | More than 120 houses | Not specified |
| Unnamed Event, Central Indus Basin Floods, Muzzaffargarh, Pakistan, July 2010 | Flood | Approx. 1.04 ft/s peak discharge | Electricity | Power poles damaged | 30 power poles, at a cost of USD 50,000 | Not specified |
| Tropical Storm Allison, Texas, USA, June 2001 | Flood | 425 m$^3$ s$^{-1}$ flow rate, causing up to 12 m of flooding | Electricity | Power cut | 4 hospitals | Up to 4 days |
| Unnamed Event, Garhwal Himalaya, India, June 2013 | Flood | River level increase of >30 m | Electricity | Destroyed | Hydropower plant | Not specified |
| Unnamed Event, Garhwal Himalaya, India, June 2013 | Flood | Not specified | Electricity | Destroyed | Hydropower plant | Not specified |
| Unnamed Event, Garhwal Himalaya, India, June 2013 | Flood | River level increase of approximately 32 m | Electricity | Filled up | 1 hydropower plant | Not specified |
| Unnamed event, Martell Valley, Italy, August 1987 | Flood | 300–500 m$^3$ of water released from reservoir | Electricity | Significantly damaged | 1 village | Not specified |
| Unnamed Event, Garhwal Himalaya, India, June 2013 | Flood | River gradient increase to 243 m/km | Electricity | Buried | Powerhouse | Not specified |
| Unnamed event, March River Flood, Austria, 2006 | Flood | Average flow of 108 m$^3$ s$^{-1}$, peak flow of 1400 m$^3$ s$^{-1}$ | Railway | Damaged | >10 km of track | Not specified |
| Unnamed Event, Austria, June 2013 | Flood | Damaged | Railway | Destroyed | 1 bridge | Not specified |
| Unnamed Event, Vorarlberg, Austria, 1995 | Flood | Not specified | Railway | Derailment caused by 3 deaths and 17 severe injuries | 1 train | Not specified |
| Event Cases                  | Trigger          | Magnitude          | CI Type | Impacts                  | Impact Scale                      | Impact Duration               |
|-----------------------------|------------------|--------------------|---------|--------------------------|-----------------------------------|------------------------------|
| Central Europe Floods, Germany, 2013 | Flood | Not specified | Railway | Closed and interrupted | 75 track sections                  | Service disruptions of up to 5 months |
| Unnamed Event, Orrell, Sweden, August 2013 | Flood | 90 mm of rain in 3 h | Railway | Tunnel blocked | 14 km tunnel | 1 day |
| Unnamed event, New York City, USA, June 2003 | Flood | Not specified | Railway | Closed | Several subway lines | Not specified |
| Unnamed event, Vastra Gotaland, Sweden, August 2014 | Flood | Not specified | Railway | Embankment damaged | Up to 20 mm of embankment at 2 sites | Not specified |
| Unnamed Event, Xiogu, China, June 2012 | Flood | 100 m length and 210 m of debris flow | Roads | Destroyed highway section | >200 m of highway pavement | Not specified |
| Unnamed event, Varmland, Sweden, August 2014 | Flood | 87 mm/day rainfall | Roads | Closed | 1 highway | Not specified |
| Unnamed Event, Altay, China, Spring 2007 | Flood | Covering 386.39 km² | Roads | Damaged | 102 km | Not specified |
| Unnamed Event, Haitong, China, June 2012 | Flood | Not specified | Roads | Barrier lake formed | 160 m of subgrade | Not specified |
| Unnamed Event, Tianmo, China, July 2009 | Flood | Not specified | Roads | Sub-grade destroyed | 1 km | Not specified |
| Unnamed event, New York City, USA, June 2003 | Flood | Not specified | Roads | Blocked by up to 3 m of water | 2 intersections | Not specified |
| Unnamed event, Acre State, Brazil, 2014 | Flood | Not specified | Roads | Blocked | 22 municipalities | 60 days |
| Unnamed event, Piedmont, Italy, April–June 2013 | Flood | 20 debris flows | Roads | Destroyed | 400 m | Not specified |
| Unnamed Event, Garhwala Himalaya, India, June 2013 | Flood | River level increase of >30 m | Roads | Destroyed | 400 m | Not specified |
