UNISDR

The United Nations Office for Disaster Risk Reduction

GAR

Global Assessment Report on Disaster Risk Reduction

2015

INPUT PAPER

Prepared for the Global Assessment Report on Disaster Risk Reduction 2015

RISK RELATIONSHIPS AND CASCADING EFFECTS in CRITICAL INFRASTRUCTURES: IMPLICATIONS FOR THE HYOGO FRAMEWORK

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A collaborative endeavor of Analytic Services Inc.

BANYAN ANALYTICS,
An ANSER Institute

17 January 2014

Table of Contents

Introduction

Disaster preparedness and management are crucial capabilities against which government performance will be benchmarked in the 21st century. This is in part due to experts' predictions that for various reasons ranging from rapid urbanization (including increasing rate of coastal settlement), aging population and global economic growth to environmental degradation and climate change, the impact, if not the rate, of natural disasters will continue to increase globally in the coming years (UNEP 2005; Neumayer and Barthel 2011; UN System Task Team 2012; Georgieva 2010). Increasing and complex interdependence of nations across economic, social, cultural, political and technological realms compound this prospect as nations are not only vulnerable to disasters that they are directly exposed to, but also to indirect consequences of disasters experienced elsewhere. This brings to the fore three significant and interrelated implications: first, it is crucial to recognize the importance of investing in and developing disaster preparedness and management skills as nations are responsible both to their populace and the global community. Second, countries cannot afford to be indifferent to each other's disaster preparedness and management capabilities; and third, disaster risk reduction efforts require global awareness as well as international collaboration and coordination.

In recognition of these implications, in 2005 the United Nations Office for Disaster Risk Reduction (UNISDR) spearheaded development and adoption of the Hyogo Framework for Action (HFA). The HFA provides a 10-year global blueprint that aims to increase awareness of and commitment to disaster risk reduction approaches and set priorities to improve resilience across countries and communities. In light of the discussions and agreements achieved during the initiating world conference, HFA identified 5 priority areas for action. States, regional and international organizations and other actors concerned with disaster risk reduction were invited to consider and implement key activities within each of these areas. These activities, known as the 22 core indicators, provide guidance to countries as they invest to reduce disaster risk. Biannual global assessment reports (GARs) have helped contribute to this goal by evaluating progress of participating countries and identifying emerging disaster risk reduction issues and needs.

The next scheduled assessment, GAR 2015, will inform modifications to the successive framework to HFA. Expectations for the successor framework to HFA are the same as if not higher than those of the original HFA: it will need to accurately identify the most salient disaster risks and the associated challenges (defining the problems), develop relevant strategies for tackling them (developing solutions), provide clear and targeted guidance to those countries interested in taking mitigating/corrective action (issuing implementation guidance), and formulate objective and consistent ways of measuring the progress in implementation (developing performance measurement).

This is no easy task. Each part requires extensive research, empirical validation and stakeholder input. Yet, ensuring the new framework's adequacy to identify the right problems (i.e., relevant and important disaster risks) is a critical precondition to avoid expending scarce resources and socio-political capital on development and implementation of inadequate or incomplete solutions. As such, one of the key requirements of designing a more compelling and improved framework is to identify the conceptual shortcomings and gaps with the current framework.

We identified the interconnected, interdependent nature of risks as an area inadequately addressed in the current HFA as well as other, parallel disaster risk reduction efforts. Although students and practitioners of disaster management have an intuitive understanding of complex relationships between various types of risks, current disaster risk reduction efforts appear to rely on a paradigm in which risks and their effects are confined to a conceptual, functional or geographical area. Implications of risk relationships and interactions are not adequately considered; as such addressing risks in an isolated manner appears to be the common practice.

This paper, prepared as an input to GAR 2015, represents the first phase of a long-term research project that aims to investigate risk interdependencies – particularly between different sectors of critical infrastructure (CI) – and the way in which unfolding disasters trigger cascading effects across different domains. We believe that understanding how CI sectors relate to one another will aid explicit consideration of risk interactions by decision-makers as they design strategies to anticipate and mitigate the cascading effects that often compound disaster impacts.

In this initial study, we first provide a brief review of the current research on risk relationships and cascading effects in critical infrastructures and conclude that a comprehensive look at interrelationships across a large number of CI sectors in the context of disasters is needed. Next, we describe the methodology and three-pronged strategy we followed to accomplish this task: First, we use cause-effect mapping techniques to develop a generic, theoretical understanding of how CI risks interact and generate cascading effects during disasters. Then, in light of this conceptual exercise, we investigate the 2011 Japanese triple disasters (a powerful earthquake, large tsunami and a major nuclear accident) to explore how CI risks interacted in a series of real-world disasters.[1] In the next section, we provide a preliminary high level assessment of the conceptual adequacy of the HFA (in the context of its 22 core indicators) and its ability to address disaster risks and impacts, including cascading effects generated by interconnected risks.

While an abstract evaluation of the HFA may provide theoretical insights, these insights would need to be validated against empirical realities for accurate, credible and pertinent insights. Further, an abstract evaluation would only address the utility and relevance of core indicators in a vacuum; this might lead to errant theories that fail to consider the real-world interplay of events and indicators. Similarly, investigation of an isolated real world event may neglect evaluation of indicators against events not encountered. To provide a more comprehensive investigation, we instead, inquire whether the HFA is capable of addressing and attending to risk interdependencies by evaluating it against both an abstract and a real-world event. Our abstract assessment evaluates the HFA against a cause-effect map. Our real-world assessment evaluates the HFA against events and real world experiences of the 2011 Japanese triple disasters. Collectively, this dual assessment required exploring a series

[1] Conducted at a high level rather than as an in-depth case study, investigation of the Japanese disaster enabled an initial proof of concept exercise for our understanding of CI risk interdependency in disasters.

of questions regarding the HFA indicators' sufficiency in addressing cascading effects, particularly across CI sectors.

In the final section, we present our initial observations and recommendations for the 2015 World Conference on how to improve existing HFA indicators. Accordingly, we recommend four new indicators to be included in the Hyogo Framework. We also offer observations from our dual assessment that confirm relevance and utility of some of the existing HFA indicators.

Subsequent phases of our research will build on these preliminary findings and continue our efforts to validate initial results.

Background

A review of the literature: critical infrastructure relationships and cascading effects[2]

Recent occurrence of significant disasters (such as Hurricane Katrina, the Haiti earthquake, and the Fukushima Daiichi nuclear disaster) have both inspired and necessitated research to build a deeper understanding of how disasters can cause cascading effects, particularly on critical infrastructures. Given the importance and broad scope and relevance of the topic, a wide range of stakeholders (i.e., scientists, engineers, government agencies, inter-governmental organizations, etc.,) have studied risk relationships and cascading effects over the years. An exhaustive capture of pertinent studies is neither possible nor necessary here. Yet, a review of some of the recent studies reveals interesting trends and observations on the state of current research.

Each stakeholder and its sector have unique interests in the cascading effects of disasters, so the body of research widely varies in scope and examines different facets of the topic. Glass et al. (2004) examined the "topologies," or structures, of critical infrastructures and argued that certain infrastructures have relatively better capacity to compartmentalize failures and therefore mitigate cascading effects. Brown (2007, 1) determined that "no single model or modeling approach is sufficient for answering the breadth of near-term and long-term questions being asked relative to critical infrastructure protection at a local to international level." Assuming central importance of telecommunications for other critical infrastructures, O'Reilly et al. (2006) assessed the impact of past hurricanes in the United States on wireless and landline telecommunications and considered implications. Conrad et al. (2006, 59) conducted similar research stating that, "cascading across infrastructures can occur in almost any order, but telecommunications always is a central component surrounding the disruption and is especially important in mitigating the disruptive effects." Participants in a 2011 EU Conference emphasized the criticality of securing the region's energy infrastructure,[3] while Haavisto et al. (2013) assessed supply chain coordination in cascading disasters.

[2] While this is not an exhaustive review of all the available literature on the subject, in this section we aim to capture what is currently and generally understood on risk interdependence and cascading effects. We pay particular attention to cascading effects on critical infrastructures owing to high risk interdependence across these sectors.

[3] See, "Securing Europe's energy infrastructure." *A Security & Defense Agenda Report*, ed. Paul Ames. A conference report, Brussels, Belgium, February 2011.

Much of the existing research on cascading effects puts an emphasis on understanding the interconnected relationship between critical infrastructures to characterize how both the relationships and the infrastructure systems themselves are affected by stress, disruptions and other changing conditions. Beyeler et al. (2002) and Rinaldi (2004) discussed the importance of modeling relationships and brought greater research attention to interdependencies among infrastructure sectors. Rinaldi (2004, 1) argued that failing to note these interdependencies would "limit the validity of analyses, and…lead to bad or inappropriate policies and decisions during crises or severe infrastructure disruptions." Rinaldi, Peerenboom and Kelly's research (2001) set the groundwork for subsequent research by defining types of interdependencies (i.e., physical, cyber, geographic, and logical), identifying factors that affect analyses of infrastructure interdependencies, and identifying types of failures (i.e., cascading, escalating and common cause failures). Kopylec et al. (2007) explored how disruptions in physical infrastructures (e.g. energy and transportation systems) impact cyber-infrastructures. Conrad et al. (2006) examined relationships among power infrastructures, telecommunications systems, and emergency services (e.g. police, fire, and medical), and assessed the impact of cascading failures among the three in financial costs incurred and number of people affected.

