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COMPOUND DISASTERS AND COMPOUNDING PROCESSES

Implications for Disaster Risk Management

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Introduction

A growing body of literature in disaster risk management begins to recognize the important connections between the otherwise unrelated disaster events. According to recent typology advancement, in some cases, the events in question can be "sequential", in that the first event directly causes the second to occur, which may in turn lead to the third and fourth, etc., under certain circumstances (EISNER, 2013). An example of this is the Great East Japan Earthquake in March 2011 which immediately caused a massive tsunami, which in turn destroyed the Fukushima Daiichi nuclear power plant. In other cases, the events in questions are coincidental but collocated in time and space, resulting in a compounding of the impact which easily overwhelms the ability of the local community and even the national government to respond. An example of this is the Great Kanto Earthquake and the subsequent fire in 1923 in Japan, which destroyed much of the then Tokyo and resulted in about 143,000 deaths. Eisner also discusses other cases of interest where one event is related to another.

The need to recognize and understand the possible and probable occurrence of multiple disaster events in one location and at about the same time, and how one event might precipitate another—thus causing an otherwise single event to become multiple—is great and growing. For the aggregate impacts of such multiple events can be devastating to any community or, indeed, a nation. With increased populations, often heavily concentrated in a few urban locations, and increased levels of economic development, both the human and economic impacts of a multiple occurrence can be much greater now and probably even greater in the future than in the past.[1] True, with increased levels of economic development and the new superior technologies associated with it, communities and countries may also develop safer ways of engaging in various economic and social activities, and be able to build stronger systems of disaster prevention and management technologically, organizationally and socially. Nevertheless, such new technology driven systems, usually involving very high levels of complexity and coupling, could also imply that a failure is inevitable (PERROW, 1999).

A study that is reputed to have foretold an event like the Great East Japan Earthquake of March 2011 to occur in East Japan, but which was not published before that event took place, described such devastating multiple occurrences as "catastrophic" disasters (KAWATA, 2011). To Kawata, catastrophic disaster events have three key characteristics: extensive, compound and prolonged. These characteristics are by no means unrelated and independent, however. Catastrophic disasters tend to be "super-wide" in areas of damage; the recovery following them can be prolonged, precisely because the damage is huge and extensive; but above all, catastrophic disasters are likely to be caused by multiple disaster events. These Kawata call "compound disasters", which he defines as double- or triple-punch

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[1] See Kawata (2011) for an analysis of the possible impact to Japan if a combined onslaught of a massive earthquake and typhoon takes place in the Tokyo metropolitan area. Note that the Kawata study, as most studies of the impact of disasters do, only considers the "direct" impact of an anticipated disaster, excluding the "indirect impact", which would include any wider human and economic repercussions of the disaster, including, for example, the loss of production due to the disruption caused by the disaster to the local, national, regional and indeed international supply chains and productions networks. In particular, as regional and international supply chains are becoming more common, the impact of a local disaster can now be much more widely felt.

disasters. Because these events are collocated in time and space, the striking of the initial event may knock out any resilience that the affected community or area might otherwise have to the next event, causing the impact of the next event, and the aggregate impact, to multiply. Such impact multiplication will, of course, severely undermine the ability of the local communities to recover.

While there is increased attention to compound disasters because of the potential scale of damage these disasters can inflict, there have actually been few systematic attempts to study the reasons for and causal mechanisms generating compound disasters. This paper aims to make such an effort, by providing a typological framework for characterizing different types of compound disaster. Specifically, it aims to consider the multitude of ways in which one disaster may precipitate another, either by directly causing it (if there would otherwise not be the second event), or by severely impairing the resilience and response of the communities in question to the second event. Effective and successful reduction and management of compound disaster risks critically depend on our improved understanding of these causal connections and mechanisms.

Compound Disasters and Compounding Processes: A typological framework

Any disaster entails a potentially compounding process, that is, one event or component event precipitating another. In some cases, this process may be cut short early enough; in others, it is allowed to be played out extensively enough as to cause multiple (component) events. Thus viewed, what are currently referred to in some literature as "compound disasters" are but a subset of cases where the compounding process is played out to such an extent that it caused multiple events to occur, resulting in extensive losses of human lives and economic damages, even on a catastrophic scale. This section develops a framework for systematically characterizing processes and mechanisms whereby one disaster event may lead or contribute to another.

Single Disaster

Let there be two disasters, the prior disaster D_1, and the posterior disaster D_2. Before we introduce D_2, however, we shall consider D_1 in isolation as if this is a single disaster. According to the standard model of a single disaster, before the occurrence of the actual disaster event, a disaster has three component causes: the occurrence of a hazard, the exposure to it by a community or population, and the vulnerability of the exposed community or population to the hazard.[2] An often used diagram is given in Figure 1a,[3] which portrays the conceptual relationships between these components and how they together cause a disaster.

Needless to say, before the event, these are all probabilities. However, while the probability of hazard may be thought of as independent, that of exposure is best considered as

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[2] For standard definitions of a hazard, exposure and vulnerability (UNISDR, 2009). Unless otherwise explicitly given, all the concepts and terms related to disaster, disaster risk reduction (DRR) and disaster risk management (DRM) used in this paper follow UNISDR (2009).

[3] http://www.focusproject.eu/web/focus/wiki/-/wiki/ESG/Risk+reduction; jsessionid=C1BE7F4BD0F10F1F3108FBBAAF92668A (Accessed 4 Jan. 2014)

conditional (probability of being exposure to the hazard if and when it occurs), and so is the probability of being vulnerable to the hazard having been exposed to it. Figure 1b provides an alternative description of the relationship between the three concepts, recognizing exposure and vulnerability being conditional probabilities.

