Nat Hazards (2007) 41:337–358
DOI 10.1007/s11069-006-9039-4

ORIGINAL PAPER

Infrastructure failure interdependencies in extreme events: power outage consequences in the 1998 Ice Storm

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Received: 22 March 2005 / Accepted: 4 December 2005 / Published online: 21 November 2006

Abstract This paper addresses the problem of interdependent failures of critical infrastructures in disasters. Disruptions to critical infrastructure systems such as electric power or transportation frequently cause major social and economic loss in disasters, both directly and through failures in one system leading to or compounding disruptions in another. Strategic approaches regarding infrastructure failures are needed to guide community mitigation and preparedness efforts. This paper defines and provides a conceptual framework for investigating infrastructure failure interdependencies (IFIs) from the standpoint of societal impacts. In order to identify empirical patterns, a unique database has been developed of IFIs observed in major electric power outage events. This paper presents analysis of this data for a major Canadian disaster, the 1998 Ice Storm that affected the northeastern region of the country. The analysis identifies IFIs due to power outage caused by the storm that are of greatest societal concern. These represent potential foci for effective, targeted pre-disaster mitigation and preparedness efforts. The framework and approach are broadly applicable across a range of natural and human-induced hazards.

Keywords Critical infrastructure · Infrastructure interdependency · Electric power · Natural disaster impacts · Disaster mitigation strategies · 1998 Ice Storm · Canada

1 Introduction

The impacts of natural disasters are often greatly prolonged and exacerbated by disruptions to critical infrastructure systems. Critical infrastructure includes electric power, water, transportation and other systems. Sometimes referred to as lifeline systems, they provide vital services for societal functions. Canadians rely on

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infrastructures that are essential to their health, safety and security in addition to their economic well-being. The loss of critical infrastructures in disasters—whether natural or human-induced in origin—can potentially result in widespread, catastrophic impacts that may seriously disrupt patterns of human activity (PCCIP 1997; Rinaldi et al. 2001). In fact, the Government of Canada (GOC) defines critical infrastructures as ''physical and information technology facilities, networks, services and assets, which if disrupted or destroyed would have a serious impact on the health, safety, security or economic well-being of Canadians or the effective functioning of governments in Canada'' (GOC 2004, p. 5).

Analysts, planners and decision makers have begun to recognize that critical infrastructure systems are highly interconnected and mutually interdependent in a variety of ways. For example, the Canadian government has taken the position that ''interdependency analysis must be integrated into risk management decisions, mitigation and preparation strategies, and response and recovery'' (GOC 2004, p. 10). Thus the disruption to electric power in a disaster, for instance, is significant not only for its direct impact on society but also in triggering or exacerbating disruptions to water, transportation, and other systems, that in turn cause further societal impacts. Following the 1998 Ice Storm, a major commission report concluded that critical infrastructures are dependent upon one another and, consequently, ''emergency preparedness policy should provide for systematic risk analysis for each essential infrastructure, including an assessment of the fragility resulting from interdependence among these infrastructures'' (Nicolet Commission 1999, p. 259).

This paper sets out a conceptual framework for characterizing the nature, extent and severity of the impacts of infrastructure failure interdependencies in disasters. We define infrastructure failure interdependencies (IFIs) as failures in interdependent infrastructure systems that can be traced back to some initial infrastructure failure associated with an extreme event. As defined by the National Science Foundation, extreme events are characterized by non-linear responses, low probabilities, high consequences and the potential for systems interaction that leads to catastrophic losses (Stewart and Bostrom 2001). Our framework is distinguished by its emphasis on interdependent failures, rather than interdependencies.

The electric power sector is a particularly important one to consider as an example for exploring infrastructure failure interdependencies. The risk of large-scale electrical failures from extreme events is increasing, because rising demand has not been met by sufficient capacity, leaving these systems more vulnerable to any kind of system disturbance. In the 1990s, consumer demand in the US increased 35%, while capacity increased only 18%. This discrepancy resulted in 41% more large outages in the second half of the decade (Amin 2004). Infrastructure systems in general are becoming more congested, making them increasingly vulnerable to failures. When major power outages affect other infrastructures, these interdependencies prolong and greatly exacerbate the consequences of the initial outage. In a real sense, the interdependency patterns are the pathways through which the secondary or indirect impacts of a major outage (due to a natural or human-induced event) ripple through societal interactions and economic activity. This will be demonstrated in this paper by applying the conceptual framework to the 1998 Ice Storm in northeastern North America as a characterization of IFIs in an extreme event disaster. Our framework can be viewed as a tool for exploring events that may occur during a large electrical failure. While other studies may provide a detailed analysis of a particular event (e.g., the Nicolet Commission report on the 1998 Ice

Storm), our objective is to develop a systematic framework for understanding IFIs that can be applied across events to develop a generalized knowledge base. It should be noted that because we focus on IFIs, our framework may not provide a comprehensive view of all the impacts in a natural disaster, excluding, for example, losses that are unrelated to critical infrastructure failures.

The next section discusses concepts and a conceptual framework characterizing IFIs. Section 3 describes the methods used for collecting data on IFIs in extreme event disasters. Section 4 presents the results of applying the framework to one particular extreme event, the 1998 Ice Storm.

2 IFI concepts and framework

2.1 Concepts of infrastructure interdependencies

Rinaldi et al. (2001) provide a basis for systematically understanding the extent to which infrastructure systems are interdependent, and thus vulnerable to multiple, sequential failures. They provide a set of dimensions for describing infrastructure interdependencies, as well as a set of definitions for these dimensions and related terms (discussed further in Sect. 2.3 below). While they clarify several aspects of infrastructure interdependencies, they only briefly discuss types of failures within complex infrastructure systems. Finally, they, and others (Thomas et al. 2003; Ezell et al. 2000) emphasize a view of infrastructures as complex adaptive systems, with emergent properties that can only be discerned by studying the system interactions in aggregate.