Many researchers and analysts rely on modeling and simulations to provide insights on how infrastructure systems may respond to certain scenarios, and gain insight into how and when a failure in one system or infrastructure is likely to cascade into another. Glass et al. (2004) provided insights into what conditions or dependencies are likely to cause cascading failures in networks or infrastructures. Helbing et al. (2007, 44) of the Swiss Federal Institute of Technology Zurich "developed models to represent causal relationships triggering cascading disaster spreading, allowing to compare the effectiveness of…response strategies," and determined that different infrastructures require different response strategies. The Idaho National Laboratory (INL) (2013) developed Critical Infrastructure Modeling Simulation (CIMS), which is capable of "construct[ing] three-dimensional models of cities and counties and run[ning] multiple infrastructure failure scenarios" to "provide emergency planners with a high-level analysis of infrastructure…" INL (2013) also developed Critical Infrastructure Protection and Resiliency Simulator (CIPR/sim) which enables emergency planners to view cascading effects of multiple infrastructure failures in real-time before the occurrence of an actual emergency.

Although not exhaustive, this review indicates that researchers have identified this area as a domain of rising concern and achieved considerable progress in understanding critical infrastructure risk interdependencies and the resulting cascading effects. Yet, our review also reveals some issues with existing research. One such issue is the inconsistency of definitions and terminology utilized by researchers across different studies. The term "cascading effects" is almost always used to reference the breakdown or failure of infrastructure systems/networks that result in subsequent breakdowns or failures of additional infrastructure systems/networks due to the dependencies between them. However, a number of other terms or labels have been used in place of "cascading effects" throughout the research with potentially different implications. For example, Helbing et al. (2007) used the term "cascading disaster spreading" to mean the spreading of failures among networks. Buzna et al. (2007) used the term "cascading failures" while Rose (2009) used the term "cascading infrastructure failures." Haavisto et al. (2013) used the concept of "cascading disasters," referring to a "toppling domino effect…where one thing leads to another," including disasters that result in cascading effects in critical infrastructures, as well as critical infrastructure failures that lead to other infrastructure failures which are considered disastrous. Other researcher use the terms "domino effect" and cascading effects interchangeably.

In addition to use of different and at times discrepant language, the diversity of the existing research may be a weakness. There are currently a limited number of studies that consider a large number of CIs simultaneously, providing a broad overview of the problem space. Various research groups have conducted studies that often cater to their own specific interests or respond to the needs of specific sectors of CI, resulting in studies that cannot be easily integrated to attain a broader view of critical infrastructure interrelationships. Such limited scope may have provided a rich assessment of the few CI sectors considered but perhaps do not provide a comprehensive understanding of how disasters impact a large number of critical infrastructures through unique interactions of sector specific risks. Moreover, in large systems with complex relationships, the ability to see "both the trees and the forest" is essential to get an accurate understanding of the specific issues and the broader environment in which such issues are informed and conditioned.

Objectives

Against this background, this paper has two objectives: first, it aims to address the second weakness noted above (i.e., limited number of studies with a comprehensive look into CI interdependencies) regarding the current literature. Instead of relating and reviewing only a couple of or few CI sectors at a time, it will provide a systemic and comprehensive (albeit preliminary) portrayal of relationships across a large number of CI sectors and do so specifically in the context of disasters. Second, this paper aims to assess UNISDR's Hyogo Framework in terms of its adequacy to address CI risk relationships and resultant cascading effects. In light of these assessments, we will present preliminary observations and insights and provide actionable recommendations to GAR 15 for consideration.

Methodology

Assessment Strategy

To accomplish the above stated objectives, the study team followed a three-step assessment strategy:

- Assessment 1: Characterization of generic relationships between key CI sectors and how they cause cascading effects during disasters
- Assessment 2: Review and assessment of cascading effects in the context of a real disaster and identification of cascading effects on critical infrastructures
- Assessment 3: Evaluation of HFA's adequacy in addressing CI relationships and cascading effects documented by the first two steps

During step 1, we mapped widely noted linkages across key CI sectors, characterizing the ways in which CI sectors relate to one another through some type of an input or output. Through this activitiy we show how these CI linkages interact with a number of other key variables (actors, needs and requirements of disaster response and broader disaster dynamics) that often shape disaster impacts. During step 2, we built on the comprehensive survey of CI interdependencies mapped during step 1 and investigated how such interdependencies triggered cascading effects in the context of a real life disaster. The study team chose to focus on the 2011 Japanese triple disasters as a real world disaster example. This decision was based on the extent of cascading effects experienced in Japan as well as the amount of information available. Moreover, Japan, as an active contributor to and participant of the Hyogo Framework, provides an example of a country with a high implementation rate of risk reduction measures. As such, it presentes a context where cascading effects experienced are more likely due to remaining gaps within HFA than implementation problems.

Approach and Tools

This study utilizes systems thinking principles, concepts and tools, to accomplish a holistic perspective on risk relationships and interactions across CI sectors and the subsequent cascading effects triggered by disasters. Disasters operate as complex systems that cannot be completely understood or effectively resolved by addressing parts (e.g., risks, actors, effects, behaviors, etc.) in isolation. Clearly, risks, actors, (anticipated or real) effects, and public/government/industry behaviors (actions) prior to and during disasters all serve as parts in this system and have feedbacks to one another. Moreover, each part is comprised of lower level systems that operate through additional parts and relationships. For example, actors include a number of stakeholders such as individuals, communities, federal/local governments, industry/private sector, voluntary organizations and NGOs. They are tied together with a network of relationships shaping their perceptions, interest and behaviors. Building on this systemic view and focusing on risks, we argue that risks do not exist independent of each other. The complex relationships between different types of risks may serve to extend vulnerabilities in one domain to multiple domains or cause emergence of new vulnerabilities. Relationships between different CI sectors provide the prime example for complex risk linkages discussed here.

This idea is particularly important in the context of disaster preparedness and risk reduction efforts, as isolated assessment of individual risks (e.g., sector specific risks) may mislead decision-makers to underestimate the potential consequences of a disruption or breakdown. Developing, executing and evaluating disaster risk reduction strategies and measures requires taking into account the whole system of risks inclusive of individual CI risks and the interactions that lead to particular disaster outcomes.

Systems thinking provides a rich portfolio of tools and methods that aid investigation and conveyance of this holistic and layered perspective. Its tools are especially effective in showing how complex problems operate as part of a broader system. In this study, among others, we used a powerful systems thinking technique, causal loop diagramming, to capture generic CI interdependencies during step 1 of our analysis. Causal Loop Diagrams (CLDs) explore a problem space or system by depicting underlying structures of feedback that generate problem behaviors. They are often used to show how system behaviors are produced by complex causal relationships and interactions between system elements (variables) and the resultant nonlinear (expected as well as unintended) effects.[4] Recognition of complex feedbacks to system behavior(s) helps uncover high-leverage intervention points required to create lasting positive change.[5]

In addition to CLDs, we used a range of other assessment tools and methods to provide a systemic perspective on the 2011 Japanese disasters and the current Hyogo Framework. For example, to assess the disaster impacts in Japan, we created a disaster timeline that is substantiated by a cataloguing of key events and mapping of Hyogo Framework indicators to events. Leveraging this timeline and the data, we created a diagram that specifically captures key disaster effects on Japanese critical infrastructures and depicts their subsequent nth-order effects. Combined, this systemic approach informs both our evaluation of the way in which risk interdependencies heighten disaster impacts and our efforts to identify insights which may improve the HFA and related disaster risk reduction efforts.

Data Collection

Data for this study were collected from open source literature and information sources such as academic studies, newspapers, government reports, and documents and reports provided by nongovernmental organizations.

Understanding risk relationships and CI cascading effects in the context of disasters

In this section, we present the first two assessments we conducted to better understand risk relationships and cascading CI effects during disasters.

Assessment 1 : Mapping of generic CI relationships and cascading effects

Although there is a growing global consensus on the importance of critical infrastructures' stability for national resilience and security, there are notable conceptual and practical differences in how countries understand and attend to requirements of critical infrastructures.[6] Presently, country approaches lack uniformity in definitions and the criteria they use to identify and designate CI sectors. These differences have practical implications. For example, the US Presidential Policy Directive/PPD-21, Critical Infrastructure Security and Resilience (2013), identifies 16 critical infrastructure sectors in the United States while

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4 CLDs also help analysts identify potential delays in effects of these interactions or policies implemented, helping with the management of expectations and time/budget allocation decisions.

5 For more information of CLDs see, John D. Sterman, *Business Dynamics: Systems Thinking and Modeling for a Complex World* (Boston: Irwin McGraw-Hill, 2000), pp.137-190.