| Unnamed event, Russian Far East, Russia, Autumn 2013 | Flood | 8,000,000 km² | Roads | Flooded and damaged | 4346 km | 8 weeks |
| Unnamed Event, Garhwala Himalaya, India, June 2013 | Flood | ~15–20 m rise in river level | Roads | Blocked | 4 m diameter tunnel | Not specified |
| Unnamed Event, Xiqu, China, June 2012 | Flood | From barrier lake with average width of 60 m and average depth of 5–6 m | Roads | Destroyed highway section | 500 m of highway pavement | Not specified |
| Unnamed Event, Garhwala Himalaya, India, June 2013 | Flood | River level increase of approximately 30 m | Roads | Destroyed | 5 km | Not specified |
| Unnamed Event, Garhwala Himalaya, India, June 2013 | Flood | River gradient increase to 243 m/km | Roads | Destroyed | 80 km | Not specified |
| Unnamed Event, Xiqu, China, June 2012 | Flood | 22 simultaneous debris flows | Roads | Interrupted Sichuan-Tibet Highway, with 100 vehicles and at least 300 people trapped | Eight sections of highway | 10 days until highway restored |
| Event Cases | Trigger | Magnitude | CI Type | Impacts | Impact Scale | Impact Duration |
|-------------|---------|-----------|---------|---------|--------------|----------------|
| Tropical Storm Erika, Dominica, August 2015 | Flood | Up to 400 mm of rain within four hours | Roads Blocked | Main road | At least 3 years |
| Unnamed event, Zézere Valley, Portugal, October 2005 | Flood | 34 debris flows | Roads Closed | National Highway | Not specified |
| Unnamed event, Västra Götaland, Sweden, August 2014 | Flood | Not specified | Roads Bridge destroyed | One 5 m span bridge | Not specified |
| Hurricane Harvey, Houston, USA, August 2017 | Flood | Not specified | Roads Blocked | One highway, 200 road sections | 4 days |
| Martell Valley, Italy, August 1987 | Flood | 300–500 m³ of water released from reservoir | Roads Destroyed or buried | One village | Not specified |
| Unnamed Event, Calabria, Italy, 2009 to 2011 | Flood | Not specified | Roads Interrupted transit | Several hamlets isolated | Not specified |
| Unnamed event, New York City, USA, June 2003 | Flood | Not specified | Roads Closed | Several roads | Not specified |
| Unnamed event, Syracuse, USA, April 2011 | Flood | Not specified | Roads Closed | Several roads | Several days |
| Unnamed Event, Tibet, China, June 1985 | Flood | Not specified | Roads Closed | Sichuan-Tibet Highway | 7 months |
| Unnamed Event, Midui, China, July 1988 | Flood | Not specified | Roads Interrupted | Sichuan-Tibet Highway | More than 6 months |
| Unnamed event, New York City, USA, January 1999 | Flood | 76 mm/h of rainfall | Roads Inundated | Three neighbourhoods | Not specified |
| Colorado Floods, Boulder County, USA, September 2013 | Flood | Resulting from more than 500 mm of rain | Roads Blocked | Throughout City of Longmont | Not specified |
| Unnamed event, Västra Götaland, Sweden, August 2014 | Flood | Not specified | Roads Closed | Two roads | Not specified |
| Tropical Storm Allison, Houston, USA, June 2001 | Flood | 425 m³/s 765 m³/s flow rate | Water Disrupted | 1 hospital | Not specified |
| Central Indus Basin Floods, Muzaffargarh, Pakistan, July 2010 | Flood | 20 m rise in river level, above normal level | Water Damaged canal network | 114 km of irrigation network | Not specified |
| Madeira River Floods, Madeira River, Brazil, April 2014 | Flood | 20 m rise in river level, above normal level | Water Contaminated drinking water | 15% of municipal population | Not specified |
| Hurricane Matthew, Princeville, USA, October 2016 | Flood | Not specified | Water Water treatment failed | City-wide | Not specified |
| Unnamed event, Martell Valley, Italy, August 1987 | Flood | 300–500 m³ of water released from reservoir | Water Significantly damaged | One village | Not specified |
| Unnamed event, Apulia, Italy, October 2005 | Flood | 6.3 m impoundment | Water Damaged railway | 1 section of railway embankment | Not specified |