In notation, let d_1 be the potential impact of the disaster event, h_1 the magnitude of the hazard that triggers the event, e_1 the level of exposure by the community or population in question to the hazard, and v_1 the degree of vulnerability of the exposed community or population to the hazard. Then the following relationship holds:

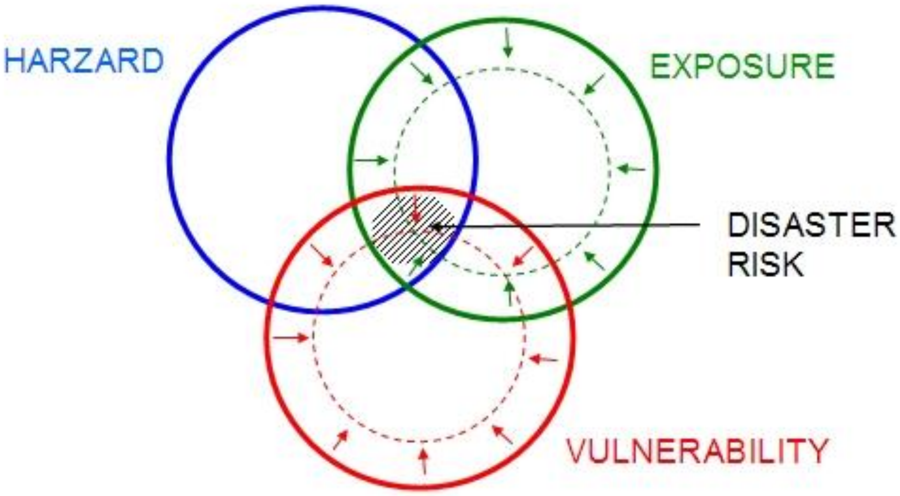

Figure 1a: The risk triangle

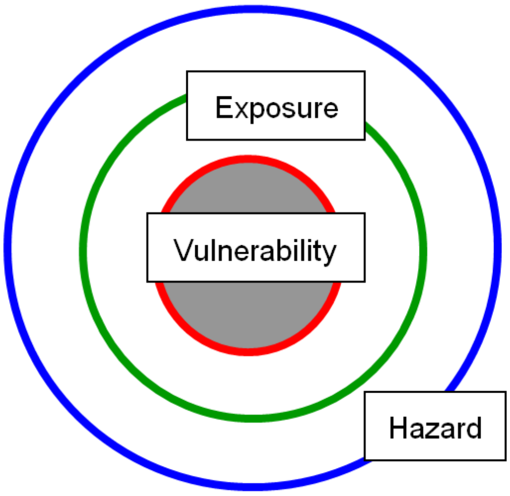

Figure 1b: Disaster risk and conditional probabilities

$$\text{Prob}(d_1) = \text{Prob}(h_1) \text{ X } \text{Prob}(e_1 \text{ l } h_1) \text{ X } \text{Prob}(v_1 \text{ l } e_1 \text{ l } h_1)$$

Note that the probabilities on the right hand side might each be a binary distribution, or in other way discretely distributed, or indeed continuously distributed, depending on the need, and the availability of prior information and data necessary for the kind of risk assessment and decision making required.

As we will see in much greater detail later, the precipitation by one disaster event of another can happen at the level of hazard (the occurrence of one hazard triggers that of another), or because the devastation brought about by the first disaster—in turn because of high exposure and poor vulnerability to h_1—increases the exposure and vulnerability of the communities in question to a second hazard when it strikes.

After a disaster event occurs, responses by the communities or populations in question to the disaster then begin. These usually follow the sequence of immediate rescue and relief (r_{f1}), rebuilding of community (r_{b1}), reconstruction of damaged homes and infrastructures (r_{c1}), and eventually—hopefully—full recovery of normal economic and social life (r_{v1}). Often the design of these works and activities, the manner in which they are carried out, and sometimes even the speed with which they are executed, may all have a "compounding effect" in terms of directly causing a subsequent disaster or making it much worse than otherwise.

While it is customary to decompose the process of a single disaster into these causal components and response phases, it is often not recognized, or at least not sufficiently explicitly discussed, that each of these causal components and phases could potentially cause or contribute to a follow-up disaster, by directly or indirectly impacting some of the same causal components leading up to the follow-up disaster event and/or its response phases. The history of disasters provides ample evidence that some of these causal connections are, in fact, quite real, and are by no means imaginary.

Multiple Disasters

Figure 2a indicates the possible causal connections—in this case leading from r_{c1}—to each counterpart causal component and response phase for the posterior disaster, D_2. Note that in both cases, D_i represents the entire disaster process consisting of a pre-event stage, E_i, and post-event stage, R_i. The pre-event stage consists of all possible phases—not specified—leading right up to the impact point of the disaster, represented by a line. In some cases, the impact point can be short and sharp, being indeed true to its name (as in the case of an earthquake). In other cases, the impact point can be prolonged (as in the case of a Typhoon, a forest fire or flood). We will return to the second situation of longer impact points shortly. For now, we assume the impact point to be short and sharp.

However, while in principle the process of the first event precipitating the second may be decomposed down to the level of each causal component and each response phase, as a first cut in this kind of analysis, we shall in this paper collapse some of these causal components and phases into more meta-entities. In particular, we shall collapse all the post-event response phases into a single post-event response phase for D_1, denoted as R_1, even though in some of our case studies reference to certain specific component response phase may be made. Also, for pre-event causal components, no attempt will be made to finely distinguish between exposure and vulnerability. Rather, following the occurrence of h_1, there is simply disaster impact d_1. For an understanding of the causes responsible for d_1—if that is indeed one's interest—a clear distinction between exposure e_1 and vulnerability v_1 is indeed important, However, for a focus on how E_1 impacts D_2, that level of fine distinction is not necessary. The reduced map of the potential causal connections between D_1 and D_2 is presented in Figure 2b.

It should also be noted that, in terms of the perspective adopted here, although the history of actual disasters can tell us much about those causal connections that did take effect in particular situations, those that could have taken effect but did not—perhaps because they were successfully prevented from taking effect by some human action—can easily escape our attention. Yet a full understanding of the extent of the potential causations requires us to study and understand not only the negative part of a disaster experience (those causations that were not prevented), but also the positive part (those causations that could have taken effect but were successfully prevented). In our empirical examples, where possible we shall highlight the latter type of positive experience, although in most cases historical records tend to record what actually happened rather than the hypothetical counterfactuals.

