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Toward Disaster-Resilient Cities: Characterizing Resilience of Infrastructure Systems with Expert Judgments

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Resilient infrastructure systems are essential for cities to withstand and rapidly recover from natural and human-induced disasters, yet electric power, transportation, and other infrastructures are highly vulnerable and interdependent. New approaches for characterizing the resilience of sets of infrastructure systems are urgently needed, at community and regional scales. This article develops a practical approach for analysts to characterize a community's infrastructure vulnerability and resilience in disasters. It addresses key challenges of incomplete incentives, partial information, and few opportunities for learning. The approach is demonstrated for Metro Vancouver, Canada, in the context of earthquake and flood risk. The methodological approach is practical and focuses on potential disruptions to infrastructure services. In spirit, it resembles probability elicitation with multiple experts; however, it elicits disruption and recovery over time, rather than uncertainties regarding system function at a given point in time. It develops information on regional infrastructure risk and engages infrastructure organizations in the process. Information sharing, iteration, and learning among the participants provide the basis for more informed estimates of infrastructure system robustness and recovery that incorporate the potential for interdependent failures after an extreme event. Results demonstrate the vital importance of cross-sectoral communication to develop shared understanding of regional infrastructure disruption in disasters. For Vancouver, specific results indicate that in a hypothetical *M*7.3 earthquake, virtually all infrastructures would suffer severe disruption of service in the immediate aftermath, with many experiencing moderate disruption two weeks afterward. Electric power, land transportation, and telecommunications are identified as core infrastructure sectors.

KEY WORDS: Disasters; expert judgment; infrastructure; interdependencies; resilience

1. INTRODUCTION

Researchers and policymakers have called for concerted efforts to make cities and interconnected urban regions more "disaster-resilient."(1–5) Although definitions of resilience differ, they imply that resilient cities can absorb shocks (from extreme events, such as natural disasters) while still maintaining function (in terms of providing the basis for well-being of residents). Much of the current literature on urban disasters has emphasized land-use planning specifically, and hazard mitigation more broadly, for reducing disaster risk.(2,6–9) An emerging body of research addresses planning for postdisaster reconstruction and recovery, emphasizing the rebuilding of communities' social as well as physical fabrics,(5,10,11) yet the resilience of cities after a disaster is largely determined by the functioning of complex, interdependent infrastructure systems. Godschalk(3) suggests that for cities to be resilient, their roads, utilities, and other infrastructure systems

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must be designed to continue functioning under extreme hazard conditions; further, public and private sector organizations must be prepared, have up-to-date information, be connected by effective communication networks, and have experience in working together.

Infrastructure systems are highly vulnerable in disasters and their failures lead to widely felt losses. In the 1994 Northridge (Los Angeles) earthquake, for example, Gordon *et al.*[(12)] estimate that nearly one-quarter of business interruption losses could be attributed to failure of highway bridges. Infrastructure systems are also highly interdependent. Nojima and Kameda[(13)] document the range of infrastructure disruptions caused by electric power outages after the 1995 Kobe (Japan) earthquake. Similar interdependencies and associated societal disruptions have been observed in hurricanes, ice storms, blackouts, terrorism events, and other types of disasters.[(14–16)]

In broad terms, the tasks facing risk managers in efforts to foster urban resilience regarding infrastructure systems have at least two components: (i) characterizing vulnerabilities and resilience[1] within existing systems to disasters, and (ii) setting priorities for mitigation efforts to improve resilience.[2] Practical methods that can be applied in cities to address these issues are urgently needed. Yet these two tasks entail some unusual complexities: they must address multiple sources of disasters, multiple pathways for system failure, multiple and cascading interdependencies among a wide array of infrastructure systems, and many potential alternative measures to reduce failure risk within and across systems, in the context of ill-defined and multilayered governance structures. All these complexities must be addressed within existing governance and planning processes, in which many of the infrastructure systems are privately owned or operated, and security concerns make information sharing difficult. These tasks may not be familiar or easy ones for risk managers, but in our view hold the potential to overcome structural obstacles and help make infrastructure systems, and thus cities, more resilient to disasters.