This paper builds directly on the work mentioned above by developing measures and characterizations of specific kinds of IFIs within a defined area of infrastructure systems (typically within a city or region). We seek to explore a set of specific questions that must ultimately be answered in order to make a systemic perspective relevant for risk management decisions:

(1) What consequences matter most when examining the potential for failures in interdependent infrastructure systems? What consequences matter most for decisions about managing these failures?
(2) How can one define and estimate the likelihood of IFIs in a given context?
(3) How can one judge the severity of the consequences of IFIs?
(4) What patterns of IFIs are the most significant sources of concern?

To address these questions, we adopt an empirical approach that seeks to characterize patterns of IFIs and their impacts. Rather than beginining with modeling infrastructure systems and their interdependencies, we start by conceptualizing IFIs from the standpoint of impacts to society.

2.2 Judgment as a basis for characterizing the societal consequences of IFIs

Any basis for answering the questions just outlined will necessarily rely on judgment. Choosing which consequences are important to society relies on values, while defining how those consequences are measured and categorized relies on technical understanding, both of which involve judgments. Many authors have stressed the fundamental role of judgments, and hence the unavoidability of subjectivity, in all kinds of risk analysis (NRC 1996; Keeney 1982; Morgan and Henrion 1990; Slovic 1999; McDaniels and Small 2003). There are well-developed methods for eliciting judgments from technical specialists (Morgan and Henrion 1990; Keeney and von Winterfeldt 1989, 1991) and value judgments from interested parties (Keeney 1992) when required for specific risk or decision analysis. However, the specificity of criteria necessary to guide analysis and thus the reliance on efforts to elicit judgments from interested and informed parties differs depending on the context and the purpose.

In this case, our purpose is to characterize the broad consequences of IFIs for society, to seek patterns of these interdependencies in specific events, and in future research to make comparisons across events, as a basis for guiding future mitigation efforts. These analyses require two kinds of judgments: (i) what types of impacts matter to society, and (ii) how to judge, in comparative terms, across a wide variety of contexts, the broad societal implications of these impacts when they occur in extreme events. For the first question, we conducted a review of the kinds of interdependencies that have been identified in others studies (e.g., Rinaldi et al. 2001), the literature on the impacts associated with natural disasters generally (e.g., Mileti 1999), and the writing regarding structuring objectives for public policy issues related to societal risk management. These steps led to a list of potential consequences from IFIs that could be important to society, depending on the scale of impacts: *human health and safety impacts, economic impacts, environmental impacts, and social impacts*. The second question calls for a common set of attributes or performance measures to broadly compare these various kinds of impacts and judge their relative significance. We drew on the writing regarding risk perception (Slovic 1987) and risk analysis (McDaniels and Small 2003) to identify several key variables that we can use as the basis for constructed scales to characterize impact levels, a widely employed approach (Keeney 1992). The scales used for these broad comparisons include the *severity* of the impact to affected groups, the areal *extent* of the impact, the *number of people* within the affected area who experience the consequences, and the *duration* of the impacts, which may well be longer than the power outage. These broad categories are similar in many respects to the characteristics used for ''risk ranking'' or *ex ante* priority setting across a wide variety of risk management contexts (Finkel and Golding 1994). Taken together, these scales provide a common basis for broad comparisons across a wide variety of impacts occurring after an extreme event, in terms of the significance of impacts to society. The specific structure and levels of these scales is discussed in the next section.

2.3 A framework for characterizing IFIs

We develop a conceptual framework in order to facilitate the characterization of infrastructure failure interdependencies with empirical data. The framework design is based upon a consideration of the questions outlined in Sect. 2.1 above, specific judgments as noted in Sect. 2.2 above, and a review of the literature on critical infrastructure interdependencies. Our framework is distinguished from others in the literature by its emphasis on societal consequences.

Table 1 summarizes the conceptual framework, in which a specific instance of an IFI is described by three major groups of characteristics (i.e., variables)—those of the electric power outage that triggers the IFI, those of the failure that is caused by

Table 1 Framework for infrastructure failure interdependencies

Characteristic	Value	Explanation
Outage		
Date	Various	Date the outage first occurred
Description of event	Various	General location and description of the event
Initiating event	Internal External	Mechanical or human error within the power system Event outside the power system such a severe storm
Spatial extent	Local Regional National International	One city or area affected More than one city or area within a province or state affected More than one state or province affected More than one country affected
Duration	Minutes, hours, days, weeks	Approximate amount of time it took to restore power to 90% of affected customers
Weather conditions	Moderate Extreme	Normal weather conditions for the season Unusual weather conditions such as a severe storm
Temperature	Cold Hot Mild	Below 32°F/0°C Above 90°F/32°C Between 32° and 90°F/0° and 32°C
Interdependency		
Impacted system	Building support, business, education, emergency services, finance, food supply, government, health care, telecommunications, transportation, utilities	System affected by power outage
Specific system	Various	Subdivisions of the impacted systems
Description	Various	A brief summary of the impact on the system

Table 1 continued

Characteristic	Value	Explanation
Type of interdependency	Physical	The system requires electricity in order to operate
	Geographic	The system is co-located with electrical infrastructure
	Cyber	The system is linked to the electrical system electronically or through information sharing
	Logical	The system depends on the electrical system in a way that is not physical, cyber or geographic
Type of IFI	Cascading	The disruption of the power system directly causes the disruption in the impacted system
	Escalating	The disruption of the power system exacerbates an already-existing disruption in the impacted system, increasing the severity or outage time
	Restoration	The power outage hampers the restoration of the impacted system
	Compound damage propagation	The power system disruption leads to a disruption that then causes serious damage/accidents/problems in the impacted system
	Substitutive	A system is disrupted due to demands placed on it to substitute for the power system
Order	Direct	The IFI is a direct result of the power outage
	Second-order	The power outage is once removed as the cause of the system disruption
	Higher-order	The power outage is twice or more removed as the cause of the system disruption
System failure leading to this effect	See impacted system for list	Electrical in the case of direct-order events; the system that caused the disruption in the impacted system in the case of second- and higher-order events
Complexity	Linear	Expected and familiar interdepencies
	Complex	Unplanned or unexpected sequences of events
Feedback	Yes	The impacted system impacts the power system
	No	The impacted system does not impact the power system
Operational state	At capacity	The impacted system was operating at 100% when the power outage occurred
	Near capacity	The impacted system was operating above 90% when the power outage occurred
	Below capacity	The impacted system was operating at 90% or below when the power outage occurred
Adaptive potential	High	The system has the ability to respond quickly in a crisis
	Low	An inflexible system that cannot respond quickly