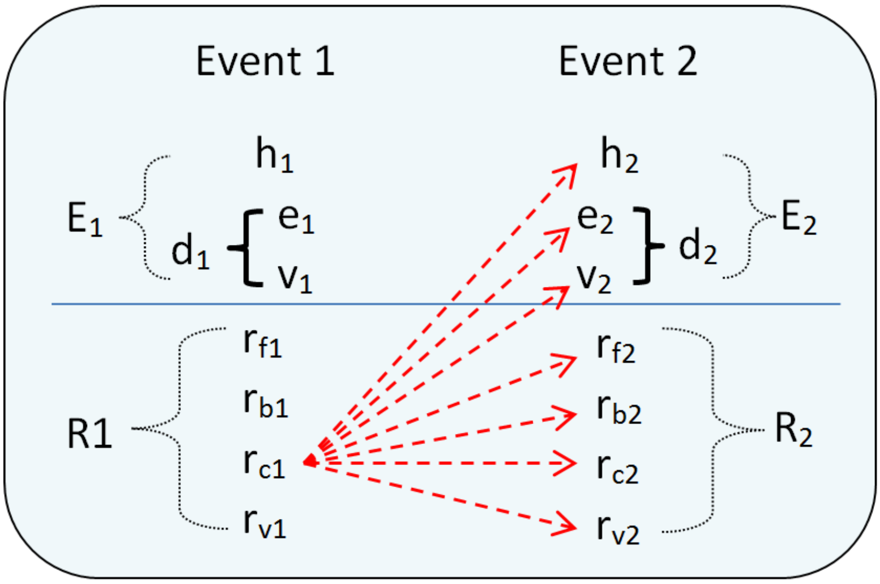

Figure 2a: Multiple disasters

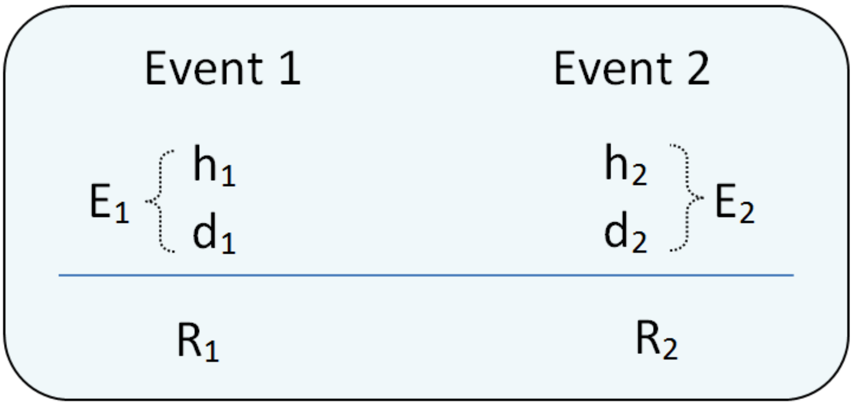

Figure 2b: Simplified multiple disasters

Multi-hit disasters

We now return to the question of impact point. As noted, while some disasters display a short and sharp impact point, others appear to have prolonged impact points lasting for days if not weeks. The striking of a single-hit earthquake causing a high number of deaths and huge economic damages to the communities in the vicinity is an example of the former. Note the emphasis on "single-hit". Some earthquakes have serious pre- or after-shocks which can be devastating in impact as well. In these cases, since the shocks are considered to be closely related and have to do with the same hazard force, they can be considered to be one disaster event, rather than multiple disaster events. However, since it produced shocks spaced out in time, its impact point is also spaced out in time.

In fact, the point about the impact point is related to another larger issue. A multi-shock earthquake may be called a "multi-hit" but single event. Although some aspects of the analytical framework developed above for studying multiple disaster events may be used to analyze the between-shock or between-hit causations, and advise on policy, it would not seem that very much more can be gained beyond what may already be understood. For example, after a major devastating tremor, most people would tend to be very vigilant against another, possibly minor, tremor almost immediately to follow, and would live in open air or make-shift tents. And since there is little time between the shocks—that is, if an after-shock does come—there is not much scope to strengthen one's resilience against the second shock if it does come, beyond the precaution one is already taking, for individuals and for the community as a whole. And in the case of earthquakes, there is of course little one can do to contain the hazard process that would cause the second shock.[4]

Of more interest is another kind of multi-hit disaster. Here, the disaster is caused by the same hazard event, but whether and how it continues to strike a community or population beyond its first bout of force is dependent on how people respond to this first bout of force. That is, here, what one does in response to the first hit does directly impact the likelihood and scale of the second hit, by influencing or controlling the physical process that would produce this second hit. A good example of this is forest fire. If one failed to respond adequately enough to control the initial bout and completely eliminate the danger, then a second bout, and possibly an even worse one, would be highly likely.

In the case of forest fire and, indeed, contagious decease, and in some cases floods, adequate responses to the first strike of the hazards in question are critical. Indeed, communities and the authorities in question should rather err on the side of over-response than under-response. A disproportionate massive response to some initial sparkles of fire, some initial cases of infection, or some initial buildups of water upstream, may seem excessive and a waste of resources. However, if these initial dangers are not removed, when they quickly build up to a gigantic scale overwhelming a community's or population's ability to respond and control, the costs in human and economic terms could be a lot higher,

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[4] Note that here we use the term "multi-hit" as opposed to "multi-punch" which Kawata (2011) adopts for reference to multi-event compound disasters. In short, "multi-punch" is about compound or multi-event disasters, while "multi-hit" relates to multiple bouts of the same hazard force afflicting a community or population.

making the apparent over-allocation of resources in controlling the initial bouts look rather insignificant.

Again, such between-hit causal linkages would seem to be perfect choices for analysis using the framework just developed for treating multiple events. However, as said previously in regard to multi-hit earthquakes, such linkages are by and large well understood, and in many cases sufficient precautions are taken by the communities and populations in question. The fact that in some cases the necessary precautions are not taken is unlikely to be because of a lack of understanding of these between-hit linkages, but because for various economic, social and political reasons, the communities and populations in question failed to act as they should.

Could the same be said in relation to between-event linkages? Not quite. Although between-event causal linkages are sometime recognized, they have by and large been off the research and policy radar screen. The recent call for increased attention to compound disasters is largely driven by a concern with the potential catastrophic impact compound disasters can bring. But as pointed out already, to effectively reduce and manage compound disaster risks, there must be an adequate understanding of inter-disaster causal linkages and connections.