The objective of this article is to develop and demonstrate a practical approach for risk managers working with infrastructure systems and communities to characterize vulnerability and resilience of infrastructure systems in disasters. We stress that this is an exploratory effort, based on two cases conducted sequentially. Our intent is not to provide generalized advice on what particular steps will make regions more resilient to infrastructure failures, since these prescriptions will be particular to and heterogeneous across regions. Rather, the intent is to explore and apply nonprobabilistic, judgment-based approaches for characterizing resilience of systems. This approach is informed by the writing on probability elicitation[(17–19)] but applied to dynamic processes. We also rely on elements of collaborative decision processes that provide a context for information sharing and learning[(20,21)] to help overcome intrinsic barriers that inhibit collective action to manage the interdependencies of infrastructure failures in disasters.

The approach is nonprobabilistic. Risk is sometimes defined as a triplet of conditions: what could go wrong, how likely it is to go wrong, and the consequences if it does go wrong;[(22)] here, we address two of these three questions. We rely on disaster scenarios to address what could go wrong in terms of an extreme event. We develop approaches that make use of historical experience with similar hazards in other contents, and the judgments of technical specialists to characterize what critical infrastructure services could be lost in a major disaster, to what extent, and for how long. We also investigate through interviews and workshop processes how disruptions in one infrastructure sector could cause ripple effects on other downstream sectors. We use these findings to characterize consensus views on effects on regional services and their broad consequences for regional residents. We neither attempt to characterize the likelihood of the initiating event (e.g., an earthquake of a given magnitude and location) nor are regional data available to characterize the probabilities of system failures, and then interdependent failures in other systems, conditional on that event. Rather, we rely on a nonprobabilistic judgmental characterization, informed by feedback and making use of the views of several specialists, to provide point estimates of resilience of systems, as a basis for subsequent planning and decision processes for mitigation.

[1] While vulnerability refers to the propensity for loss in the event of a hazard, resilience refers to the capability of withstanding and recovering quickly from such an event. These concepts could be considered at levels ranging from individuals to nations. Here we address urban resilience with a focus on sets of infrastructure systems.

[2] Other challenging tasks include (i) obtaining funding for long-term risk reduction, which competes with near-term operating and service priorities, and (ii) implementation in upgrading or siting new facilities. We do not address these topics here.

This article makes three contributions. First, we outline a set of challenges that lead to an ongoing "market failure" in terms of information availability and thus investment to address resilience of infrastructure systems at the community or regional level. These challenges motivate the need for communication among infrastructure system owners about the resilience of their individual systems in a given event, which will necessarily be based on judgments, given the lack of shared knowledge about the resilience of other systems. Second, we develop and apply an approach to expert elicitation of resilience in terms of two variables, service disruption and recovery over time. Although elicitation of probabilities from experts has been practiced for decades,[19,23] our iterative nonprobabilistic approach, focusing on disruption and recovery over time, is a new opportunity and approach for expert elicitation. Third, the work sets out a series of steps for iteratively characterizing, communicating, and updating the overall resilience of the set of infrastructure systems in a region in response to a scenario of an extreme event.

This article is structured in the following manner. Section 2 discusses four concepts that are crucial to this effort: a brief review of existing treatment of resilience and interdependency in sets of urban infrastructure systems; the obstacles to effective management of infrastructure interdependencies in extreme events; the importance of collaborative information sharing to help overcome these obstacles; and the role of expert judgments in such assessments. Section 3 discusses the methodological approach we developed to characterize infrastructure vulnerability and resilience, emphasizing infrastructure interdependencies. This approach has similarities to methods for eliciting probabilities (a well-known technique in decision analysis and risk analysis), but with some important differences. We apply this approach in two different cases in Vancouver, British Columbia. Section 4 summarizes the results and synthesizes over the two cases. Section 5 provides discussion and conclusions.

2. CONTEXT AND LITERATURE

2.1. Resilience Within Infrastructure Systems

Resilience of complex systems (the ability to absorb shocks while maintaining function) has emerged as a fundamental concern for systems managers and researchers[24] and for those affected by system failure, such as elected officials, agencies, private organizations, and civil society. Much of the interest in resilience has arisen in work regarding complex social-environmental systems, although concepts of resilience are also directly relevant for engineered systems,[25] including infrastructure systems within communities.[16,26,27]Because of the potential for large-scale infrastructure failure interactions and the spatial implications of infrastructure system failures, a community or regional perspective on infrastructure resilience would be highly useful. Yet much of the work on resilience in regional contexts either is theoretical, with a focus on the role of institutions,[28,29] modeling-oriented, often with a focus on specific subsystems,[30,31] or aimed at understanding resilience of economic entities and systems to infrastructure disruption, rather than the resilience of the infrastructure systems themselves.[31,32] There is a need for methods to characterize infrastructure resilience in applied, real-world contexts, based on the limited information at hand regarding performance in extreme events.