Table 1 continued

Characteristic	Value	Explanation
Restart time	Minutes, hours, days, weeks	The amount of time required for the impacted system to return to pre-outage operating capacity once electric power has been restored
Consequence		
Severity	Minor	Minor modifications in daily routine or plans that cause negligible hardship to the person or entity
	Moderate	A few modifications in daily routine or plans that cause some hardship to the person or entity
	Major	Significant modifications in daily routine or plans that cause considerable hardship to the person or entity
Type	Economic, health, safety, social, environmental	Primary category under which the consequence falls
Spatial extent	Local	One city or area affected
	Regional	More than one city or area within a province or state affected
	National	More than one state or province affected
	International	More than one country affected
Number of people	Few	In the spatial extent of the consequence, one neighborhood or isolated individuals were affected
	Many	In the spatial extent of the consequence, up to 50% of the population was affected
	Most	In the spatial extent of the consequence, at least 50% of the population was affected
Duration	Minutes, hours, days, weeks	The amount of time the consequence endures, which may be greater than the restart time

power outage in an interdependent infrastructure, and those of the societal consequences of this interdependent failure. Table 1 lists the characteristics and defines the actual, range, or type of their associated values.

The first group in Table 1, outage characteristics, provide a typology of power outage events that can be used to structure a systematic comparison of IFIs across event types. Weather conditions, duration of outage, and spatial extent of the outage are all expected to influence the occurrence probability, type, and severity of disruptions to dependent infrastructures, as well as the ensuing societal impacts. Outages arising from within the electrical system (e.g., due to mechanical problems) are likely to be materially different from those that arise from outside the system in the context of complex natural disasters.

The interdependency characteristics shown in Table 1 are largely drawn from key concepts in the literature. The seminal work of Rinaldi et al. (2001) and Peerenboom et al. (2002) on understanding infrastructure interdependencies characterized four types of interdependencies—physical, cyber, geographic and logical—with human decisions playing a particular role in the logical interdependencies. The concepts of ‘‘cascading’’ and ‘‘escalating’’ interdependencies are also generated from their work.

Further insightful concepts are adopted from the ‘‘lifeline interactions’’ literature in the study of natural disasters. This literature provided particularly useful empirical observations and conceptual characterizations of interdependencies from the perspective of interdependent failures. The work of Nojima and Kameda (1996) on lifeline interactions in the Kobe earthquake developed the concepts of ‘‘compound damage propagation’’ and ‘‘restoration’’ types of IFIs. Yao et al. (2004) use multiple earthquakes to develop their classification of lifeline interactions and discuss all of the IFI types mentioned above, albeit with different labels. They also include an additional category, substitute interaction, which is called ‘‘substitutive’’ in our framework.

Rinaldi et al. (2001) distinguish between dependency and interdependency, defining dependency as a unidirectional relationship and interdependency as a bidirectional relationship between systems. We make no such distinction in our framework, except for the inclusion of a feedback characteristic that indicates whether a particular IFI has a return effect on the power system. The IFI characteristics of complexity, operational state and adaptive potential are articulated in Peerenboom et al. (2002).

The final group of characteristics in the framework relate to societal consequences. Of the five consequence characteristics in the framework (type, duration, severity, spatial extent and number of people affected), all except ‘‘type’’ relate to the magnitude of the impact. To accommodate different potential data types and to facilitate analysis, these characteristics are defined in relative terms along essentially simple, 3-point constructed scales. The specific levels or values chosen for each reflect the experience of the first author in extensive work regarding the socioeconomic impacts of disasters. While the selected levels are judgment-based, as are all constructed scales, they also provide a consistent basis for simple ‘‘low–medium–high’’ characterizations of the societal consequences in terms of each scale. We also implement a relative weighting scheme for quantifying these consequence scales, as shown in Table 2.

This weighting scheme permits synthesizing these four consequence characteristics into two indices that can be, respectively, labeled ‘‘impact’’ and ‘‘extent.’’ The

Table 2 Weights for consequence levels

Consequence characteristic	Weight = 1	Weight = 2	Weight = 3
Duration	Hours	Days	Weeks
Severity	Minor	Moderate	Major
Spatial extent	Local	Regional	National/International
No. people affected	Few	Many	Most

Impact Index (ranging from 1 to 9) is defined as the product of an IFI's duration and severity weights. High values of impact indicate consequences that are severe and of long duration. The Extent Index (ranging from 1 to 9) is defined as the product of the IFI's spatial extent and affected population weights. High values of extent indicate great numbers of people affected over a large geographic area.

3 Data and methods

The framework outlined above can in principle be implemented with a broad range of data types, including data from interviews, surveys, investigative reports, and media accounts. It can also be used to compare and integrate data on IFIs across data sources. Each type of data entails certain advantages and disadvantages. Interview data (e.g., key informant interviews with emergency managers) can provide detailed, contextualized, and little-known information; however, they are relatively difficult or costly to obtain—particularly for comparative study across many disasters—and represent the perspectives of individuals who may only be aware of limited aspects of the disaster. They are also reliant on personal and institutional memories, which can be inaccurate. Survey data can provide a broader cross-section of perspectives, but are even more resource-intensive. Investigative reports (e.g., reports by commissions) can be very useful, but are not available for many disasters. They are also methodologically inconsistent across disasters when available; for instance, commission reports often focus on the causes of a disaster or on policy recommendations but do not necessarily gather detailed data on IFI impacts.