### Table A1. Cont.

| Event Cases                                                                 | Trigger                          | Magnitude          | CI Type         | Impacts                                      | Impact Scale | Impact Duration |
|----------------------------------------------------------------------------|----------------------------------|--------------------|-----------------|----------------------------------------------|--------------|-----------------|
| unnamed event, South-West Dieppe, France, December 2012                     | Ground collapse                  | 100,000 m³        | Buildings       | House on 40 m of cliff edge destroyed       | 1 house      | Not specified   |
| unnamed event, Northern Apennines, Italy, April 2004                        | Landslide                        | 100’s of shallow landslides | Agriculture | Damaged                                      | Not specified| 3 months        |
| unnamed events, Flanders, Belgium, n.d.                                     | Landslide                        | Not specified     | Agriculture     | Damaged                                      | Not specified| Not specified   |
| Phøjal Nalla Flood, Kullu District, India, August 1994                       | Landslide                        | Not specified     | Agriculture     | Arable land lost                            | Not specified| Not specified   |
| Bugobero Village Landslide, Bugobero, Uganda, December 1997                 | Landslide                        | 100,000 m³ moved 2.5 km | Agriculture     | Destroyed plantations                       | Not specified| Not specified   |
| unnamed event, Calabria, Italy, February 2010                              | Landslide                        | Length of ~400 m, width of ~120 m, an area of ~4.8 ha, estimated volume of ~720,000 m³, mean slope gradient of ~17°, and 3 m scarp | Buildings | Destroyed and damaged                       | 1 petrol station and a number of houses | Not specified |
| Sextas Landslide, Tena Valley, Spain, Summer 2004                           | Landslide                        | 8–10 m surface rupture, landslide 1.8 km long | Buildings | Damaged                                      | 1 ski-field chair lift | Not specified |
| unnamed event, San Fratello, Italy, February 2010                          | Landslide                        | 230 m long, including 23 m high reinforced earth wall | Buildings | Damaged                                      | 1 warehouse  | Not specified   |
| Typhoon No. 23, Kansai, Japan, October 2004                                | Landslide                        | 420 m long, 100 wide, with 35 m scarp | Buildings | Damaged                                      | 1 km²        | Not specified   |
| unnamed event, Teziutlán, Mexico, October 1999                             | Landslide                        | Not specified     | Buildings       | Buried                                       | Part of a village | Not specified |
| Sextas Landslide, Tena Valley, Spain, June 2008                             | Landslide                        | Not specified     | Buildings       | Damaged                                      | Snow cannon infrastructure | Not specified |
| unnamed event, Flanders, Belgium, n.d.                                     | Landslide                        | Not specified     | Electricity     | Damaged                                      | 1 cable      | Not specified   |
| Central Europe Floods, Germany, 2013                                       | Landslide                        | Not specified     | Railway         | Closed and interrupted                       | 75 track sections | Service disruptions of up to 5 months |
| unnamed event, Gimmigiano, Italy, January 2010                             | Landslide                        | Not specified     | Roads           | Destabilised                                 | 1 bridge     | Not specified   |
| Hurricane Patricia, Colima, Mexico, October 2015                            | Landslide                        | Not specified     | Roads           | Bridge destroyed                            | 1 bridge     | Not specified   |
| La Selva Landslide, Tena Valley, Spain, April 2009                          | Landslide                        | 145 cm/year movement | Roads          | Major damages                               | 1 road       | Not specified   |
Table A1. Cont.