6 In fact, surveying the definitions in use by different countries, a NATO document on the protection of critical infrastructures concludes that "in some countries , those criteria [that define the criticality of CIs] stress the finality or purpose of the infrastructure (i.e. the infrastructure is critical because it performs a function that is vital to society), whereas in others they stress the severity or effects of the disruption or destruction of a given infrastructure on society (i.e. the infrastructure is critical because its loss would be extremely disruptive)" (NATO 2007).

Japan's National Security Information Center organizes its critical infrastructures along ten sectors (Clemente 2013, 14).[7]

Part of the reason for this discrepancy is the variance in geographical, social, political and cultural contexts across localities. Different countries may face different types of hazards, experience different vulnerabilities, rely on different governance and collaboration models, work with different laws/regulations and face different budgetary constraints. Similarly, even if countries have designated the same infrastructures as critical, these CIs may be configured differently. As a result, the same disaster scenario may not lead to the same effect(s) in different countries. These differences in perspectives may complicate efforts to standardize approaches to risk reduction efforts.

However, this is not to say that developing a generic map of critical infrastructure linkages to better understand potential cascading effects is not feasible or helpful. Regardless of the substantive differences in CI sectors or vulnerabilities across countries, such mapping exercises encourage a more realistic conceptualization of CIs as part of a larger system, facilitate an explicit consideration of implications, and provide the groundwork for identifying critical points of systemic failure or high leverage policy interventions to improve resilience.

In Figure 4, we present a general causal loop diagram (CLD)[8] that portrays high level relationships across key CI sectors. The causal linkages captured in the CLD across CIs show the way in which different sectors relate to one another. These linkages form the basis of feedback dynamics at work in CI operations, indicating when and why cascading effects may be triggered by a disruptive incident.

The CLD is composed of variables and links that are based on observations and analysis presented in the previous studies that documented key CI relationships. The CLD was then supplemented with additional variables/relationships that represent common issues and impacts typically seen within the broader disaster contexts. Accordingly, the CI sectors represented in the CLD (shown in red font) include:

- Chemical sector
- Commercial facilities (represented in the CLD by "disruption of businesses" node)
- Communications

[7] PPD-21 identifies the following sectors as CIs in the United States: Chemical sector, commercial facilities, communications, critical manufacturing, dams, defense industrial base, emergency services, energy, financial services, food and agriculture, government facilities, healthcare and public health, information technology, nuclear reactors, materials and waste, transportation system, water and wastewater systems. On the other hand, Japanese CIs include: data communications, finance, airlines, railway, electric power, gas, government and administrative services (including municipal governments), medical, water service and logistics (Clemente 2013, 14).

[8] CLDs are composed of text and arrows. While text represents key variables involved in a problem space or system, arrows represent the causal relationships between the variables. Polarity signs attached to arrows represent the type of relationship between two variables. A plus (+) sign indicates that the two variables move together in the same direction. That is, "if the cause increases, the effect increases above what it would otherwise have been, and if the cause decreases, the effect decreases below what it would otherwise have been" (Sterman 2000,139). Similarly, a minus (-) sign indicates that the two variables move in the opposite direction. That is, "if the cause increases, the effect decreases below what it would otherwise have been, and if the cause decreases, the effect increases above what it would otherwise have been" (Sterman 2000, 139).

- Critical manufacturing (represented in the CLD by "disruption in local and global manufacturing plants")
- Dams
- Emergency services (represented in the CLD by "effectiveness of emergency management activities")
- Energy (represented in the CLD by the nodes of "natural gas production/operations", "disruption to oil/fuel systems", "disruption in electric power", and "damage to power grid")
- Financial services (represented in the CLD by the node of "banking and financial operations")
- Food and agriculture
- Government facilities (represented in the CLD by the "disruption of government services" node)
- Healthcare and public health
- Information technology (represented in the CLD by the nodes of "availability of information-technology systems" and "disruption of SCADA systems")
- Transportation system (represented in the CLD by the nodes of "disruption of travel by motor vehicles and train", "disruption to air travel", "effective management of navigable waterways", "damage to pipelines")
- Water and wastewater systems.

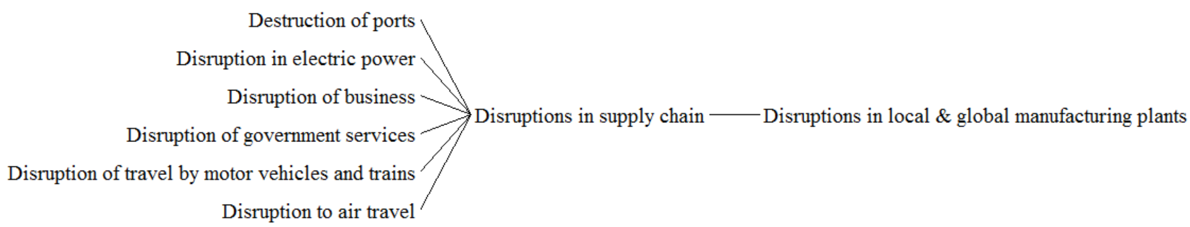
Rather than discussing the special trajectories through which certain effects may come into play, this CLD tells a high level story, providing a comprehensive overview of the CI landscape and disaster impacts. Developed as a generic map of systemic connections of CI networks, this CLD, by design, does not take into account the hazard type. As such, it may exclude some hazard-specific dynamics and associated feedbacks. Even so, this simplified version of reality offers several feedback loops, providing testimony to the complexity of the issue. Despite its hazard-agnostic outlook, the CLD provides insight into common CI feedbacks that are likely to hold across many localities and hazards.

A sample of these connections includes but is not limited to:

- Water systems provide water essential for production, cooling and emissions reductions – essential elements within the operation of a number of other CIs such as electric power systems, telecommunications, energy (natural gas/oil) systems, etc. (Rinaldi, Peerenboom and Kelly 2001, 15).
- Electric power systems provide power for switches, signaling, pump and lift stations, storage and control systems. As such, electric power is essential to telecommunications, transportation systems, water systems, and energy (oil/natural gas) systems. (Rinaldi, Peerenboom and Kelly 2001, 15).
- Transportation systems provide mostly shipping services without which other CIs would be considerably disabled.
- Telecommunication systems provide communication services as well as the SCADA (i.e., supervisory control and data acquisition) systems essential to ensure smooth functioning and protection of other CIs.

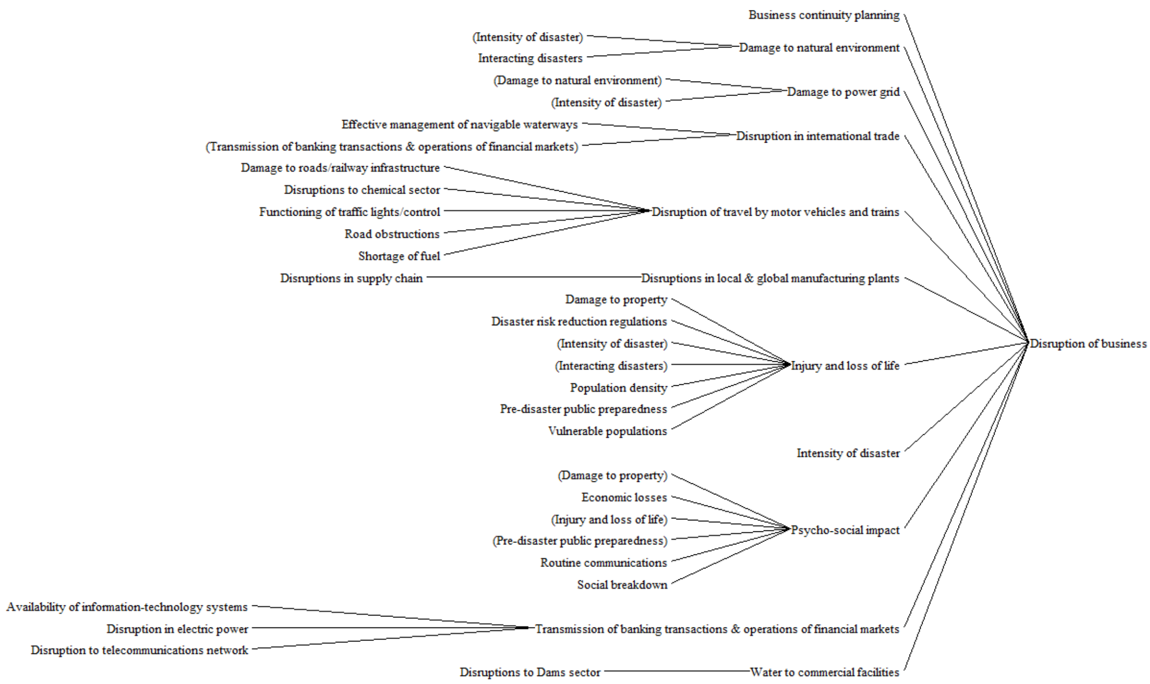
In addition to these widely published CI linkages, the CLD presents examples of interactions by less studied CIs such as commercial facilities, government services, emergency services, manufacturing plants and food/agriculture sectors. For example, damage to ports, disruption of business operations (caused by multiple CI failures), government services, and motor vehicle/rail/air transportation all lead to delays and disruptions in supply-chain operations. This will, in turn, trigger disruptions in operations of local and global manufacturing plants (Figure 1).