In developing a framework for studying between-event linkages, it is important to conceptually separate these linkages from those between-hit linkages which strictly apply to a single event. Ultimately, of course, this depends on how one defines a disaster event as opposed to a hit within an event. Our notion of a disaster event is in line with the commonly used one, which categorizes a disaster event primarily by the same striking of a hazard. There may be multiple hits within a single disaster event, but these hits are united by the same exercise of a hazard force that causes them.[5]

Although between-hit linkages are not the focus of our interest, in analysis of between-event linkages, issues of multi-hits and inter-hit linages will inevitably arise. Figure 2c provides a framework for analysing between-hit linkages. Any response which fails to adequately respond to the previous hit, either by eliminating the hazard entirely, or removing vulnerability sufficiently to a second hit, will result in a second hit, until the hazard is eliminated, at least within the time frame in question. The framework shares some similarity with the one developed for analyzing between-event linkages. The various hits belong to the same hazard event, and occur broadly at the same location and in about the same time. Each hit, however, causes damage d, followed by response r. The subscript numerical numbers and English letters indicate the parent event and the bout or hit in question, respectively. For example, for bout a in event 1, after hit h_{1a}, there is damage d_{1a}, followed by response r_{1a}. If this response is not more than adequate in responding to hit h_{1a}, then

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[5] Not only conceptual clarity but also convention seem to be involved in categorizing a given disaster event as a disaster event in its own right, rather than as one of the "hits" of some other event. Location and intervening time are some of the factors, even though the hazard causes of the two "events", or "hits", may be traced to the same origin. A good example is New Zealand's Christ Church earthquake in February 2011, which has been treated as a separate geophysical disaster but it has also been argued by some that it was caused by a follow-up tremor following an early one hitting Canterbury, New Zealand, some 40 km away and some five months back (BRADLEY and CUBRINOVSKI, 2012).

there will be hit h_{1b}, causing damage d_{1b} (or if h_{1b} is beyond the influence of human action, there will be d_{1b} following h_{1b}), etc. Whether or not the response is adequate enough is indicated by the inequality sign.

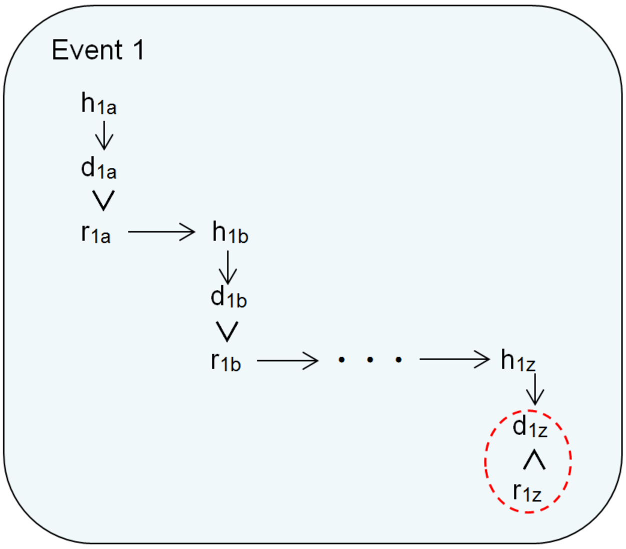

Figure 2c: Multi-hit disasters

Determinants of inter-event linkages

While recognition of the scale of inter-event linkages is important, understanding the factors responsible for the nature and extent of such linkages is even more critical, as any intervention to reduce these linkages must be based on an understanding of these determinants.

Factors determining if and how the compounding process associated with an initial event is played out include physical and human factors. Depending on the nature of the initial event, the former can include hydro-climatological and geological factors (e.g. an earthquake causing a tsunami, or prolonged rainfalls causing a landslide). The latter may include human activities and policies at a macro level, such as urbanization, energy and environmental policies and actions, and community-level factors, including the usual array of measures to reduce particular hazard risks locally, to reduce the level of potential exposure and vulnerability to them before they strike, and the relief, recovery and reconstruction activities following a disaster. What this paper argues is that just as there are many potential ways for one disaster event to lead to or impact another, there are also many ways to potentially reduce or even eliminate such linkages.

It should be noted, though, that although one may broadly distinguish between physical and human factors, where presumably only human factors are potentially subject to intervention, even physical factors or processes can sometime involve a human input. Prolonged rainfalls causing a major landslide because of the destruction to the local ecosystem is an example. But even the prolonged rainfalls themselves could be due to change in weather patterns which may in turn, as an accumulating body of scientific evidence indicates, have to do with human activities. It used to be thought in the study of disasters that humans do not have a role in shaping "natural hazards". With global warming and climate change induced by human action, that supposition is beginning to be challenged.

Nevertheless, although even the underlying natural hazard processes may involve a human role, the kind of interventions we are exploring in order to reduce the inter-disaster linkages must relate to more immediate factors determining the disaster events in question. To this extent, physical processes are indeed by and large physical and beyond human control. But even accepting this limitation, there is still ample scope for human action, and a role for policy. These would primarily relate to our actions on exposure and vulnerability before an event, and responses after it.

Finally, there is one area where human action is particularly relevant to the study of inter-event linkages. Centuries of development have enabled us to develop and depend on efficient but complex technological systems. However, as our reliance on these systems increases, the impact of any failure also multiplies. As these systems are characterized by a high level of coupling of the components, the likelihood of a failure can be high, as Perrow (1999) well argues. Moreover, there is increased scope of interaction between these risks and natural hazard processes, as demonstrated by the failure of the Fukushima Daiichi nuclear power plant. It is important for societies to come up with more reliable technological systems, but it is also important for communities and populations to be prepared for possible failures of these systems in the middle of a natural disaster, caused by an unsettling of the environment these systems depend on, following the occurrence of a natural hazard.

Compound Disasters: Some cases

In this section we review some disaster cases to illustrate the kind of inter-event linkages that may exist, in order to bring home the point that such linkages are real and can be important in impact, and they need to be taken up seriously in studies of disasters. In particular, in selecting these cases, we emphasize the natural hazard-technology interactions and the importance of timely and adequate response to an initial event. We consider not only the negative but also positive experiences in making such responses.

A. The Great Kanto Earthquake and Fire (Japan, 1923)

This is a well-known, well-recorded and well-studied case of compound disaster. It shows how one disaster event (an earthquake) can catalyze another hazard (a fire) which, because of a high level of vulnerability that existed among the population to this second hazard, and because the first disaster event also knocked out crucial infrastructures within the community to respond to the second hazard, caused a catastrophic disaster involving a huge number of deaths.

The Great Kanto Earthquake with a magnitude 7.9 struck the Kanto region of Japan on September 1, 1923. It was the most powerful earthquake to have struck the region in the recorded history. Japan’s capital city Tokyo is located in this region. With a high concentration of population, the earthquake and the ensuing fire it partially caused became the deadliest disaster in the history of Japan (SCHENCKING, 2013).