| Event Cases                      | Trigger          | Magnitude                                                                 | Cl Type | Impacts            | Impact Scale | Impact Duration |
|---------------------------------|------------------|---------------------------------------------------------------------------|---------|--------------------|--------------|-----------------|
| Unnamed event, Calabria, Italy,  | Landslide        | ~400 m, width of ~120 m, an area of ~4.8 ha, estimated volume of ~720,000 m³, mean slope gradient of ~17°, and 3 m scarp | Roads   | Disrupted          | 1 road       | Not specified   |
| February 2010                    |                  | 8–10 m surface rupture, landslide 1.8 km long                              |         |                    |              |                 |
| Unnamed Event, San Fratello, Italy, February 2010 | Landslide | 300 landslides | Roads | Destroyed | 1 km² | Not specified |
| Unnamed event, Piedmont, Italy, April–June 2013 | Landslide | 100 m³ of earth movement | Roads |                     |              |                 |
| Unnamed Event, Rest and be Thankful, Scotland, December 2015 | Landslide | Not specified | Roads |                     |              |                 |
| Unnamed Event, Itmündener Wand, Germany, Winter 1974 | Landslide | Not specified | Roads |                       |              |                 |
| Peace River, Canada, May 2013 | Landslide | 8–10 m surface rupture, landslide 1.8 km long                              | Roads   | Destroyed          | 1 km²        | Not specified   |
| Unnamed Event, Calabria, Italy, 2009 to 2011 | Landslide | 100 m³ of earth movement | Roads |                     |              |                 |
| Cyclone Sidr, Sarankhola Upazi, Bangladesh, November 2007 | Storm | Category 4 cyclone, with average wind speed of 237 km/h | Agriculture | Cropland destroyed | 0.65 million ha | Not specified |
| Hurricane Sandy, Rockaway Peninsula, USA, October 2012 | Storm | Not specified | Buildings | Damaged | 16 of 46 primary health facilities | Not specified |
| Hurricane Sandy, Rockaway Peninsula, USA, October 2012 | Storm | Not specified | Buildings | Damaged | 24 of 46 primary health facilities | Not specified |
| Hurricane Katrina, New Orleans, USA, August 2005 | Storm | Category 4 hurricane, with winds up to 119 kph and rainfall of up to 550 mm within 96 hours | Buildings | Severe damage or destroyed | Most houses in Florida Keys County | Not specified |
| Hurricane Irma, Florida, USA, September 2017 | Storm | Not specified | Communications | Damaged or collapsed | Entire Gulf Area | Not specified |
| Event Cases                              | Trigger          | Magnitude                                                                 | CI Type          | Impacts                           | Impact Scale                  | Impact Duration |
|-----------------------------------------|------------------|---------------------------------------------------------------------------|------------------|-----------------------------------|------------------------------|-----------------|
| Unnamed Event, Slovenia, January to February 2014 | Storm             | Freezing rain of up to 150 mm/hr                                          | Electricity      | Power cut                         | 250,000 people            | Not specified   |
| Hurricane Irma, Florida, USA, September 2017 | Storm             | Category 4 hurricane, with winds up to 119 kph and rainfall of up to 550 mm within 96 hours | Electricity      | Power cut                         | 36% of Florida customers | 10 days         |
| Unnamed Event, Northeast United States, n.d. | Storm             | Not specified                                                              | Electricity      | Disrupted                         | Not specified               | Not specified   |
| Hurricane Katrina, Gulf Coast, USA, August 2005 | Storm             | Category 5 hurricane, with sustained wind speeds up to 215 km/h          | Electricity      | Damaged or collapsed               | Entire Gulf Area           | Not specified   |