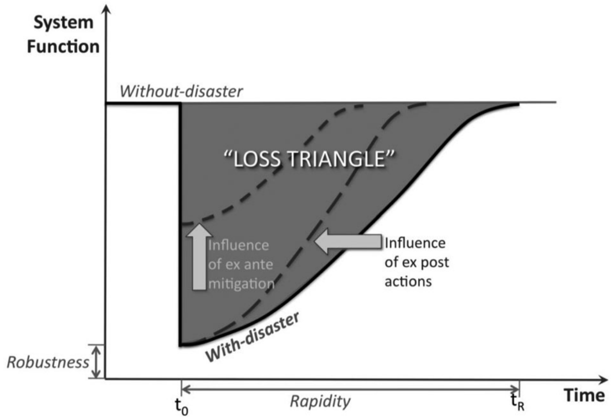

Fig. 1. Resilience concept.

Fig. 1, adapted from Bruneau *et al.*[26] and McDaniels *et al.*,[16] provides a schematic representation of the resilience concept in a particular infrastructure system in terms of system function (e.g., the number of customers served by a municipal water system) before and after an extreme event. At time t_0 shown on the graph, an extreme event such as an earthquake occurs. The degree to which system function is not forced to zero at that point represents the system robustness, or ability to withstand an extreme event of a given level and still maintain some degree of system function. Over time, system function recovers until at t_R it is fully restored. (Note that in some cases, the new system configuration may differ from the preevent configuration, as discussed in Holling.[(25)]) Increasing resilience, which is equivalent in the diagram to reducing the loss triangle, can be accomplished through *ex ante* measures such as installing backup generators for a hospital or *ex post* actions such as rerouting traffic.

Addressing infrastructure interdependencies is central to fostering infrastructure resilience. Yet the emerging literature on infrastructure interdependencies has been dominated by systems engineering approaches in which the goal is optimization, rather than resilience. These engineering studies have focused on the technical complexities of interdependent systems. Some have developed computer-based simulation models of infrastructure systems and their linkages.[(33,34)] Others have proposed model representations and analytical approaches to characterize interdependencies and identify key vulnerabilities, particularly from terrorism threats.[(35,36)] Linkages between infrastructure and social systems are rarely considered; where they are, these are limited to modeling how physical infrastructure loss would affect economic sectors.[(34,37)] Decision making is generally addressed indirectly, if at all, through mathematical optimization; for example, by identifying system links that would have the greatest consequences if damaged in an extreme event.

To foster infrastructure resilience, research is needed that links urban physical systems with human communities, that supports the information and communication needs of infrastructure organizations, and that directly addresses infrastructure decision making at the urban and regional scales.[3] A first step in such research is to develop methods to characterize how a given region may be vulnerable to the direct loss of infrastructure system services in a specific extreme event, and also vulnerable to infrastructure failure interdependencies (IFIs) that prolong and extend the loss of services. (IFIs occur when failure in one system leads to failures in other, dependent systems; e.g., when power outages lead to malfunction of pumps in water systems.[(16)] These methods should also characterize how much infrastructure systems can recover function to the extent possible within a given period of time (as in Fig. 1). In addition to this resilience information, a second need is to foster the capacity of infrastructure organizations to address risk. Berke and Campanella[(5)] suggest that fostering community resilience in general requires building networks among community groups, in part to relay information related to risk and risk reduction. They observe that where groups have no history in working together, intermediary groups may be useful to foster attention and agreement.

[3]Such studies on infrastructure interdependencies are rare. One example is work by McNally *et al.*[(38)] that develops a GIS-based information system to help infrastructure professionals learn about the behaviors of interdependent infrastructures. The approach incorporates visual representations, disruption scenarios, and expert knowledge.