Figure 1 : Disruption of Manufacturing operations as a result of Cascading effects



Another significant cascading effect seen in the CLD is losses incurred by businesses (and more broadly by the private sector) as a result of CI failures (See Figure 2). Some CI sectors appear particularly essential for functioning businesses such as power, water, telecommunications, banking and finance systems, and transportation. In addition to these and other direct effects (e.g., facility damage), businesses endure indirect losses as a result of death toll and injury and the psychosocial impact on its workforce as well as the broader society. Combined, these effects create great strains on businesses lowering their profitability and competitiveness locally and, given the interdependent nature of economy and financial markets, globally. These cascading effects indicate that the private sector has significant incentive to take disaster risk reduction measures and incorporate disaster risk concerns into their investment and planning processes. Similarly, collaboration on disaster risk management issues is in the best interest of public and private sectors as both sides have common goals and would serve to benefit from an optimal use of limited resources.

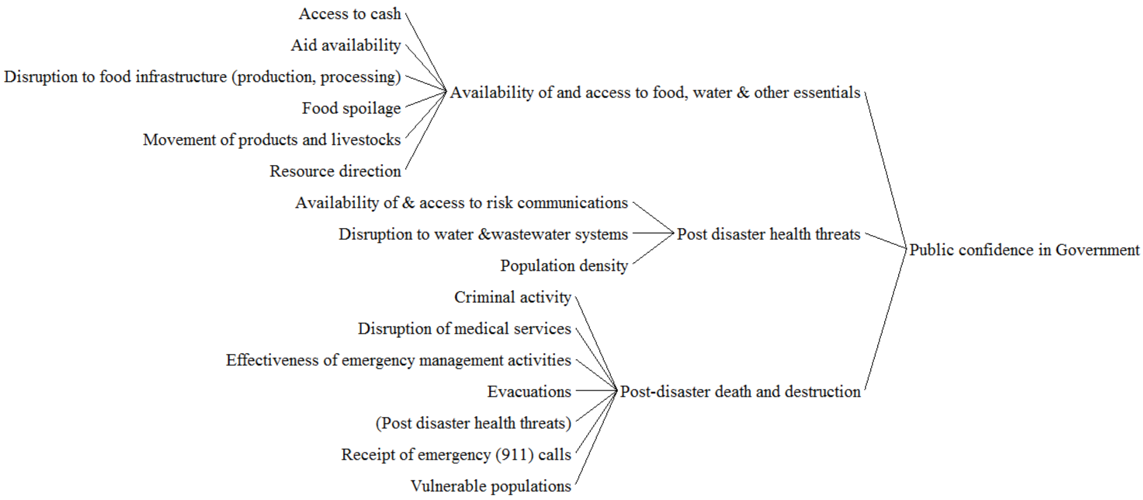
Figure 2 : Cascading Effect of Critical Infrastructure Failures on Businesses



These CI-specific linkages are important to characterize to anticipate potential cascading effects during disasters and design measures that can minimize negative impacts. Nonetheless, CIs never operate in a vacuum. When disasters strike, they impact not only the CI sectors, but also the broader societies which the CIs serve. As such, the societal, economic or cultural trends experienced in particular localities inevitably interact with impacts of CI interruptions, shaping the broader disaster outcomes. These interactions may have significant implications for effective response activities during disasters or prioritization of recovery activities once the crisis management phase is over. For example, presence of vulnerable populations (e.g., the elderly, children, etc.) and high population density are two societal trends that are likely to interact with CI disruptions. It is widely accepted that the presence of vulnerable populations and high population density are likely to increase initial loss of life and injury when disasters strike. This is, however, not the entire story. Post-disaster death and destruction is likely to be a function of, among others, the disruption in medical services, the presence of vulnerable populations, the initial injury levels and post disaster health threats. Similarly, post disaster health threats may increase as a result of disruption of water and wastewater systems, disruption of medical services and high population density. This, in turn, contributes to post-disaster death and destruction. These examples clearly show that local societal trends interact with CI failures to amplify disaster impacts. In other words, CI failures that cause relatively minor inconveniences in one locality may result in much more serious ramifications in a different locality.

The CLD also shows that CI failures may cause far reaching consequences in the broader societal realm. For example, the reduced availability of and access to essential goods (e.g., water, food, etc.), the increased post-disaster health threats, and the increased post-disaster death and destruction combined are likely to cause loss of public confidence in government (see Figure 3). Such societal dynamics may have implications that endure long beyond the disaster timeline by inducing changes in public attitudes, political trends, and electoral outcomes.

Figure 3 : Public Confidence in Government during Disasters



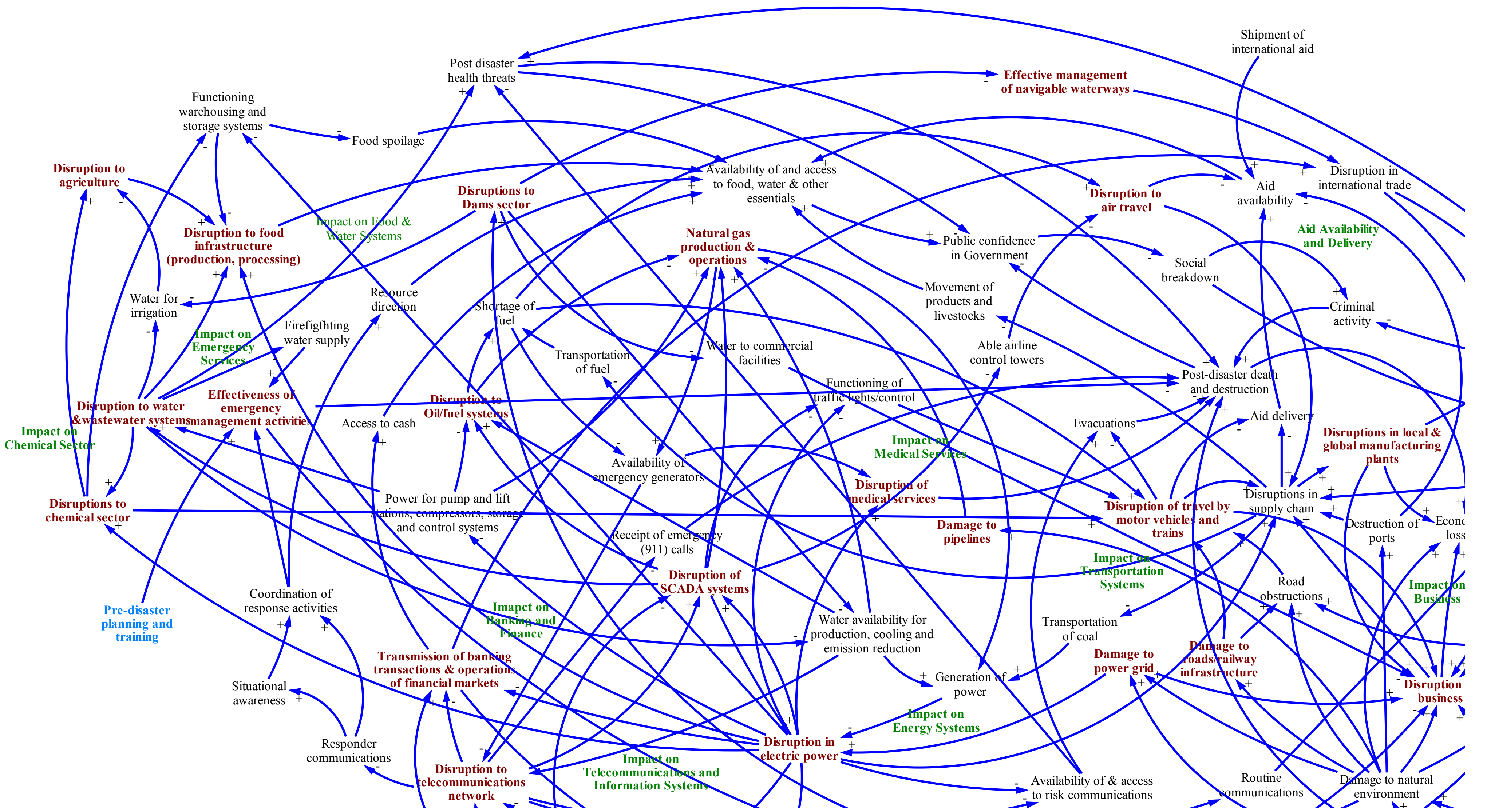
The CLD also incorporates select preparedness measures (shown in blue font) that help reduce some of the disaster risks. While pre-disaster public preparedness reduces injury and loss of life, property damage and psychosocial impact, disaster risk reduction regulations are shown to reduce loss of life and injury as well as property damage. Pre-disaster planning and training increases effectiveness of emergency management activities. Finally, public sector continuity of operations and private sector business continuity planning help reduce disruptions in government and business operations.

In addition to these specific observations, the CLD provides general insights about the CI sectors. Each CI sector provides a service that feeds into another sector as an input, enabling operations and services there. Yet, given the number of relationships (to include both the incoming and outgoing arrows), some CI sectors appear more "critical" than others. Electric power, telecommunications network, transportation systems and water systems appear to serve as hub nodes in the CLD indicating a large of number of other variables' dependence on continuity of these systems. Particularly telecommunications systems (inclusive of information systems and SCADA) emerge as the most cross-cutting CI service.