Print media accounts have three principal advantages: accessibility, a focus on impacts, and comprehensiveness. They are readily available at low cost and, particularly for recent disasters, accessible online and via search engines. They are a particularly good source of information on societal impacts, such as deaths, dislocation, or disruption of economic activity. Perhaps the most important advantage is their comprehensiveness: they provide the "big picture" of societal impacts across all dimensions of impacts and sectors of communities that are beyond the purview of any individual. For example, they may contain data on economic disruptions that an emergency manager would not be cognizant of. They also provide snapshot records of situations across many points in time, such as on a daily basis throughout the duration of the disaster. Potentially, a fourth advantage is that of consistency, to a reasonable degree, in the availability of data across disaster events. It is for these reasons that we draw primarily on data from newspaper articles in developing our database on IFIs. While newspaper accounts may not be the most favorable data source for any single event, they represent perhaps the best source for making systematic comparisons across events.

It is important to recognize the limitations of this type of data. Some of the most significant limitations include various concerns about potential bias. Newspaper accounts may suffer from biases of both inclusion and exclusion. They may report on sensational stories that are unimportant or inflated from the standpoint of societal impact. On the other hand, they may fail to report on important impacts for any number of reasons—lack of information, lack of awareness, lack of attention if another issue is dominating the news cycle, etc. It is likely that certain types of IFIs and impacts will be systematically under-reported in media accounts, including "near-misses" (i.e., interdependent failures that were close to actually occurring), IFIs considered sensitive for security or safety reasons, and IFIs occurring in small towns, rural areas, or under-privileged neighborhoods. These limitations suggest the need to validate and supplement data from newspaper accounts with information from other sources. However, it is reasonable to expect that reporting issues may be of lesser concern in the case of truly significant societal impacts; that is, a major fire that causes numerous deaths is likely to be reported in any circumstance.

In order to characterize IFIs in various power outages, we have built a database that applies the characteristics and values in our conceptual framework. This database is populated using data drawn primarily from newspaper articles and supplemented by the work of other researchers. Each record in the database consists of an observed IFI that was sufficiently noteworthy from a societal standpoint to be reported in major media or other reports. This database already contains close to a thousand IFIs occurring in eight major events, including the August 2003 Northeast blackout, the 1998 Ice Storm also in the Northeast, the 1995 earthquake in Kobe, Japan, and several windstorm and hurricane events in the US. Human and mechanical failures caused the 2003 blackout, unlike the other events where natural hazards initiated the outages. Each record in the database represents a unique IFI, so that multiple mentions of the same IFI in several articles or sources are consolidated into a single entry. As indicated in Table 1 above, each IFI record contains information on the dependent infrastructure sector that was affected by the outage, the ensuing service disruption, and categorical measures of the various dimensions of consequences for the affected communities. This database is distinguished by its focus on IFIs, its coverage of many disasters, and its emphasis on societal impacts.

4 The 1998 Ice Storm

To illustrate the framework application, the empirical portion of this paper focuses on one of these events, the January 1998 Ice Storm. This disaster, one of the most severe in recent Canadian history, began as several waves of freezing rain. Failures in the electric power transmission and distribution systems "transformed the weather disaster into a technological disaster, with the other technological [critical infrastructure] systems then experiencing the repercussions of the power outage" (Nicolet Commission 1999; p. 253). The 1998 Ice Storm left some 4.7 million people in Canada, or 16% of the population, without power for hours, days or weeks at the height of the storm (Lecomte et al. 1998). The disaster caused 30 deaths and cost various levels of Canadian government some $1.7 billion. Considering quantifiable losses to the private sector as well, the cost to Quebec has been estimated at nearly $3 billion (Nicolet Commission 1999). Purcell and Fyfe (1998) note that the Ice Storm demonstrated how dependent Canadian society is on electrical power and how vulnerable it is to power outages.

4.1 Database

A database of infrastructure failure interdependencies was developed for this disaster using the framework presented above and various data sources, consisting primarily of articles appearing in the *Montreal Gazette* and the *Ottawa Citizen*. We generated a list of relevant sources for our database by performing keyword searches (e.g., electricity, power, blackout, ice storm) on news articles through the ProQuest® online information service. Once relevant articles were identified, we applied several criteria for including information as an IFI record in the database: (1) the impact must be related to the power outage, rather than due exclusively to other factors such as ice buildup; (2) the impact must be caused by a failure in some other critical infrastructure that in turn was caused by power outage; and (3) information must be available on societal impacts. Once an IFI was identified for inclusion it was described by filling in, to the extent possible, the various characteristics in the framework shown in Table 1 above. In addition to the characteristics in Table 1, information was also entered as a freeform description of the IFI and on the source article itself. An iterative process was applied, whereby all mentions of IFIs were first entered, then subsequently consolidated, organized, and iteratively verified.

The database includes 107 records of IFI occurrences and their impacts. IFIs were noted in 11 sectors: building support, business, education, emergency services, finance, food supply, government, health care, telecommunications, transportation and utilities. These are almost identical to the Canadian government's list of critical infrastructure sectors: energy and utilities; communications and information technology; finance; health care; food; water; transportation; safety; government; and manufacturing. The IFIs identified by our study are also similar to the five essential infrastructures named in the Nicolet Commission report, including : (1) information and communications, (2) transportation, (3) energy, (4) the banking and financial system, and (5) vital human services such as drinking water systems, emergency services, health care, and food supply systems (Nicolet Commission 1999). Appendix Table 3 provides an extract of the database in terms of a listing of the recorded IFIs in the 1998 Ice Storm database and their index values. Each IFI record is labeled by a sector and identifier number; for example, Building Support [11] refers to a datapoint characterized as lack of electrical heating that led to four deaths from hypothermia.