2.2. Obstacles to Fostering Resilience

The obstacles to fostering infrastructure resilience are not trivial, particularly when interdependencies are acknowledged. Three challenges are particularly noteworthy. First, organizational interests are often at odds with regional interests. The objectives of infrastructure managers, insofar as disaster risk is concerned, include reducing physical damage to their own infrastructure system, minimizing investment and repair costs, minimizing revenue losses, and maintaining the organization's reputation. Private infrastructure providers are further accountable to their shareholders. Infrastructure providers have few incentives to be concerned with the effects of own-system disruptions on other, dependent infrastructures (referred to here as *downstream* effects). In the case of electric power blackouts, for example, the current legal standards and precedent are such that it is not the electric power utilities but rather the dependent service providers (e.g., building maintenance, in the case of lighting for emergency stairwells) that are liable for consequent losses (e.g., injury from stairwell falls in power outages).[(39)] Thus infrastructure providers have little incentive to understand the downstream effects of their system's outages and to consider them in decision making. Actions such as retrofitting infrastructure that may have large societal benefits, especially through reducing infrastructure failure interactions, may not be undertaken because they are not sufficiently cost effective or beneficial to the infrastructure organization itself.[(40)]

A second challenge pertains to security concerns and barriers to information sharing. Infrastructure organizations are well aware that their systems represent prime targets for acts of terrorism, and so may be reluctant to share information about system vulnerabilities. After the attack of September 11, 2001, public availability of information about critical infrastructure has become much more restricted.[(41,42)] This means that infrastructures that are vulnerable to disruptions in other systems (here referred to as *upstream* disruptions)—hospitals dependent upon electric power, for example—have difficulty gathering information about what to expect in future disasters as a basis for their preparedness planning. (This is an even greater problem for community groups than for downstream infrastructures.)

A third challenge derives from the observation that few infrastructure managers have direct experience with major disasters. For example, even in Los Angeles—a city with high seismic hazard—the last two major earthquakes took place in 1994 and 1971. Our case study region, Metro Vancouver, is in a moderate-to-high seismicity zone, but no major earthquakes have occurred in the region in living memory. The concept of adaptation and learning from experience is central to concepts of resilience.(3) The paucity of direct experience suggests the importance of learning from other regions' experiences of disaster.

To summarize, these three challenges (*partial incentives, limited and asymmetric information*, and *lack of experience*) create a form of market failure, in which it is difficult or impossible for individual infrastructure operators to understand their potential robustness to an extreme event and resilience within a set of regional infrastructure systems. As a result, there will be underinvestment in efforts to improve the resilience of individual systems, and thus the set of regional systems, compared to the level that would be socially optimal. An individual firm's business continuity planning cannot be expected to overcome these challenges because of the lack of knowledge about the performance of other systems, and the differences between private and social incentives regarding mitigation investments.

The approach we develop in this article addresses these three challenges through structured data gathering, elicitation of judgments, information sharing, and integrated analysis in a collaborative approach, as discussed later.

2.3. Planning for Infrastructure Resilience

The planning and risk management literatures have long emphasized the conceptual merits of collaborative approaches to decision making, often involving civil society groups, as well as technical specialists and agency staff.(20) Although many important benefits of collaborative planning involving citizens and technical specialists have been articulated,(43) the experience in practice has been mixed, although still encouraging, based on evaluations of citizen involvement in complex environmental and technology issues. One notable aspect of collaborative planning is the appropriate role of technical specialists who provide and share technical information regarding potential alternatives and their consequences to address a policy question.(44) The role of technical specialists with understanding of specific infrastructure systems is crucial when considering vulnerability and resilience of systems to natural disasters. In sum, we believe that collaborative approaches are crucial for overcoming the three challenges discussed to building resilience.