As Rinaldi, Peerenboom and Kelly (2001, 11) state, "the notion that…critical infrastructures are highly interconnected and mutually dependent in complex ways, both physically and through a host of information and communications technologies (so-called 'cyber-based systems'), is more than an abstract, theoretical concept." Identifying and capturing CI interdependencies and considering their implications in the broader disaster context, as this generic CLD has done, is essential for grounding the cascading effects discussions in empirical realities. It is also the first step in identifying and developing countermeasures for the types of cascading effects documented by this causal mapping exercise.

In the next section, we explore the timeline and impacts of a real disaster – the 2011 Japanese triple disasters – to complement our theoretical characterization of CI risk linkages and cascading effects with empirical realities.

Figure 4 : Causal Loop Diagram of Critical Infrastructure-Induced Cascading Effects in Disasters



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Assessment 2 : Cascading CI Effects in 2011 the Japanese Triple Disasters

Japan has a rich history of earthquakes, tsunamis, typhoons, landslides, and other natural calamities. Given the nature of its geography and its past experiences with natural disasters, preparedness is engrained in Japanese culture. This is in stark contrast to other countries where preparedness may be in anticipation of a relatively abstract risk. Yet, many experts and researchers believe that Japan was not prepared for what it faced in 2011.

On March 11, Japan experienced a series of severe disasters. An earthquake off the northeastern coast of Honshu commenced the incident, causing significant damage on land. The earthquake, then, triggered a series of large tsunami waves devastating the Tohoku region (northeastern Honshu) and other Northeastern coastal areas of the country. The tsunami, in turn, caused a major nuclear accident at the Fukushima Daiichi Nuclear Power Station along the coast.[9] The 2011 earthquake in Tohoku was of magnitude 9 and lasted over 3 minutes. It was the most powerful known earthquake ever to have hit Japan, and one of the five most powerful earthquakes on record, since 1900 (Guha-Sapir D et al. 2012, 25). According to the Japanese Meteorological Agency, the earthquake early warning was sent 8 seconds after the detection of the first P-wave (Suppasri, Mas & Imamura 2013).

The ensuing tsunami inundated the east coast of Japan with waves reaching heights of up to 40 meters along the Sanriku coast. The tsunami resulted in overtopping of the 10-meter sea walls in Miyako city in Iwate Prefecture. The waves traveled 10 kilometers (six miles) inland in Sendai, affecting 271 square miles of the Sanriku coast. The hardest hit areas were in Iwate, Miyagi and Fukushima prefectures. According to the Japanese Meteorological Agency, the tsunami warning was issued just 3 minutes after the earthquake (Suppasri, Mas & Imamura 2013).

Complicating things further, the earthquake and tsunami disabled the power generators necessary to maintain operation of the Fukushima Daiichi Nuclear Power Plant in Okuma, Fukushima prefecture. Due to subsequent overheating, the Daiichi Plant suffered full meltdown in three reactors, resulting in a level 7 event (on International Nuclear Event scale of 1-7), exceeding the impact of the 1986 Chernobyl disaster. According to the Japanese Nuclear and Industrial Safety Agency, the radiation levels measured at the gate of the power plant property were more than eight times the normal level (CNN 2013).

Although, only "100 people died in the earthquake itself…almost 20,000 people lost their lives in the tsunami" (Ferris and Solis 2013). At the peak period of March 2011 to August 2011, there were a total of 399 evacuation centers in Iwate Prefecture and a total of 54,429 evacuees. As of 11 March 2013, 150,000 people remained evacuated from Fukushima prefecture, living in temporary housing.

In the course of the 2011 Japanese triple disasters, many CI sectors in affected prefectures suffered extensive damage. As a result, Japan experienced significant cascading effects as depicted in Figure 5.

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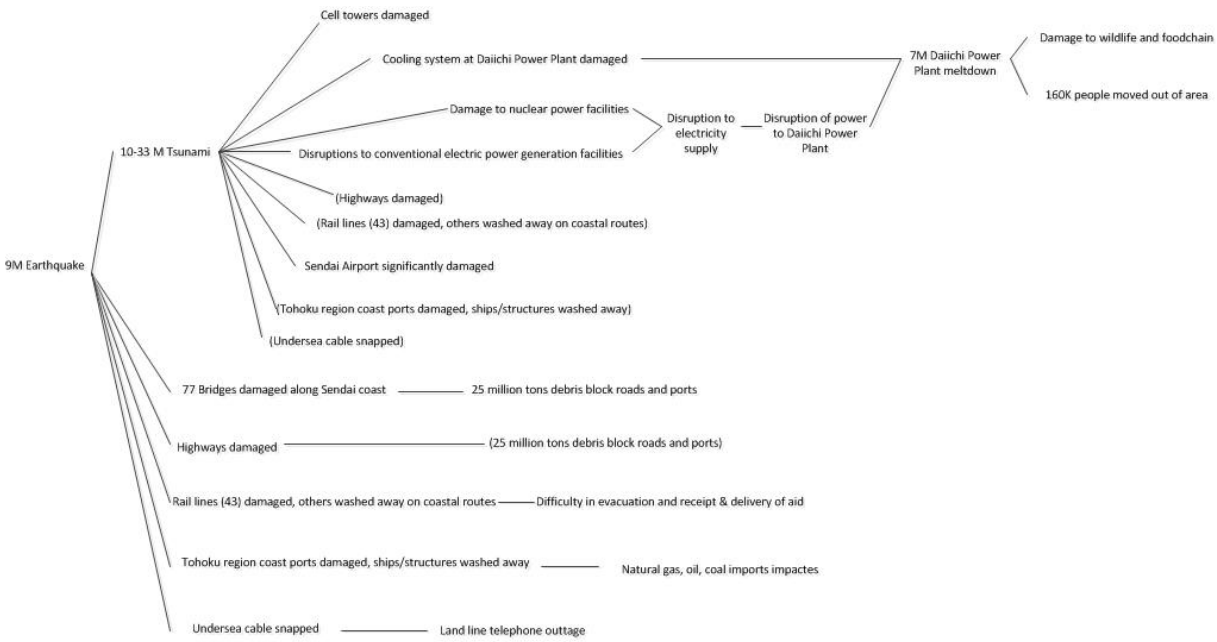
[9] Common references to the 2011 disasters in Japan include "the great East Japan earthquake" and "the Tohoku earthquake." Unless the study team considers a specific disaster's impact alone (i.e., earthquake only), this paper refers to the series of 2011 incidents experienced in Japan hereafter as "the 2011 Japanese tripple disasters" to ensure comprehensive reference to all three disasters.

Figure 5: Critical Infrastructure Cascading Effects Experienced during the 2011 Japanese Triple Disasters



The impact of the earthquake and tsunami was significant on the transportation sector. 3559 roads and highways and 77 bridges were damaged by the disasters. Further, 43 railway lines were damaged with 600 points on the rail destroyed, and 22 km of railway washed away or inundated by the Tsunami.

The earthquake and tsunami also damaged various air and sea ports, disrupting the transportation system further. Sendai Airport was significantly damaged by the tsunami, which flooded the airport and the runways. Tohoku region coast ports were devastated while port facilities, including cargo handling equipment and quay walls, were damaged (Tomita, Arikawa and Asai 2013). The destruction of the transportation network along with the resulting amount of debris singificantly disrupted the logistics of response activities (e.g., evacuation of residents) as well as the subsequent relief efforts (receipt and dissemination of aid). Moreover, the disabling of the transpotation sector in the mentioned areas temporarily suspended industrial and economic activity in the region (e.g., imports of natural gas, oil and coal).

Another CI sector whose disruption triggered cascading effects was the telecommunications sector. The earthquake and tsunami damaged undersea cables, cell towers and communications equipment, disrupting post-disaster communications and also telecommunications input to other CI sectors such as banking and financial operations.The Nippon Telegraph and Telephone Corporation (NTT), a Japanese telecommunications company, restricted 90% of mobile phone service to allow emergency communications among responders and Japan's government. More than 750,000 internet and telephone circuits were down.

The earthquake and tsunami disrupted the energy sector by damaging several nuclear power facilities as well as the conventional electric power generation facilities. 30% of (1.4 million barrels per day) Japans refinery capacity shut down due to the earthquake and aftershocks. Sources reported that " some 2.74 million households lost power after the earthquake" across the entire Japan…A month after the disaster, almost 100,000 households in the [Miyagi] prefecture still lacked power (Carafano 2011).[10] The loss of power caused adverse spill-over effects in rail transportation, manufacturing (with significant supply chain disruptions), potable water supply, and gasoline supply. Moreover, Japan experienced lingering economic effects deriving from the shutdown of nuclear reactors. Having increased oil imports to address the gap in energy supply, the country consequently suffered from "record trade deficits, in the order of $78 billion in 2012" (Ferris and Solis 2013).