4.2 Analysis

Analysis was conducted to examine patterns of societal impacts caused by IFIs and to identify IFIs and critical infrastructure sectors and subsectors that were associated with the most severe societal consequences. Each of the major infrastructure sectors includes many subsectors, and each of these can potentially experience different types of IFIs. For example, the transportation sector includes subsectors such as mass transit and road transportation. IFIs for road transportation may include non-functioning traffic signals and inoperational gas stations for refueling vehicles. The severity of the IFI consequences was measured according to the Impact and Extent indices described in Sect. 2.3 above.

Figure 1 plots the 107 identified IFIs for the Ice Storm in two-dimensional space according to their Impact and Extent indices. IFIs with the same pair of index values are plotted as a single point with multiple record labels. The labels identify

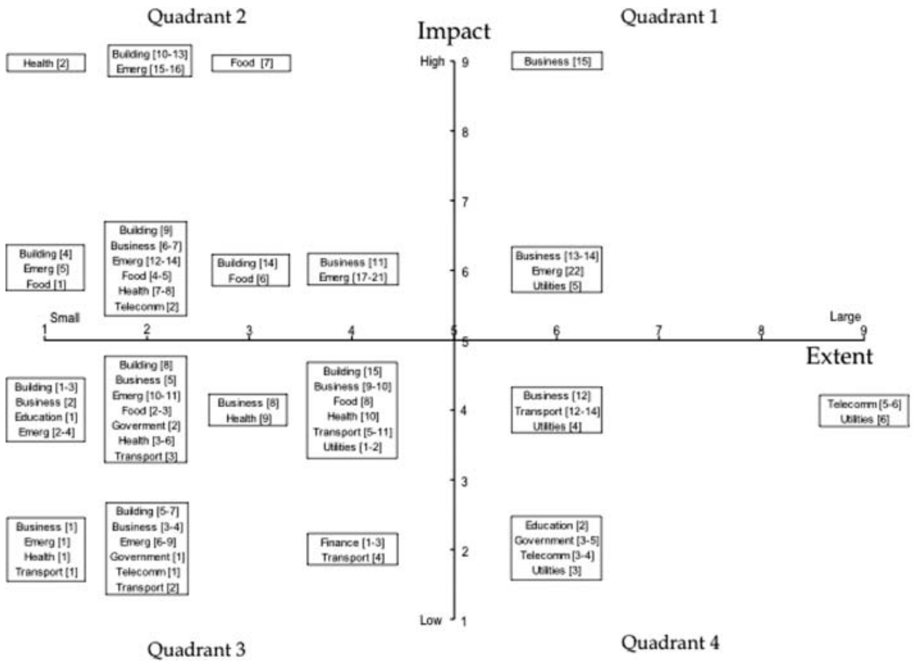

Fig. 1 Impact and extent of electric power IFIs in the 1998 Ice Storm

individual IFIs in terms of their sector and (in square brackets) identifier number within that sector. These identifiers can be used to look up the IFIs in the data abstract in Appendix (Table 3).

Figure 1 also separates the IFIs into four quadrants. Axes separating the quadrants are located at the respective midpoint values of the potential range of Impact and Extent index values (i.e., 5 on a scale of 1–9). Quadrant 1 represents major disturbances to a majority of the population, while Quadrant 2 includes major disturbances to a small percentage of the population. Quadrant 3 indicates minor inconveniences to a small percentage of the population. Quadrant 4 represents IFIs that caused minor inconveniences to a large percentage of the population.

From a societal point of view, IFIs in Quadrant 1 may be of greatest concern. All else equal, IFIs with both high impact and broad extent of impact are of greater concern than those with lesser impact and/or extent. In the Ice Storm event, five IFIs were in Quadrant 1, the most disruptive of which (Business [15]) was that major employers south of Montreal reported that they would be shut down for up to 2 weeks due to the power outage. Not only were large numbers of people affected in this case, but severity and duration of the consequences were also high. The manufacturing industry was one of the sectors that contributed to the short-term loss of $1.6 million in Canadian dollars (CAD) to the economic output of the country—a 0.2% loss in overall real gross domestic product (Lecomte et al. 1998). Other IFIs in the quadrant 1 include communication difficulties in emergency services and fuel shortages due to temporary closure of two major oil refineries. Consumers were affected by businesses that ran low on critical, high demand items (e.g., candles, batteries, fireplace logs and emergency supplies). Power outages caused Hydro Quebec to request voluntary closures from business in order to accelerate repairs.

Quadrant 2 contains IFIs that had high impact but relatively small extent. For example, several Montreal hospitals experienced periodic power outages lasting up to several hours and many had problems associated with contaminated water. Important hospital routines were also disrupted (e.g., elective surgery and clinics were cancelled, ambulances were too busy to provide inter-hospital transfers). Farmers suffered an estimated 14 million CAD in lost revenues in Quebec and 11 million CAD in Ontario (Lecomte et al. 1998). Reasons for these losses ranged from no refrigeration, no heating and improper air circulation in barns, to loss of dairy cows due to milking machine failures (some of which died because they could not be milked). There were also countless other problems stemming from heat system failures. Four people died from hypothermia, and seven people died from carbon monoxide poisoning while using poorly ventilated heating sources. Emergency crews (especially firefighters) also became strained when many houses and apartments caught fire. Five people died during these fires, and a total of 28 deaths were attributed to the Ice Storm (Lecomte et al. 1998).

Quadrant 3 contains IFIs that caused inconveniences to a small portion of the population. As shown in Fig. 1, this quadrant contains more records than any other. Examples include reduced bus service, cancellation and delays of flights at airports, and motorists having difficulty finding functioning gas stations. Furthermore, people had no information on road conditions due to the communication failures. Many people experienced basement flooding from melting ice, and numerous households that suffered bursting pipes were unable to react when sump pumps could not be powered up. It should be noted that burst pipes were the third most expensive item for insurers.