Because the earthquake struck at noon of the day, when many families were cooking their lunch, fire from the toppled cooking stoves quickly lit up debris in the collapsed wooden buildings. At the same time, a distant typhoon fanned the fire, causing conflagrations across the Tokyo city. The fire was so strong that it took nearly two full days to be completely put out.

The same earthquake also caused a tsunami with waves as high as 12m to hit the Sagami bay causing death of 800 people. The combined death toll from the earthquake, the fire, and the tsunami was 143,000, with an estimated direct economic loss of 600 million US$ at the time of disaster (EM-DAT).[6]

Figure 3a indicates the between-event linkages in this case. The initial earthquake is event 1, the ensuing tsunami event 2, and the conflagration event 3. Since event 2 was comparatively minor in scale and impact, our focus is on the linkages between events 1 and 3. The impact of event 1, d_1, catalyzed h_3. Further, because most of the houses at the time in Tokyo city were built of wood, vulnerability to fire (v_3) was understandably high. When fanned by strong winds, this high level of vulnerability would already have caused serious fires in the city. However, the matter was made even worse because the earthquake also damaged roads and water mains, preventing any effective fire-fighting and allowing the conflagrations to spread and intensify across the city, until no further structures were available to fuel them on their way. The majority of the estimated number of deaths was as a result of the fire (SCAWTHORN et.al, 2004).

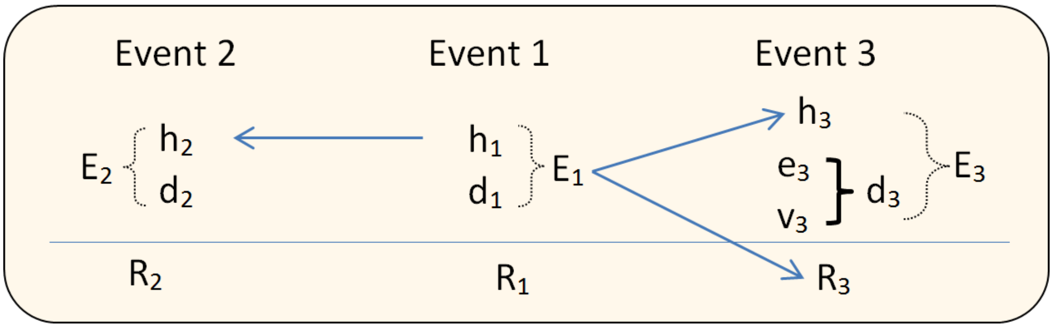

Figure 3a: Compounding process of the Great Kanto Earthquake and Fire

B. The Taiwan Earthquake (1999)

The previous case provides an example of how one natural disaster event can lead to another. But a natural disaster event can also catalyse some otherwise dormant technological hazard and result in a technological disaster, with a huge economic and possibly human impact. The case of the Taiwan Earthquake in 1999 is one such example.

The earthquake in question occurred in central Taiwan on September 21, 1999, with a magnitude of 7.6 (USGS). The effects of the earthquake were most severe in central Taiwan, where buildings and major bridges were badly damaged, with many having to be torn down later. There earthquake and its aftershocks also caused a total of 132 landslides. Some these landslides were responsible for extensive losses of live as rock-falls crushed houses (SCHIFF and TANG, 2000). The total death toll due to the earthquake was 2,264 (EM-DAT).

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[6] http://www.emdat.be/database (Accessed 5 Jan. 2014)

In terms of economic losses, the direct impact of the earthquake was, in fact, relatively minor, compared with the massive impact caused by the follow-up event. The earthquake caused an electricity transmission tower to collapse, resulting in widespread transmission failures and power station stoppages, as well as forcing the temporary automatic shutdown of the three nuclear power plants in Taiwan. National electricity provider Taipower stated that a day after the quake power had been restored to only 69% of the country, reflecting the extent of the power stoppage.

The power stoppage hit hard the high-tech semiconductor and RAM manufacturers in the Hsinchu Science Park some 120 km from the epicentre. The greater part of the economic damagees associated with the whole disaster was, in fact, accounted for by the losses inflicted here due to the sensitive nature of the production processes and market conditions. Taiwan accounted for a significant proportion of the world supply of semiconductor and RAM at the time. Production stoppages at the Hsinchu Science Park and other factories caused computer memory prices to triple on world markets. This was, in fact, the first time that global production networks and supply chains were affected by a disaster. The total economic damage of the disaster is estimated to be 14.1 billion US$ (EM-DAT).

Figure 3b highlights important between-event linkages for the case. The earthquake is event 1, and widespread power failure event 2. Although the earthquake did not bring any direct physical damage to the Hsinchu Science Park, because of the highly tight coupling nature of the technology and production systems involved, the power failure the earthquake caused did lead to a massive breakdown of these systems. In turn, because the productions were part of a wider network of global supply chains, the failure in fact caused major disturbances to global production and supply of the products in question, as well as huge losses to the Taiwanese manufacturers.

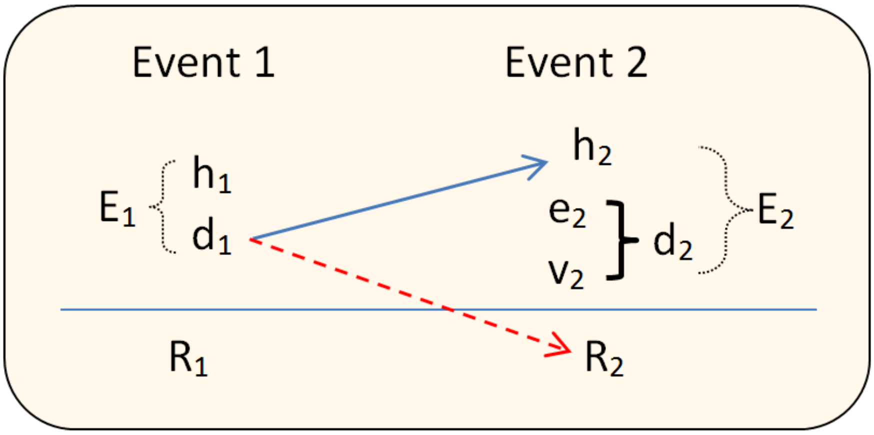

Figure 3b: Compounding process of the Taiwan Earthquake

C. The Great East Japan Earthquake (2011)

The previous two cases looked separately at how a natural disaster event may lead to another or may cause a technological disaster. The Great East Japan Earthquake provides an example where the same natural disaster event first caused a second natural disaster event, and then a technological disaster.