Moreover, loss of power caused major nuclear fallout by triggering a complication in the Fukushima Nuclear Power Plant. As widely published, subsequent to the knockout of electric power by the earthquake, the backup generators were washed out by the tsunami, disabling the cooling systems. This in turn resulted in explosions, meltdown and release of significant levels of radioactive materials. This disrupted the power supply, and more importantly "complicated the overall response requiring evacuations, sheltering of evacuees, support for those sheltering in place, and disaster response assets that had to be dedicated to the incident" (Carafano 2011). According to the Japan Reconstruction Agency, 154,000 people were forced to evacuate the area strictly due to safety concerns associated with the radiation release (Tisdall 2014). Moreover, notwithstanding the overall economic cost of the incident, the resultant and the ongoing (to date) radiation leak has far reaching ramifications in terms of wildlife and food chain reservation as well as the long-term population migration and inhabitation trends in the impacted area. According to sources "… 21,000 residents of the area remain evacuated because of continuing high radiation levels… In the worst affected zone, return will not be allowed before 2017 at the earliest" (Tisdall 2014).

The Japanese triple disaster caused significant loss of life, injury and economic damage to the country. Accordingly, "the mega-disaster caused nearly 19,850 deaths, representing 64.5% of worldwide disaster mortality in 2011" (Guha-Sapir D et al. 2012, 1). The earthquake and tsunami comprised "the most expensive natural disaster ever recorded, with estimated economic damages of US$ 210.0 billion [3.9% of Japan's GDP]" (Guha-Sapir D et al. 2012,1,13).[11]

Both the earthquake and the tsunami were overpowering given their magnitude; nonetheless, the high population density, high rate of vulnerable populations and extensive infrastructure built in the region were compounding factors of the resulting cascading effects. Several sources report that in the areas hit by the triple disasters (rural, coastal towns), the average age was particularly high, complicating rescue and relief operations

[10] The original source for this information is from (as cited by Carafano 2011) The Special Headquarters for Measures to Assist the Lives of Disaster Victims, "Conditions of Lifeline and Infrastructure in the Affected Areas (Mainly in Iwate, Miyagi and Fukushima Prefectures)," April 14, 2011, at *http://www.cao.go.jp/shien/en/0-infra/infra.pdf* (May 17, 2011).

[11] This statistic only captures the natural disaster part of the 2011 triple disasters in Japan and does not include the cost of nuclear crisis it triggered.

(Associated Press/Huffington Post 2011).[12] According to Japanese National Police Agency statistics, "more than 56% of those who died were aged 65 or older, and almost three-quarters of those missing were over 60," making the large number of elderly victims "a defining characteristic" of the 2011 Japanese triple disasters (The Burn-Murdoch 2012).

Implications for Disaster Risk Reduction Efforts

Assessment 3 : Evaluation of the Hyogo Framework

In the previous sections, we emphasized the significance of understanding and attending to risk relationships in CI sectors to develop relevant risk reductions measures that minimize cascading disaster effects. We also advocated the idea that CI risks cannot be accurately characterized and effectively addressed by looking at sector specific risks alone; instead, owners and operators of CIs are required to recognize interactions of these risks and emergence of new ones. We developed a causal loop diagram that portrayed generic CI relationships in the context of a disaster and broader disaster impacts. To complement this theoretical framework and confirm its empirical validity, we reviewed events and effects of the 2011 Japanese triple disasters. Equipped with theoretical and empirical insights about CI linkages and the associated cascading effects during disasters we now turn to the task of assessing the adequacy of HFA indicators in addressing CI risks, cascading effects and the related risk reduction activities.

To accomplish this, we first mapped the 22 core HFA indicators to actual events encountered in the 2011 Japanese disasters and then subsequently mapped the indicators to disaster risk variables in the generic system map. These analyses were conducted to determine if the 22 HFA indicators corresponded to major events in a real-world scenario (whether those aimed at reducing risk or those responsible for creating risk) and variables in a generic system model.

Mapping of indicators to events and generic map variables was not a straight forward activity and inevitably required some exercise of subjective interpretation. However, the team sought to limit subjectivity by establishing and following clear rules for determining a match between an indicator and an event/variable. To further reduce subjectivity, team members were instructed not to 'force fit' a relationship between an indicator and an event/variable. Mapping of indicators to events/variables were guided by the following rules:

1) Enforcement of the indicator led directly to the (favorable) event, or could directly lead to a similar event in the future. As an example, in the Japanese triple disaster, upon receiving the tsunami warning, children in Kamaishi City evacuated their school and assisted elderly residents' evacuation efforts. We paired this event with HFA Indicator, 3.2 "School curricula, education material and relevant training include disaster risk reduction and recovery concepts and practices." In pairing this indicator with the event, we hypothesize that specific education and training programs prepared the school children for a disaster's expected effects and enabled them to assist others. Further, we believe education and training will be key to recreating a

[12] Statistics indicate that 23 percent of Japan's population is over the age of 65.

similar level of preparedness among school-age children during disasters faced elsewhere around the world.

2) Enforcement of the indicator could have prevented or mitigated effects of a particular disaster event. It is important to note that the team's assessment of these relationships does not include a risk-benefit assessment, therefore, relationships between indicators and events do not represent value judgments on decision making, but only note a relationship. For instance, our assessment paired HFA indicator 4.4 "Planning and management of human settlements incorporate disaster risk reduction elements including enforcement of building codes" with the failure of the Fujinuma Irrigation Dam in Sukagawa, which resulted in floods that washed away homes. This relationship assumes that planning human settlements downstream from a dam may lead to flood risks, which is counter to HFA indicator 4.4.

3) Multiple indicators may correspond to a single event.

4) Events and CLD variables that do not have clear or direct counterpart within HFA (i.e., lack of a pairing of event/variable with an indicator) indicate areas that HFA should incorporate for enhancement.

In accordance with the identified rule set, we began to map HFA indicators to events in the timeline for the 2011 Japanese triple disasters. Upon completing the mapping, we identified events that did not have associated HFA indicators. These events were then binned into categories of like events in an effort to identify outliers and one-off events. Categories of identified events were used to determine whether potential gaps in the HFA indicators existed. In addition to identifying potential gaps, our assessment yielded additional results of interest (e.g., indicators appearing most frequently, indicators with seemingly low relevance to real-world events, etc.). This timeline, with associated indicators is provided in Figure 6.

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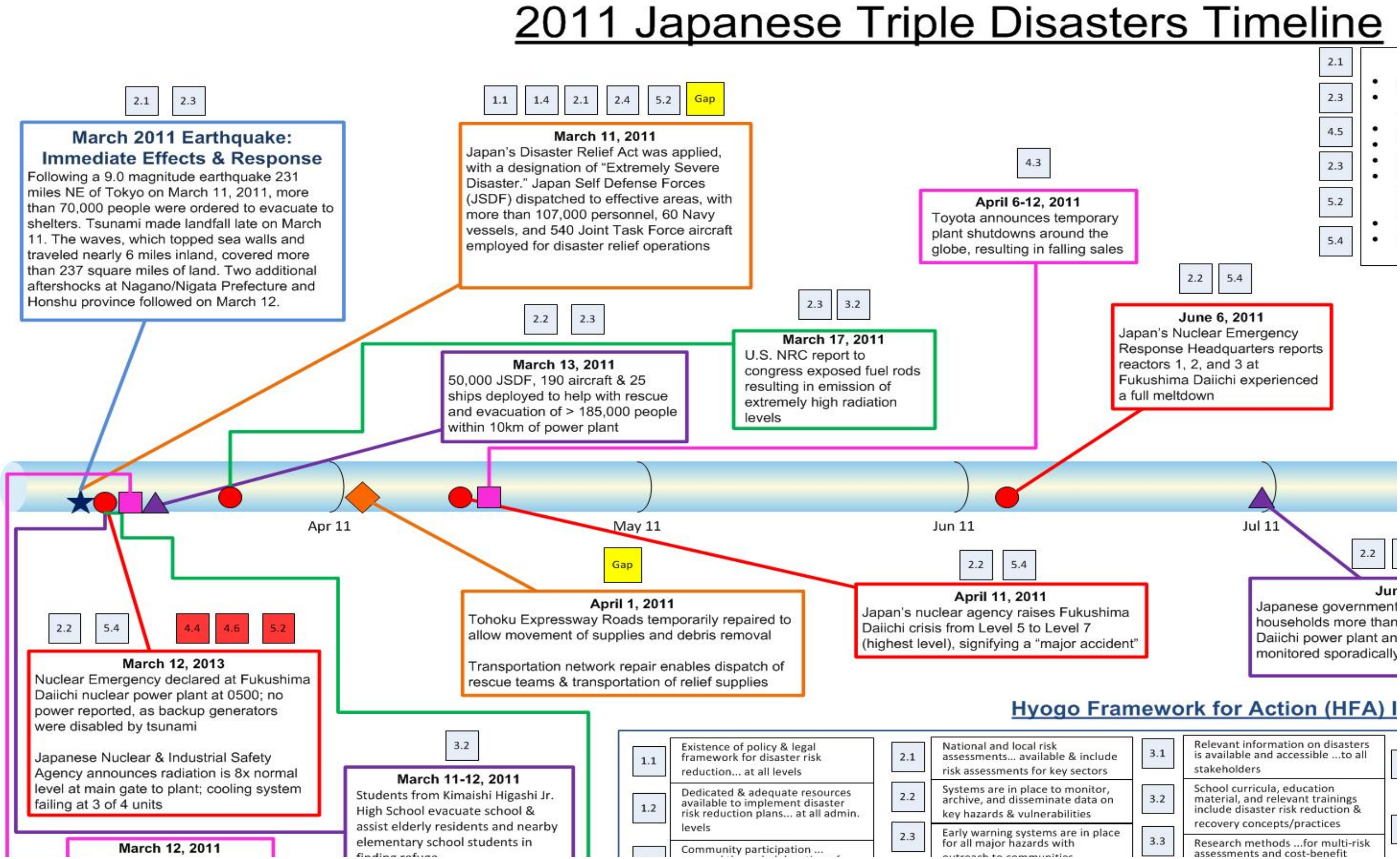
Figure 6: Japanese Triple Disaster Timeline with Indicators*