Quadrant 4 contains IFIs with high population inconveniences. While many people were affected by these IFIs, the impacts were not as severe and/or long-lasting as in Quadrant 1. Some of the more notable inconveniences include massive school closures and lack of power for pumping fuel. Water pressure became a concern due to fires from improper heating. As water plants had only 4–6 h of clean water left, the general public was issued a water boiling advisory. Perhaps the most time-consuming problem was associated with telecommunication challenges. Public fears were exacerbated through intermittent or poor communication.

Figure 1 also allows a comparison of IFIs across dependent infrastructure sectors from the point of view of societal impacts. IFIs from disruptions to Finance infrastructures were confined to Quadrant 3, i.e., were relatively low in both Impact and Extent. Building Support, Food Supply, and Health Care IFIs were relatively low in terms of Extent, but could be high in Impact, with some IFIs even resulting in deaths. Education, Government, Telecommunications, and Transport IFIs tended to be relatively low in Impact, but could be high in Extent. Emergency Services, Utility, and Business IFIs spanned three or four quadrants and included some of the most disruptive impacts.

In sum, the application of the Infrastructure Failure Interdependencies framework to the case of the 1998 Ice Storm has provided insights into how electric power outages affect other critical infrastructures and consequently cause disruptions to society in extreme event disasters. It further demonstrates strengths and limitations of the methodological approach taken here for investigating IFIs. Three points are particularly noteworthy. First, this approach provides the "big picture" of infrastructure failure interdependencies. It systematically presents data to show that IFIs from power outage were pervasive and greatly compounded the direct effects of the ice storm itself. Power outages caused disruptions to all 11 other critical infrastructures in the form of 107 distinct IFIs. Of these, significant disruptions—defined as IFIs with relatively high Extent and/or Impact indices (Quadrants 1, 2, and 4 of Fig. 1)—included some 50 IFIs across 10 dependent infrastructures. This type of holistic view of a disaster's impacts exceeds the purview of any individual or group of individuals. It further reveals some surprises; for example, that manufacturing plant shutdowns due to the power outage were the most significant IFI from the perspective of overall societal impacts, even though this may not have been as memorable or dramatic as other dimensions of the disaster.

It should be noted that the data and analysis describe IFIs from power outage as they occurred in a particular disaster event. Should another similar ice storm strike the same region again, the pattern of IFIs and their consequences could very well be different—infrastructure providers, businesses, and households may have learned from the previous disaster and engaged in preparedness and mitigation actions. Indeed, differences in IFI patterns would be able to provide some indication of the effectiveness of these actions. Similarly, pattern differences can also be used to identify more and less-resilient communities from among those that faced a similar outage event.

Second, the analysis identifies IFIs, critical infrastructure sectors, and subsectors that, from the perspective of vulnerability to power outages, particularly merit further research and mitigation attention. These (found in Quadrants 1, 2, and 4 of Fig. 1) should be compared to empirical data from other extreme event disasters to identify recurrent patterns of vulnerability and disruption. The significance here is that these priorities are based on a consideration of IFIs that caused the greatest societal disruptions—not from a technical perspective of physical vulnerabilities in the infrastructure system.

Third, the analysis demonstrates both the advantages and disadvantages of using media data for preliminary investigation of IFIs. As discussed in Sect. 3 above, the advantages include ready access, a focus on consequences, and a comprehensive view of the disaster. For these reasons, media data are particularly well-suited to developing a knowledge base that makes comparisons and generalizations across disaster events and types. However, the disadvantages of this type of data, including for example biases and omissions, should be investigated through comparisons with other types of data, including key informant interviews, official commission reports where available, etc.

5 Conclusions

Virtually every crucial economic and social function depends on the secure, reliable operation of critical infrastructures. Electric power systems constitute a fundamental infrastructure in modern society (Amin 2004) whose disruption can cause ripple effects throughout other infrastructure systems. The 1998 Ice Storm demonstrated the wide array of system and interdependent infrastructure failures that can occur in and exacerbate the effects of natural disasters. Increasing societal resilience to disasters requires understanding and mitigating not only the risks to individual infrastructure systems, but also mitigating how failures in one system can lead to disruptions in others, exacerbate response and recovery efforts, or result from common cause failures. Understanding such interdependencies is necessary if planners, operators and emergency response personnel are to deal effectively with infrastructure disruptions (Peerenboom et al. 2002).

This paper presents the conceptual basis, approach and initial progress on an investigation of infrastructure failure interdependencies (IFIs) caused by electric power outages. Strategic approaches are needed to guide mitigation and community preparedness for future major outages and their disruptive effects. Such mitigation requires systematic empirical knowledge about IFIs, which has hitherto been scant. This paper makes three initial advances toward addressing this knowledge gap. First, it presents a conceptual framework for characterizing IFIs on the basis of societal, rather than technical, considerations. Second, it develops a unique database of IFIs observed in a major Canadian disaster, the 1998 Ice Storm. Third, it demonstrates how the framework can be applied to empirically identify IFIs of greatest societal concern. These represent potential focal points for pre-disaster mitigation and preparedness efforts, which should be investigated in further research.

The preliminary analysis presented here suggests several areas for further research. The analysis does not incorporate weights or value judgments across types of IFI impacts. From a policy perspective, severe economic disruptions such as temporary business closures may not be equivalent, for example, to severe safety impacts such as deaths. Frameworks for addressing different types of consequences are needed. For example, the Nicolet Report placed a strong focus on public discussion during their analyses. The Commission toured 22 municipalities and traveled to 14 Monteregie MRCs (regional county municipalities) affected by the disaster and as a result, were also able to speak to the psychosocial impact of the disaster (Nicolet Commission 1999). Also, the empirical approach adopted here can be used to complement probabilistic, systems-based and simulation models of power outages and their impacts. Such models may identify low-probability, high-consequence events and impacts that could potentially but have not yet actually occurred, which therefore would not be amenable to empirical analysis. However, such modeling approaches also require empirical data for calibration and validation. Methodologically, it will be important to apply the framework to other types of data sources besides media reports in order to develop better understandings about data completeness, validity, and reliability. Another area which requires further research is the development of a robust empirical basis that incorporates experiences across a range of event and community types. Commonalties and differences in IFI occurrence across types of natural, technological and willful disasters should be explored; for example, to identify those IFIs that occur in many types of events and would be promising targets of mitigation from a multi-hazard perspective. Further, while this study focuses on IFIs deriving from electric power failure, the framework can be readily extended to assess other types of infrastructure interdependencies and for setting priorities about potential ways to mitigate the likelihood and consequences of their interdependent failures.