| Cyclone Phailin, Odisha, India, October 2013 | Storm             | Category 5 hurricane, with sustained wind speeds up to 215 km/h          | Electricity      | Power cut                         | North and West of state, 1,500 MW of electricity transmission lost | 1 week          |
| Cyclone Phailin, Odisha, India, October 2013 | Storm             | Category 5 hurricane, with sustained wind speeds up to 215 km/h          | Electricity      | Rural power cut                   | Not specified              | 1 month         |
| Cyclone Phailin, Odisha, India, October 2013 | Storm             | Category 5 hurricane, with sustained wind speeds up to 215 km/h          | Electricity      | Urban power cut                   | Not specified              | 1 week          |
| Hurricane Sandy, New Jersey and New York, USA, October 2012 | Storm             | Approximately 1770 km storm diameter                                       | Electricity      | Disrupted                         | Not specified              | More than 1 week |
| Hurricane Sandy, Connecticut, USA, October 2012 | Storm             | Maximum wind speed of 16 m/s⁻¹                                            | Electricity      | Power cut                         | Over 500,000 customers    | Up to 9 days    |
| Unnamed event, Hua-Qing Highway, China, 2004 | Storm             | Not specified                                                              | Roads            | Disrupted                         | 20 meters, with a 10 m vertical face | Not specified   |
| Unnamed Event, Loch Insh, Scotland, December 2014 | Storm             | 496 mm of rain, with intensities up to 78 mm/h                            | Roads            | Blocked                           | 333 locations             | Not specified   |
| Typhoon Roke, Tokai, Japan, September 2011 | Storm             | From >460 mm of rain in under 24 hours                                     | Roads            | Blocked                           | 63 roads                   | Not specified   |
| Cyclone Sidr, Sarankhola Upazi, Bangladesh, November 2007 | Storm surge       | Up to 5.18 m                                                              | Roads            | Roads and embankments destroyed or damaged | 85% of region infrastructure | Not specified   |
| Cyclone Sidr, Sarankhola Upazi, Bangladesh, November 2007 | Storm surge       | Up to 60 km inland from 480 km of shoreline                              | Agriculture      | Cropland destroyed                | 0.65 million ha            | Not specified   |
| Odisha Super Typhoon, Odisha, India, October 1999 | Storm surge       | 0.7 m of skew surge, flooding 7 km² with up to 2.48 m of water            | Agriculture      | Farmland rendered infertile       | 200,000 ha                 | Not specified   |
| Unnamed event, Solent, UK, March 2008     | Storm surge       | 0.7 m of skew surge, flooding 7 km² with up to 2.48 m of water            | Buildings        | Flooded and damaged               | 150 buildings, including at least 30 houses, 100 caravans, and a ferry terminal | Not specified   |
| Event Cases | Trigger | Magnitude | CI Type | Impacts | Impact Scale | Impact Duration |
|-------------|---------|-----------|---------|---------|--------------|----------------|
| Hurricane Katrina, New Orleans, USA, August 2005 | Storm surge | 7.3 to 8.5 m high | Buildings | Inundated | 80% of the city under 6 m of water | 21 days |
| Hurricane Katrina, New Orleans, USA, August 2005 | Storm surge | Not specified | Buildings | Inundated | 80% of the city, including 228,000 housing units | Not specified |
|Unnamed event, Avarua, Cook Islands, December 1967 | Storm surge | Not specified | Buildings | Houses inundated | Affecting 270 residents | Not specified |
| Storm surge | Not specified | Buildings | Destroyed | All wooden constructions on the coastline | Not specified |
| Cyclone Sally, Avarua, Cook Islands, January 1987 | Storm surge | Waves 10 m higher than normal | Buildings | Heavily damaged | Avatiu Harbor | Not specified |
| Cyclone Sally, Avarua, Cook Islands, January 1987 | Storm surge | Waves 10 m higher than normal | Buildings | Damaged | Entire North Coast of Avarua | Not specified |
| Cyclone Sally, Avarua, Cook Islands, January 1987 | Storm surge | Not specified | Buildings | Destroyed | Half the town | Not specified |