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Following assessment of indicators and events of the 2011 Japanese disasters, we compared indicators to variables within the generic causal loop diagram. This pairing utilized the same rule set, excluding rules applying to actual events. Similar to the outcome of the mapping of indicators to the timeline of events, this mapping revealed potential gaps in the HFA framework. Interestingly, initial results by both mapping exercises appear to indicate significant overlap in terms of potential gaps identified in the HFA framework. Below we provide a detailed discussion of insights attained.

Preliminary Results

Insights from mapping of the HFA indicators and disaster events

Our first mapping exercise focused on the relationship of indicators to the timeline of events in the 2011 Japanese triple disaster. At the most abstract level, this analysis reviewed frequency of indicator occurrence and ability to pair indicators with events. This analysis yielded two recommendations for change and some informative observations.

Recommendations:

Emerging from this mapping activity, we found events that spoke to the receipt of international aid did not have a corresponding indicator. Specifically, HFA indicators did not clearly map to the timeline's event of the United States' support to disaster relief efforts under United States Pacific Command (USPACOM) Joint Support Force Tomodachi. In the Japanese triple disasters, as well as in other major disaster events, international aid is often offered to facilitate country recovery. It is likely that in instances where international aid is needed, country officials will be focused on saving life and property (i.e., activities associated with immediate crisis management) and will have difficulty focusing on establishing policy and protocols for receipt of international aid. Nonetheless, timely acceptance and delivery of aid will be critical to recovery activities. In Japan's case, acceptance of international aid was difficult due to the chaotic nature inherent to post disaster operations in large scale disasters. Compounded this chaos though, were laws and regulations that limited international contributions, as well as "…other challenges regarding acceptance procedures and the organization of compensation systems for accident claims." (Cabinet Office of Japan, 2012, p. 10). As such, we recommend countries establish policies and protocols to facilitate acceptance of international aid in advance of disaster events. Specifically, we recommend the addition of a new indicator in *Action Area 1*. This indicator should address existence of national policy, protocols and/or legal frameworks that support the acceptance of international aid and provisions that reduce the impact(s) of disaster events.

Recommendation: Add indicator to *Action Area 1.* Address need for national policy, protocols and legal frameworks that support acceptance of international aid

Our analysis also highlighted the expediency with which Japan attended to repair of roadways, highways and bridges (Junko and Ishiwatari ND). This in turn, aided their ability to dispatch rescue teams and deliver supplies; mitigating further degradation of post-disaster conditions. Currently, *the HFA Indicator 5.2 (Disaster preparedness plans and contingency* *plans are in place)* speaks to general disaster preparedness plans. The indicator however, does not specifically address risks flowing from inter-related CI sectors. We propose to expand disaster planning activities to explicitly include prioritization of critical infrastructure recovery operations. While we fully recognize countries are susceptible to many threats, we believe it is possible to identify the most highly connected CI sectors in a country with greatest potential for cascading failures. As they embrace the philosophy of the HFA, countries should consider the interconnectedness of their CI sectors and the implications of losing any one particular sector. Japan's rapid movement to repair their transportation infrastructure was a critical enabler of their recovery, suggesting that flow of goods may be a critical enabler of broader recovery operations in many domains. By identifying critical infrastructure dependencies and risks, and incorporating strategies to prioritize CI recovery operations into disaster plans, countries may be able to reduce their overall disaster impact and minimize preventable post-disaster crises. Currently, *HFA Indicator 2.1 (National and local risk assessments based on hazard data and vulnerability information are available and include risk assessments for key sectors)* speaks to identifying hazards and vulnerabilities of key sectors, but does not provide a framework within which to take action to reduce risks of key sectors, nor does it discuss understanding how risk is amplified when more than one key sector is impacted. In light of these insights, we recommend adding an indicator, or sub-indicator to *Action Area 5*. This indicator should address the identification of CI interdependencies and prioritization planning for CI recovery operations.

Recommendation: Add indicator to *Action Area 5.* Address need to identify interdepencies across critical infrastructure (CI) and prioritize CI recovery operations

Though not directly flowing from the timeline analysis, we recommend an addition to HFA Action Area 2. This indicator should point towards National and regional risk assessments that account for interrelated disasters. As seen in the Japan triple disaster, each subsequent disaster further cripled already weakened infrastructures and communities; testing effectiveness and adequacy of even the most well implemented risk reduction measures. Therefore, HFA indicators should promote the recognition of highly correlated, interrelated disaster events (e.g. earthquake and tsunami) and the ensuing challenges associated with these events.

Recommendation: Add indicator to *Action Area 2.* Address National and regional risk assessments that account for interrelated disasters

Observations:

While recommendations flowed from gaps in the indicator/event pairing, several observations emerged from further assessment, primarily the frequency analysis.

Frequency analysis reveals *HFA Indicators 2.2 (Systems are in place to monitor archive and disseminate data on key hazards and vulnerabilities)* and *5.4 (Procedures are in place to exchange relevant information during hazard events and disasters and to undertake post* *event reviews)* had the strongest relationship to events in the timeline. These indicators, which address monitoring and warning capabilities and exchange of relevant information, proved instrumental in reducing impacts of cascading disasters. Ongoing monitoring and timely warning allowed Japanese residents to evacuate danger zones, which in turn reduced loss of life. These warnings were made possible by exchange of relevant information by different organizations with disaster monitoring responsibilities. While no recommendations flow from this observation, we believe countries should prioritize reporting and warning systems, as these save lives when protection activities fail.

Observation: Ongoing monitoring and timely warning allowed Japanese residents to evacuate danger zones, thus countries should prioritize reporting and warning systems

Frequency analysis also identified a relationship between undesireable events and poor implementation of indicators. For instance, we mapped a particular set of indicators to a set of negative disaster events. Specifically, we found indicators in *Action Area 4* most frequently mapped to negative critical infrastructure consequences. For instance, we mapped a relationship between the nuclear emergency at Fukushima Daiichi nuclear power plant and *HFA Indicator 4.1 (Disaster risk reduction is an integral objective of environment related policies and plans, including for land use, natural resource management and adaptation to climate change).* Here we propose placement of a nuclear power plant in a tsunami zone is counter to ideas communicated by *Indicator 4.1.* Similarly, we map the failure of Fujinuma irrigation dam to *HFA Indicator 4.4 (Planning and management of human settlements incorporate disaster risk reduction elements, including enforcement of building codes).* Here we propose establishment of settlements downstream from dams does not align with *Indicator 4.4.* As in our previous observations, recommendations do not flow from this observation. We do, however, view this observation as a reminder of the importance of risk –benefit decisions countries must make when planning communities and CI facilities.

Observation: Countries should consider risk-benefit decisions when planning communities and critical infrstructure facilities

Based on our frequency analysis, several indicators played a significantly lesser role in reducing risk-related events during the Japanese triple disaster timeline. These indicators spanned *Action Areas 1, 3, 4, and 5* and included *HFA Indicators 1.3, 3.3, 4.2, and 5.1*. Themes relevant across these indicators were not immediately intuitive. Indicators such as *1.3 (Community participation and decentralization is ensured through the delegation of authority and resources to the local levels)* and *3.3 (Research methods and tools for multi-risk assessments and cost benefit analysis are developed and strengthened)* reference more fundamental practices and capabilities that were likely established/employed long before the start of our timeline. However, further research into the 2011 Japanese triple disasters and/or other major disasters may bring to the fore additional observations and indicate patterns that are not obvious within this case study.

Independent of our frequency and gap analyses, two other insights emerged from consideration of the HFA indicators within the context of events unfolding across the Japanese disaster timeline.

Our first insight relates to the positive outcomes associated with implementing *HFA Indicator 4.5. (Disaster risk reduction measures are integrated into post disaster recovery and rehabilitation processes)* Specifically, our mapping analysis demonstrated a relationship between indicator 4.5 and rail system risk reduction. Following the 1999 Kobe Earthquake and its catastrophic impact on rail systems, Japan implemented an improved the Shinkansen Early Earthquake Detection System. During the 2011 disaster, this improved system automatically stopped power transmission to the trains but still allowed for application of emergency brakes. Although 19 high-speed trains were online when the earthquake struck, there were no casualties or train derailments (Cabinet Office of Japan 2012). This evidence provides a powerful case for incorporation of lessons learned into risk reduction activities and how they can save lives and prevent additional destruction. As we apply this forward, we see that a recent report by the Japanese government states Tokyo Electric Power Co.'s (TEPCO) response to the crisis experienced at the Fukushima Daiichi nuclear power plant was insufficient (Hancocks 2012). This creates an opportunity to identify lessons learned from response insufficiencies and incorporate them into future disaster plans, building codes, and community plans.