The Great East Japan earthquake was a magnitude 9.0 mega earthquake that struck the coast of eastern Japan on March 11, 2011. It was the most powerful earthquake to ever hit Japan since 1900. However, compare with the losses caused by the subsequent tsunami, the impact of the earthquake was rather minor with only few buildings damaged or collapsed. Within 15 minutes, tsunami waves as high as 38 m (Earthquake Research Institute, The University of Tokyo)[7] brought massive destructions to some 450 km coastlines, accounting for most of the victims who perished over the course of the events (WORLD BANK, 2012).

In addition to destroying the cities along the coastlines, the tsunami also sent waves over the protective dyke of Fukushima Daiichi Nuclear Power Plant and compromised the reactors' cooling system. The fuel rods in the reactors were exposed and massive explosions took place on 12 March, resulting in a nuclear disaster and forcing the evacuation of entire communities with a 20 km radius. The total death toll caused by the three events was 19,846, with economic losses estimated at around 210 billion US$, the highest loss recorded for any single (compound) disaster.

Figure 3c outlines the inter-event linkages. The earthquake is event 1, tsunami event 2, and the nuclear plant disaster event 3. In spite of its powerfulness, the earthquake did not cause much physical damage to communities, but it led directly to the tsunami, which did cause extensive deaths and damages. This event demonstrated the sheer power of nature, and exposed the hidden unforeseen vulnerabilities that populations along some sections of Japan's coastlines are exposed to.

In turn, the tsunami compromised the cooling system of the Fukushima Daiichi nuclear power plant. However, if adequate drastic actions were taken immediately after the tsunami waves struck, the damages could be contained and controlled. However, that was not so. The lack of the adequate and timely response led to still greater damages, eventually resulting in an explosion and forcing the abandonment of the plant. Even now some amounts of radioactive substances are still released, keeping the surrounding areas a high risk zone unsuited for human habitation.

The ability to respond adequately to the initial damages to the cooling system was also undermined by the earthquake and tsunami which destroyed the road system leading up to the plant. As a result, certain spare parts could not be timely transported to the plant, but the principal culprit of the nuclear disaster was human negligence.

In some way, this attests to Perrow's view that for highly complex and tightly coupled technological systems, the risk that some failure may occur is almost always there. From this viewpoint, the tsunami merely played the role of catalysing that hazard, which is always there with the systems.

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[7] http://news.sciencemag.org/2011/04/japans-tsunami-topped-37-meters (Accessed 5 Jan. 2014)

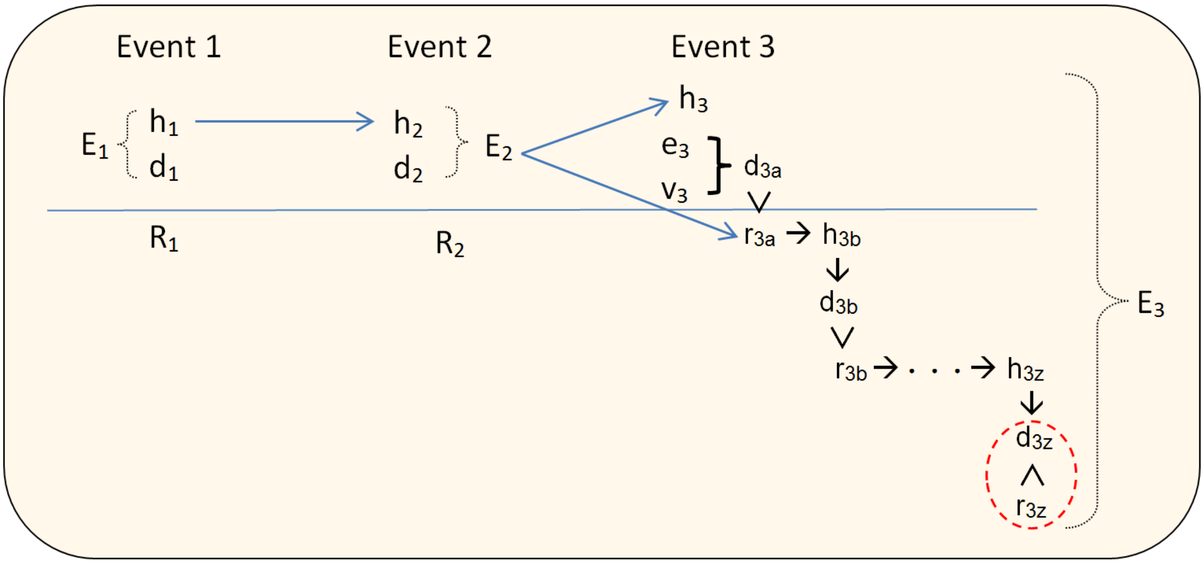

Figure 3c: Compounding process of the Great East Japan Earthquake

D. The Haiti earthquake (2010)

In this and next two cases, we consider the role of adequate and timely responses to imminent dangers brought about by a prior natural disaster.

An earthquake of magnitude 7.0 struck Haiti on January 12, 2010. The epicentre was right next to its capital city Port-au-Prince. Most buildings in the city collapsed, including the Presidential Palace, National Assembly Building, and headquarter of the UN Stabilization Mission. Moreover, there were widespread devastations and damages to the vital social infrastructure, such as police stations, hospitals and transport facilities necessary for making adequate responses to the disaster (USGS).[8]

After the disaster, the recovery progress was slow and the sanitation conditions were very poor due to the damages to the related infrastructures and the collapse of the public health system. Ten months after the earthquake, a cholera epidemic started, introduced by some relief crew, after its disappearance in the country for more than a century. The epidemic affected 6% of the population and caused 8,231 deaths. The total death toll due to the earthquake and cholera was 222,570, and economic losses amounted to 8 billion US$ (EM-DAT).

Figure 3d presents the major between-event linkages. Again, the earthquake is event 1, and the cholera epidemic event 2. The earthquake played a number of different roles in causing the epidemic. First, it brought in the relief crew who introduced the cholera bacterium. Secondly, the damages to the sanitation and other physical and social infrastructures significantly increased exposure of the population to the risk. Thirdly, the social and economic hardship suffered by the population in the wake of the earthquake also raised the

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[8] http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/us2010rja6/#summary (Accessed on 5 Jan. 2014)

level vulnerability to the disease after exposure. Fourthly, the collapse of the public health system and healthcare systems also meant that no timely and effective responses were in place to deal with the disease after its first spread, causing the disease to be spread even more widely, resulting in an epidemic. In short, the epidemic was a multi-hit process, which only ended when adequate effective responses were eventually meted out to overcome the problem.