Acknowledgements This research was supported by the U.S. National Science Foundation under grant number CMS-0332002. An earlier version of this paper was presented at the 1st Canadian Risk and Hazards Network Symposium in November 2004.

Appendix

Table 3 Database of infrastructure failure interdependencies in the 1998 Ice Storm (selected variables)

Impacted system	No.	Specific system	Description	Extent index	Impact index
Building support	1	HVAC (heat, vent., air conditioning)	37 elderly women evacuated from their seniors' residence in downtown Montreal	1	4
Building support	2	HVAC	55 elderly or infirm people who had no power or heat refused to leave their homes	1	4
Building support	3	Security	Thieves hit several homes knowing alarm system is down	1	4
Building support	4	HVAC	Emergency generator provided light but no heat for 70 residents, many bedridden	1	6
Building support	5	Garage door	People unable to use vehicles b/c they are unable to open electric garage doors	2	2
Building support	6	HVAC	Provisions for looking after pets were inadequate	2	2
Building support	7	Plumbing	Plumbers extremely busy in responding to calls from people who want to have their pipes drained	2	2
Building support	8	Plumbing	If power returns and water heater tank is empty, it could end up burning out the internal heater in the tank	2	4
Building support	9	HVAC	More than 100 reported cases of carbon monoxide poisoning	2	6
Building support	10	HVAC	Some houses caught fire due to continually burning wood in fireplaces	2	9
Building support	11	HVAC	Four die of hypothermia	2	9
Building support	12	HVAC	Five people die in fires from makeshift heating	2	9
Building support	13	HVAC	Six die of carbon monoxide poisoning from fumes gas and oil heaters	2	9
Building support	14	HVAC	Carbon monoxide buildup leaves more than 200 residents homeless	3	6
Building support	15	Plumbing	People experienced flooding after sump pumps were rendered inoperable by power outages	4	4
Business	1	Other	A power outage at the Mont Royal Crematorium meant bodies could not be incinerated for several days	1	2
Business	2	Retail	Two businesses were looted overnight	1	4

Table 3 continued

Impacted system	No.	Specific system	Description	Extent index	Impact index
Business	3	Retail	Direct debit systems were not always operational and some stores began to accept I.O.U.'s	2	2
Business	4	Retail	Line ups of an hour for firewood and kerosene	2	2
Business	5	Restaurants	Restaurants powered by generators begin to run out of food	2	4
Business	6	All	People laid off as businesses closed	2	6
Business	7	Retail	Most stores have exhausted their supply of bottled water	2	6
Business	8	Insurance	Bursts pipes are expected to be the third most expensive item for insurers	3	4
Business	9	Insurance	The second-highest cost for insurers will be to replace food that has gone bad	4	4
Business	10	Retail	Crowded stores of people in search of candles, batteries, fireplace logs and emergency supplies	4	4
Business	11	Hotels	Hotels and motels booked solid by people looking for shelter	4	6
Business	12	Retail	Many businesses take advantage of situation and charge extra on high demand items	6	4
Business	13	All	Hydro-Quebec officials called on shops, businesses and industry to shut down	6	6
Business	14	Retail	In short supply were batteries, flashlights, candles, kerosene, naphtha, lamp oil, wicks, propane, firewood, drinking water	6	6
Business	15	All	Major employers south of Montreal say they all be shut down for up to 2 weeks	6	9
Education	1	Daycare	Daycare with no heat and lack of food	1	4
Education	2	Schools	Virtually every school board in and around Montreal canceled classes for up to a week	6	2
Emergency services	1	Shelters	A person had to be moved from shelter to a hospital, suffering an anxiety attack	1	2
Emergency services	2	Police	Police report an apparent surge in the number of cases of domestic violence	1	4
Emergency services	3	Police	Due to vandalism and a break-in, the town of Hudson imposed an 8 p.m. curfew on youth	1	4

Table 3 continued

Impacted system	No.	Specific system	Description	Extent index	Impact index
Emergency services	4	Shelters	Frayed nerves and overcrowding are taking a growing toll on more than 2,000 ice-storm refugees	1	4
Emergency services	5	Police	Local police station without power	1	6
Emergency services	6	911	Exceptionally high call volume for 911, partly due to weather	2	2
Emergency services	7	All	RDI news reports that all of Montreal will be blacked out, creates panic as emergency lines become flooded	2	2
Emergency services	8	Police	Three times as many police on duty, many of them patrolling the streets (looting)	2	2
Emergency services	9	Police	Police in Montreal begin exercising powers to force people they deem to be at a health risk to leave their frigid homes	2	2
Emergency services	10	Fire	Firefighters busy pumping water out of basements where sump pumps stopped	2	4
Emergency services	11	Shelters	Shelters at Claude Robillard sports center and the Little Burgundy sports complex forced to close due to losing power	2	4
Emergency services	12	All	Without computers, it was impossible to access vital information including phone numbers and addresses of emergency responders and vulnerable people, civic address lists, maps, and prescription information	2	6
Emergency services	13	All	Many people refuse to leave homes, raising concerns over food, water, and medication safety	2	6
Emergency services	14	Fire	Several fires leave many homeless, caused by improper heating and power surges	2	6
Emergency services	15	Fire	Three "suspicious fires" were reported at a rooming house, a restaurant and an old factory	2	9
Emergency services	16	Fire	Several fires take lives caused by improper heating and power surges	2	9
Emergency services	17	All	Some back-up power systems did not work due to improper maintenance or needed winter fuel	4	6