Observation: Japan's triple disasters provide a powerful case of effectively incorporating lessons learned to reduce risk

Our second insight relates to the role of indicator 4.3 (*Economic and sectorial policies and plans have been implemented to reduce the vulnerability of economic activities*) in the Japanese triple disaster. As noted in the disaster timeline, a major Japanese manufacturer, Toyota, incurred heavy damage to its suppliers' production plants. This later led to significant and global economic ramifications, as Toyota suffered a $1.2 billion loss in revenue. Although in Japan's case, "more than 70 percent of major companies...had completed or were developing [Business Continuity Plans] BCPs…" (Cabinet Office 2012, 26), the economic ramifications were still present. This incident speaks to the importance of strong economic policies with implications for both public and private sector entities.

Observation: Economic policies should encourage business continuity plans for both public and private sector entities

Insights from mapping of the HFA indicators and CLD variables

Our second mapping exercise focused on the relationship of HFA indicators and variables identified in the disaster CLD. Unlike our prior analysis, wherein we looked for frequency of occurrences, this analysis relied solely on noting a relationship between a HFA indicator and a CLD variable. Following the same rule set applied when mapping indicators to timeline events, we viewed each variable in the CLD and noted any correlated HFA indicators. Variables that lacked correlated variables were identified as potential gaps. These potential

HFA indicator gaps were then compared to the HFA indicator gaps noted in the timeline event. Interestingly, although we applied a different analytic approach and a generic model, our results were quite similar. As such, our recommendations and observations stemming from this analysis are comparable to those developed in the timeline analysis.

In this analysis, we looked at hub nodes, or variables with the most links connecting them to other variables in the disaster landscape. As an example, and as noted in the CLD analysis section of this paper, examples of two hub nodes in the CLD include the variables of disruptions in supply chain and disruption of power.

The supply chain is fundamental to recovery operations. One of the key reasons for its importance resides in its relationship to movement and eventual delivery of aid resources. As documented in the CLD, disruptions in the supply chain directly flow from port operations, road obstructions, damages to road/railway infrastructure and disruptions to air travel. As such, the urgency with which the transportation sector is up and running has direct implications for the supply chain. The real-world application of this was seen in the Japanese disaster timeline wherein road ways and bridges were repaired early on in the recovery process. This in turn, allowed for flow of supplies and aid to hard hit regions.

Similarly, as portrayed in the CLD, aid availability is predicated upon 1) open ports/roads 2) functioning supply chain 3) national aid availability 4) international aid. Currently items 1, 2 and 4 do not have corresponding indicators. These gaps within the HFA were noted during our evaluation of Japan's disaster response activities, wherein both the acceptance of international support and the rapid repair of the transportation sector occurred independently of related HFA indicators. These observations substantiate our recommendations regarding inclusion of new indicators within the HFA.

We also observed the supply chain's role in continuity of business. As theorized in our CLD, disruptions in the supply chain lead to disruptions in local and global manufacturing. This creates disruption amongst business operations, which in turn can impact economic sectors. This observation may suggest the need for indicators which specifically address private sector preparedness and coordinated planning between governments and the private sector. Furthermore, private sector entities may benefit by understanding the interrelated nature of CI risks and how cascading failures may impact their industry.

Our research found evidence of this causal relationship in the 2011 Japanese triple disasters. In this example, Toyota incurred losses due to the difficulties experienced in the production and distribution of parts by supplier industries within Japan. A major challenge was the disabling of a primary producer of automotive electronics in northeast Japan. Due to this, Toyota had to cut down on its auto production globally leading to severe economic ramifications. According a Global Assessment Report by UNIDSR, "Toyota lost $1.2 billion in product revenue from the Japanese quake due to parts shortages that caused 150,000 fewer cars to be manufactured in the United States and a 70 percent reduction in production in

Recommendation: Add indicator to *Action Area 5.* Address *Private Sector's* need to identify business and CI interdependencies and establish robust continuity plans that account for CI failures

India and a 50 percent reduction in China" (2013, 30). In fact the same report indicates that businesses lose their lifelines when disasters strike critical infrastructures. Clearly, critical infrastructure interdependencies amplify that effect when failure in one sector causes spill over failures in other sectors.

Our final observation relates to the strong relationship of HFA indicators to our CLD's exogenous variables such as situational awareness, pre-disaster planning and training, and vulnerable populations. With the exception of transmission of banking transactions and operation of financial markets, hub-nodes within the loop are not directly addressed by indicators. *The HFA Indicator 4.6 (procedures are in place to assess the disaster impacts of major development projects, especially infrastructure)* suggests procedures should be in place to assess risk impacts of a major project especially infrastructure; *Indicator 2.1 (National and local risk assessments based on hazard data and vulnerability information are available and include risk assessments for key sectors)* calls for risk assessment of key sectors; and *Indicator 5.2 (Disaster preparedness plans and contingency plans are in place at all administrative levels, and regular training drills and rehearsals are held to test and develop disaster response programmes)* speaks to having preparedness plans and exercises. However, as noted in during our evaluation of the 2011 Japanese disaster impacts, indicators do not speak to prioritizing key sectors from a protection and recovery standpoint. These observations, attained by mapping of the HFA indicators and CLD variables, further substantiates our recommendation to develop specific indicators that address interrelated CI risks.

> **Observation: HFA indicators do not speak to prioritizing key sectors from a protection and recovery standpoint**

Conclusion

The World Risk Report (2012, 14) defines risk as "interaction between a hazard (earthquake, flood, cyclone, drought, rising sea level) and the vulnerability of societies" wherein vulnerability is understood as "social, physical, economic and environment- related factors that make people or systems susceptible to the impacts of natural hazards and adverse consequences of climate change." In other words, whether environmental, natural or man-made hazards will result in a disaster, depends in part on our ability to design structures, develop processesses, and build capabilities and cultures that reduce risk. The Hyogo Framework, a UNISDR blueprint for disaster risk reduction, aims to guide partcipating countries to risk reduction activities.

Prepared as an input to GAR 2015, this paper focused on risk relationships and cascading effects in CI sectors in the context of disasters. We argued that the current research has made substantial progress in understanding risks relationships and cascading effects during disasters. There is growing understanding of complex interdependencies across CI sectors; nonetheless language and scope differences across studies makes it difficult to attain a comprehensive overview of the CI landscape and the related risks. This paper aimed to address this difficulty and also provide an assessment of the UNISDR Hyogo Framework for Action (2005-2015) by evaluating its adequacy to address disaster risks, in partiuclar interrelationships of CI risks and the subsequent cascading effects triggered by disasters. To accomplish these objectives, we provided three types of assessments:

First, using causal loop diagramming technique, we mapped generic relationships across a large number of CI sectors and characterized the relevant feedback structures that inform the critical pathways through which cascading effects occur. We also incorporated broader disaster variables into this map to account for the interaction of CI sector disruptions with the broader system elements (populations, activities, etc.). Then, we reviewed events of the 2011 Japenese triple disasters, characterizing the way in which various CI sectors were impacted and, in turn, how these impacts induced adverse consequences on local, national and even global scales. Finally, in light of this theoretical and empirical assessment, we evaluated whether the Hyogo Framework was sufficiently comprehensive to address the critical issues noted pertaining to CI risks, and cascading effects. Our preliminary observations and insights led us to present several informative observations along with four crucial recommendations to GAR15 for consideration during revision of the Hyogo Framework. Accordingly, our recommendations included:

1. In *Action Area 1*, a new indicator should address existence of national policy, protocols and/or legal frameworks that support the acceptance of international aid and provisions that reduce the impact(s) of disaster events.
2. In *Action Area 5*, a new indicator should address the identification of CI interdependencies and prioritization planning for CI recovery operations.
3. In *Action Area 2*, a new indicator should address National and regional risk assessments that account for interrelated disasters.
4. In *Action Area 5*, a new indicator should address the Private Sector's need to identify business and CI interdependencies and establish robust continuity plans that account for CI failures.

In this paper, we also presented the following observations:

- Ongoing monitoring and timely warning allowed Japanese residents to evacuate danger zones, thus countries should prioritize reporting and warning systems.
- Countries should consider risk-benefit decisions when planning communities and critical infrastructure facilities.
- Japan's tripple disasters provide a powerful case of effectively incorporating lessons learned to reduce risk.
- Economic policies should encourage business continuity plans for both public and private sector entities.
- HFA indicators do not speak to prioritizing key sectors from a protection and recovery standpoint.

The results presented here are preliminary insights of the first phase of our research. The next phases of our research efforts will focus on refining and validating these initial findings by studying cascading CI effects in the context of other disasters and collecting primary source data (interviews with government officials, emergency response planners and disaster management experts).

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