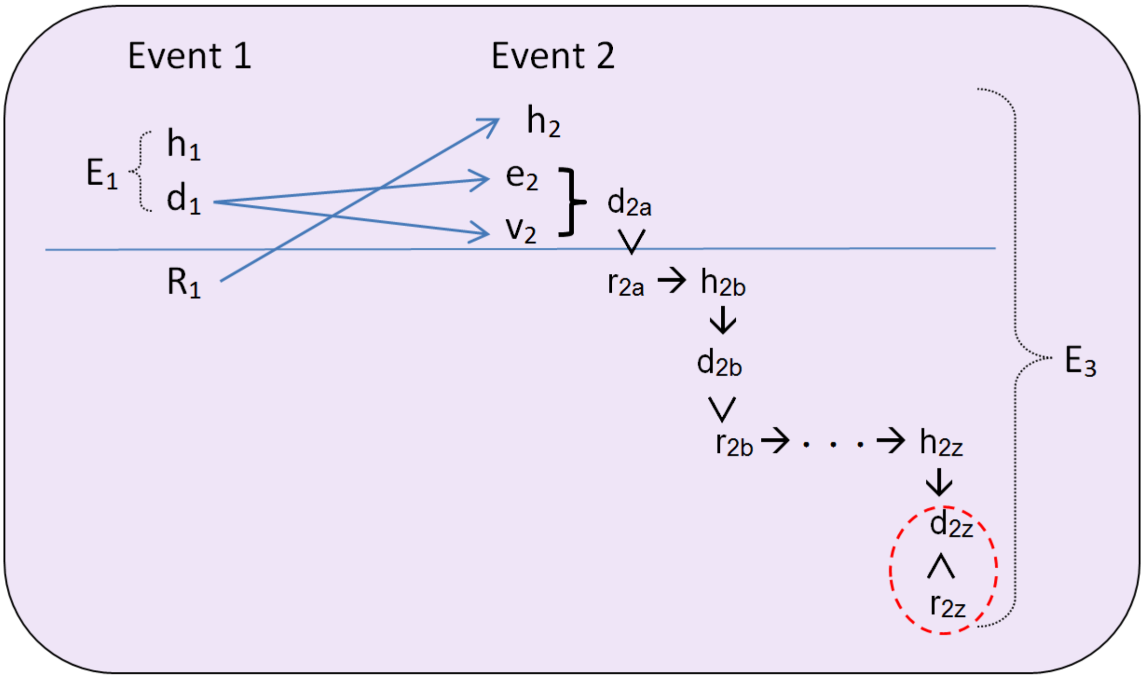

Figure 3d: Compounding process of the Haiti Earthquake

E. The Edo Earthquake (1855) and Typhoon (1956)

Also known as the Great Ansei Earthquake, the Edo earthquake occurred on November 11, 1856, and was one of the major disasters in the late-Edo period. Estimated at magnitude 7.0, the epicentre was close to Edo (now Tokyo), causing considerable damages to the Kanto region both as a result of the shock itself, and as a result of the subsequent fires and minor tsunamis. The combined death toll was estimated at 6,757 (NOAA).[9]

Almost a year later, on September 23, 1856, while recovery effort following the earthquake was still being made, a strong typhoon hit the same region causing severe flooding in already affected areas. According to Kawata (2011), the typhoon destroyed 10 times as many houses as the earthquake in the previous year.

Figure 3e indicates the linkages between the two apparently separate events, and underlines the importance of timely response to a disaster after it occurs. When the 1855 earthquake occurred, it severely damaged the structures earlier erected as defences against typhoon

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[9] http://www.ngdc.noaa.gov/nndc/struts/results?eq_0=1991&t=101650&s=13&d=22,26,13,12&nd=display (Accessed 4 Jan. 2014)

events. In other words, d_1 had drastically raised v_2. However, if strong actions had been taken to rebuild these defences, the damages caused by the 1856 typhoon would not have been as great. The actual response to the 1855 disaster (R_1) was much less than adequate, and certainly not timely. Thus when the typhoon (h_2) struck in 1856, it caused extensive damages.

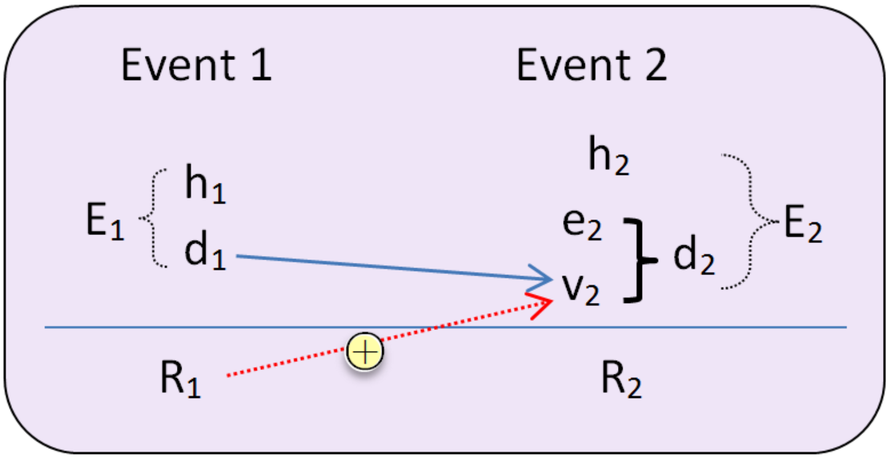

Figure 3e: Compounding process of the Edo Earthquake and Typhoon

F. The Sichuan Earthquake (2008)

We close this section on a more positive note. The Sichuan earthquake measured at magnitude 8.0 occurred on May 12, 2008, in China's Sichuan province. Strong quakes and aftershocks caused a total of 87,476 deaths, with economic damages estimated at 85 billion US$ (EM-DAT). The earthquakes caused widespread collapses of buildings in Mianyang, Beichuan and Wenchuan, among which many were school buildings. The low quality of the construction work that erected these buildings was the principal reason for the collapse of these buildings, with devastating consequences. Thousands of school children were among the dead. The earthquake exposed major problems of public safety in China (USGS).[10]

In addition to the damages linked to the collapse of buildings, many rivers became blocked as a result of massive landslides caused by the quake and aftershocks. Many "earthquake lakes" were formed behind "dams" created by landslides. Massive amounts of water were being flown at a fast rate to these lakes, behind the highly unsafe dams made of the debris of the landslides. It was clear that these rapidly filled up lakes would soon burst their dams, resulting in massive flash floods down to communities and populations living below them.