| Cyclone Sally, Avarua, Cook Islands, January 1987 | Storm surge | 200 m incursion, to >30 m beyond high tide mark | Buildings | Inundated | Lowland settlement | Not specified |
| Cyclone Sally, Avarua, Cook Islands, January 1987 | Storm surge | 200 m incursion, to >30 m beyond high tide mark | Buildings | Hospital and other buildings damaged | Lowland settlement | Not specified |
| Cyclone Meena, Avarua, Cook Islands, February 2005 | Storm surge | Waves up to 14 m, surge reaching 360 m inland at 2 m above high tide mark | Buildings | Damaged | Much of North and Northwest coast | Not specified |
| Cyclone Sally, Avarua, Cook Islands, January 1946 | Storm surge | Not specified | Buildings | Church wall destroyed | 1 church | Not specified |
| Cyclone Sally, Avarua, Cook Islands, January 1987 | Storm surge | Waves 10 m higher than normal | Buildings | Shops inundated | 1 commercial center | Not specified |
| Cyclone Sally, Avarua, Cook Islands, January 1987 | Storm surge | Waves 10 m higher than normal | Buildings | Buildings damaged | One commercial center | Not specified |
| Cyclone Sally, Avarua, Cook Islands, December 1967 | Storm surge | Not specified | Buildings | Damaged, buried | 1 hotel | Not specified |
| Cyclone Sally, Avarua, Cook Islands, January 1987 | Storm surge | Waves 10 m higher than normal | Buildings | Restaurant destroyed | 1 restaurant | Not specified |
| Cyclone Meena, Avarua, Cook Islands, February 2005 | Storm surge | 10 m waves | Buildings | Inundated | Several areas | Not specified |
| Cyclone Nancy, Matavera, Cook Islands, February 2005 | Storm surge | Waves up to 14 m, surge reaching 360 m inland at 2 m above high tide mark | Buildings | Damaged | Several buildings | Not specified |
### Table A1. Cont.

| Event Cases                  | Trigger          | Magnitude                          | CI Type                      | Impacts                  | Impact Scale                | Impact Duration |
|------------------------------|------------------|------------------------------------|------------------------------|--------------------------|-----------------------------|-----------------|
| Cyclone Nancy, Ngatangiia Harbour, Cook Islands, February 2005 | Storm surge      | Not specified                       | Buildings                   | Damaged                  | Several buildings           | Not specified  |
| Unnamed event, Mid-Atlantic Coast, USA, 1962 | Storm surge      | Not specified                       | Buildings                   | Destroyed urban structures | Up to 32 km inland          | Not specified  |
| Unnamed event, Solent, UK, March 2008 | Storm surge      | 0.7 m of skew surge, flooding 7 km² with up to 2.48 m of water waves up to 14 m, surge reaching 360 m inland at 2 m above high tide mark | Roads                       | Flooded                  | 22 roads                    | Not specified  |
| Cyclone Meena, Avarua, Cook Islands, February 2005 | Storm surge      | Waves up to 10 m higher than normal | Roads                       | Damaged                  | 500 m of coastal road       | Not specified  |
| Cyclone Sally, Avarua, Cook Islands, January 1987 | Storm surge      | 1.5 m                               | Roads                       | Destroyed                | 6 km of coastal road        | Not specified  |
| Cyclone Sidr, Sarankhola Upazi, Bangladesh, November 2007 | Storm surge      | Waves 10 m higher than normal      | Roads                       | Roads and embankments destroyed or damaged | 85% of regional infrastructure | Not specified  |
| Unnamed event, Avarua, Cook Islands, December 1967 | Storm surge      | Not specified                       | Roads                       | Eroded, buried           | 1 coastal road              | Not specified  |
| Cyclone Heta, Avarua, Cook Islands, January 2004 | Storm surge      | 10 m waves                          | Roads                       | Inundated and damaged    | 1 seawall road              | Not specified  |
| Superstorm Sandy, New York, October 2012 | Storm surge      | 4.3 m                               | Water                       | Damaged wastewater infrastructure | 560 million gallons of untreated sewerage released | Not specified  |

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