Table 3 continued

Impacted system	No.	Specific system	Description	Extent index	Impact index
Emergency services	18	Fire	As a result of fire, water pressure becomes a concern for firefighters	4	6
Emergency services	19	Shelters	Many of the 200 shelters across Quebec running out of supplies	4	6
Emergency services	20	Shelters	Six of Montreal's shelters are filled to capacity	4	6
Emergency services	21	Shelters	Tens of thousands of people forced into emergency shelters	4	6
Emergency services	22	All	Communication was the most time consuming problem, the weakest link	6	6
Finance	1	ATM	Several bank machines out of service, no backup power	4	2
Finance	2	Banks	Many banks and credit unions closed due to lack of power	4	2
Finance	3	Credit cards	Credit cards not accepted everywhere	4	2
Food supply	1	Production	Farmers worked furiously to protect livestock	1	6
Food supply	2	Production	Automatic feeders on dairy farms sitting dormant	2	4
Food supply	3	Storage	92,000 bushels of apples in danger of rotting if generator does not work well enough to get air circulating	2	4
Food supply	4	Production	Thousands of chickens die from suffocation	2	6
Food supply	5	Production	Getting water for dairy herd is a challenge with electric pumps not working	2	6
Food supply	6	Storage	13.5 million liters of milk dumped	3	6
Food supply	7	Production	Cows can suffer severe infections and their supply will eventually dry up if not milked	3	9
Food supply	8	Storage	Food stores without backup generators can only watch perishables wilt, rot or sour	4	4
Government	1	Services	Most museums, art galleries and many libraries in the city closed indefinitely	2	2
Government	2	Services	Montreal's municipal court will be closed, but employees are expected to show up for work	2	4
Government	3	Offices	Most governmental offices closed	6	2
Government	4	Services	Canada Post notified employees not to report to work, to help restoration of electricity by closing high-tech sorting stations	6	2

Table 3 continued

Impacted system	No.	Specific system	Description	Extent index	Impact index
Government	5	Services	Canada Post offices on Montreal Island and the South Shore were closed	6	2
Health care	1	Hospitals	Medication distributed by staff hiking the stairs between the hospital's six floors	1	2
Health care	2	Public health	In residence for handicapped adults, fireplace overheated and starts fire, kills one, three taken to hospital	1	9
Health care	3	Hospitals	Patients staying longer to avoid returning to blacked-out homes, tying up beds needed for new patients	2	4
Health care	4	Hospitals	Hospitals affected by an influx of influenza cases from crowded shelters	2	4
Health care	5	Public health	American Red Cross issues urgent call for blood donations	2	4
Health care	6	Public health	Due to crowding in shelters a rash of influenza cases occur	2	4
Health care	7	Hospitals	Jewish G.H. calls for volunteer nurses, the Montreal G.H. and Royal Victoria H. looking for help from volunteers with no hospital or medical experience	2	6
Health care	8	Public health	Elderly tenants were without power for their oxygen tanks and other medical equipment (apartment buildings)	2	6
Health care	9	Public health	Many pharmacies closed and therefore unable to refill needed medication	3	4
Health care	10	Hospitals	Five health care centers forced to rely on emergency power	4	4
Telecommunications	1	Cable	Videotron service was interrupted, has battery backup, but the batteries last only 3–5 h	2	2
Telecommunications	2	Land line telephones	The theft of a Bell generator in the Lachute area deprived area residents of phone service for a week	2	6
Telecommunications	3	Media	Radio station could not find enough fuel to power the station's generators	6	2
Telecommunications	4	Media	The daily newspapers in cities were unable to publish yesterday	6	2
Telecommunications	5	All	Communication was the most time consuming problem, the weakest link	9	4
Telecommunications	6	Land line telephones	Telephone service to Bell Canada customers knocked out	9	4

Table 3 continued

Impacted system	No.	Specific system	Description	Extent index	Impact index
Transportation	1	Roads	A motorist with a flat tire unable to locate a station open to repair flat tire	1	2
Transportation	2	Taxi	Taxi-drivers scrambled to find gas stations so they could work throughout the night	2	2
Transportation	3	Roads	Traffic lights went off causing dozens of fender-benders	2	4
Transportation	4	Mass transit	The closure of some metro stations caused long lineups at bus stops	4	2
Transportation	5	Air	Dorval airport lost its principal power feed yesterday evening, Airport low on jet fuel	4	4
Transportation	6	Air	Flights canceled or delayed because of lineups of planes awaiting de-icing	4	4
Transportation	7	Mass transit	The Montreal South Shore Transit Corp. canceled 46 of its rush-hour bus routes	4	4
Transportation	9	Roads	Consumers had to drive for miles yesterday to find a gas station that had not been hit by power failures	4	4
Transportation	10	Roads	Road conditions were unknown due to no communication	4	4
Transportation	11	Bus	Limited buses service	4	4
Transportation	12	Gas stations	Most gas stations unable to pump fuel	6	4
Transportation	13	Air	Major airlines canceled 255 flights	6	4
Transportation	14	Rail	Rail lines were shut down b/c crossing signals, operating signals, and switches were no longer working	6	4
Transportation	15	Roads	Traffic lights out in blacked-out zones and reduced visibility	6	4
Utilities	1	Electricity	Ontario Hydro to pay $150 million in repairs due to ice storm	4	4
Utilities	2	Electricity	Hydro Quebec to pay $600 million in repairs due to ice storm	4	4
Utilities	3	Water	The Atwater and Desbaillets water plants, had 4–6 h worth of clean water left in reservoirs	6	2
Utilities	4	Water	As a result of fire, water pressure becomes a concern	6	4
Utilities	5	Oil	Fuel was a critical commodity because of no pumping power	6	6
Utilities	6	Oil	Montreal's two east-end oil refineries and two fuel terminals were knocked out	9	4

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