According to reported statistics, two weeks after the major quake, 34 lakes were so formed blocking and damming the rivers. It was estimated that 28 of them would pose serious danger to the local population. Entire villages had to be evacuated because of the likely flash

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[10] http://earthquake.usgs.gov/earthquakes/eqinthenews/2008/us2008ryan/#summary (Accessed on 5 Jan. 2014)

floods and flooding. Immediate steps were taken to evacuate the populations concerned and blast open the landslide-caused dams.

Figure 3f portrays the possibilities. The earthquake and aftershocks can be regarded as event 1. Event 2 is the likely bursting of the dams of the earthquake lakes. These lakes and the hazards they posed were directly caused by event 1. If event 2 materialized, major loss of human lives and economic damages would likely follow. The authorities responsible for responses to event 1 took decisive action to remove the hazard in question, preventing a possible second event.

This case is an example of the value of studying the kind of counterfactuals which could have occurred, furthering our understanding of inter-event linkages. Even though these linkages are based on counterfactuals, they are nevertheless real. A study of compound disasters cannot just be based on records of actual disaster events, which tend inevitably to be accounts of negative experiences. Throughout the history of mankind rising to challenges of disasters, there must be a parallel account of those disasters that could have been real but were successfully prevented.

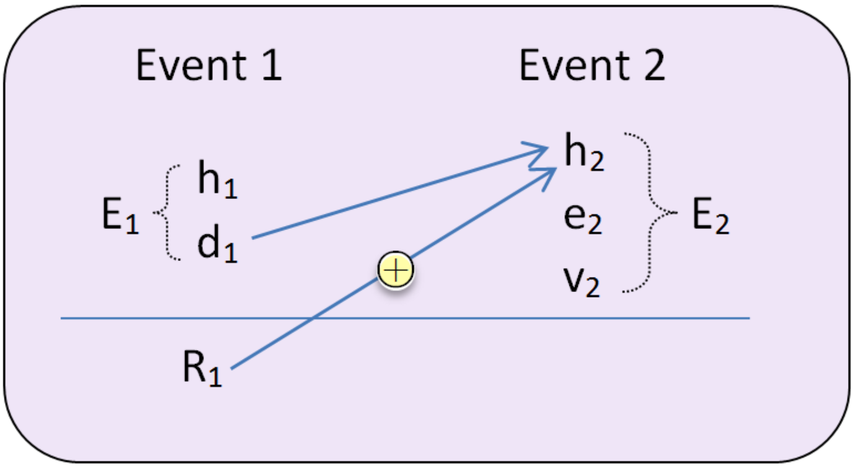

Figure 3f: Compound process and potential disaster of the Sichuan Earthquake

Implications for Disaster Risk Management

While the evidence that natural disasters have become more frequent in recent decades remains controversial, there is ample evidence that they have become more devastating in impact and more complex in the processes and mechanisms that caused them. In particular, compound disasters are now more frequently observed. In some cases, they are the result of one natural disaster event leading to another; in others they involve the catalysing of a hidden technological hazard by some prior natural disaster event. The aggregations of the impact of an inter-related series of disaster events, or a compound disaster, collocated in time and space can overwhelm the ability to respond of any community or country, as the recent Great East Japan Earthquake, and the tsunami and the nuclear power plant disaster that followed, attest.

While some literature has begun to recognize the importance of dealing with interrelated disaster events, the current Hyogo Framework for Action (HFA) is decidedly mute on it (UNISDR, 2007). It is time that any replacement core international action framework on disasters and disaster risk reduction and management recognized the increasing threats of compound disasters, took action to study the processes and mechanism leading to them, and advised on policy. This input paper aims to make such a contribution by providing a typological framework for discussing and analysing inter-related disaster events.

From our analysis and review of the selected cases, our main conclusions and policy implications are:

1. Any disaster entails a potentially compounding process, whereby one event precipitates another. In some cases, this process is cut short early enough; in others, it is allowed to be played out extensively enough as to cause multiple disaster events.

2. What are currently referred to in some literature as "compound disasters" are but a subset of cases where the compounding process is played out to such an extent that it caused multiple events to occur, resulting in extensive losses of human lives and economic damages, sometimes on a catastrophic scale.

3. Factors determining if and how the compounding process associated with an initial event is played out include physical and human factors. Depending on the nature of the first event, the former can include hydro-climatological or geological factors. The latter may include human activities such as urbanization, energy and environmental policies at a macro level, and community-level factors including the relief, recovery and reconstruction activities following an earlier disaster.

4. In designing effective DRR and DRM strategies, it is important to recognize the increased threats of compound disasters, to study the nature and characteristics of the possible compounding processes and the range of human and non-human factors involved, and to recommend necessary measures to control and limit the process.

5. In particular, with increased use of and dependence on the highly complex and coupled technologies and productions systems, it is important to be vigilant to the wide range of possibilities of natural disaster-technology interaction, and to minimize the chances of single natural disasters turning into a wider technological disaster.

6. An explicit and strengthened perspective on inter-disaster linkages also implies that timely and adequate responses to one disaster may be the key to preventing another. Thus disaster responses are not simply "responses" to the aftermath of a prior disaster; they are also—and should be treated as such—an integral part of any disaster prevention policy.

7. It is unlikely that such timely and adequate responses can all be pre-planned. Much will rest on the ability to respond flexibly and effectively under a fluid post-disaster situation, and sometimes improvise. But this does not mean complete passivity. An

experience and knowledge of the range of possibilities, and the ability to anticipate and react based on this experience and knowledge would be especially important.

8. The perspective also indicates that an apparent single disaster may contain a success story of the communities and populations in question, and the authorities in charge, taking the necessary and timely actions to avoid a follow-up disaster, rather than merely a story of failure not to have prevented the first disaster. A close reading of both the negative and positive parts of a disaster experience could increase our understanding of what it takes to design and conduct successful DRR and DRM policies and programs.

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