2.4. Reliance on Judgments

All risk analysis and risk management relies on judgments regarding both technical issues and preference issues, made either implicitly or explicitly.(45,46) One approach with wide recognition and application in decision and risk analysis is elicitation of probabilistic expert judgments, typically expressed as a cumulative density function over a well-defined quantity that is specified in time and space, made in response to a set of conditioning assumptions, within a predefined structure.(19,23,47)Many examples of probability elicitations have been published. The judgment tasks explored in this study employ the basic concepts and structure of probability elicitation, but with an important difference, which can be understood with reference to Fig. 1. In contrast to Fig. 1, probability elicitation employs a cumulative probability density function (cdf) to record and communicate expert judgments regarding uncertainty for a precisely defined variable, typically at one point in time (unless duration is the variable). If our focus were probability elicitation, then the structure of Fig. 1 would be quite different and would require multiple representations. A probabilistic version of Fig. 1 would show either the cdf for the system function at a point in time, or the cdf of duration to achieve a given level of recovery of system function, which could be measured in terms of percentage of service area or customer accounts served. In our approach, Fig. 1 is dynamic over time, but shows no uncertainty regarding the level of service at each point in time. Of course, the psychological nature of the judgment tasks is also different. In our view, the judgment tasks required to construct Fig. 1 are highly relevant for the issues of regional infrastructure resilience, and for understanding potential IFIs, because resilience (in terms of robustness and recovery time) is elicited directly. The kinds of information in Fig. 1 are particularly relevant given the purpose of the assessments is to broadly inform understanding of regional infrastructure resilience through considering the resilience of the individual infrastructure sectors.

3. METHODS

3.1. Overview

The sequential protocols for probability elicitation typically involve some version of the following steps:(19,47) *structuring, conditioning, motivating, eliciting, revising*, and *verifying.*[4] These steps all involve judgments by the elicitor regarding appropriate processes to follow, in order to achieve more manageable and consistent judgment tasks for the expert, in hopes of improving the quality of elicitation results. Because judgments about risk issues are subject to considerable influence from heuristics and biases,(48) the processes often make use of question structures to help overcome well-known biases.(19) The psychology of behavioral judgments regarding issues of resilience within complex systems is far less well defined or explored in research than for the uncertainties typically addressed with expert elicitation. However, one could expect that overconfidence by experts and a lack of alertness to a wide range of failure modes would be key concerns. The judgment tasks for resilience of a region are made even more complex because of heterogeneity in both the initial effects of an extreme event over space, and the rapidity with which recovery occurs over space and time.

Although these complexities are daunting, the purposes and uses of the analysis should help keep the complexities in perspective. We are not attempting to model the spatial patterns of specific system interdependencies and failure patterns in order to, say, estimate economic losses from a given extreme event. Rather, we seek to explore broad patterns of resilience over whole regions, with a particular emphasis on IFIs, in order to help inform *ex ante* understanding of regional resilience and ultimately point toward opportunities for low-cost, high-consequence mitigation opportunities.

Our approach for eliciting resilience judgments adopts a similar structure to probability elicitation protocols, with some important differences. We have four linked sequential phases: (1) *structuring and conditioning,* in which we develop and test ways to structure the expert judgments, develop specific detailed hazard scenarios, and conduct background research about similar hazard events; (2) *expert interviews,* in which we motivate the process with discussion of why this issue is important, and elicit their preliminary judgments on resilience of one specific infrastructure, operated by their organization; we also interview experts about potential interactions with other infrastructure systems; (3) *data synthesis*, in which we assemble the results of several interviews into a set of diagrams; and (4) *information sharing, feedback, and revisions,* in which the infrastructure system operators and the analysts meet together, to allow information sharing, and updating of the original estimates, based on learning about the vulnerability and resilience of other systems. These steps are summarized in Fig. 2 and discussed in more detail later.

We have conducted this whole process twice, once in 2008 addressing an earthquake scenario, and once in 2009 addressing a flood scenario, both in reference to the Metro Vancouver region of British Columbia. We refined the methods over the course of the two processes. In what follows, we present a synthesis of the methods as they have evolved.

3.2. Structuring and Conditioning

3.2.1. Scenario

One initial step is to develop a hypothetical but realistic hazard scenario that characterizes a significant threat to the region. In our two studies of 2008 and 2009, we employed one scenario in each year (one earthquake, one flood). Here we provide a brief overview of the earthquake scenario used in the 2008 work.[5] This earthquake scenario was used

[4]The approach of Cooke(23) has an additional step at the beginning of the process, which focuses on calibration (gauging judgment quality) as a basis for selecting experts to serve as the source of judgments. The approach is clearly relevant for repeated judgment contexts with rapid feedback (e.g., weather forecasting). In considering judgments for rare events, the approach relies on answers to almanac-like questions, to infer some general level of calibration. For this study, we worked with the best available experts, for each type of infrastructure system, selected by the infrastructure system operators. Hence, we had no direct basis for or need for addressing generalized calibration.

[5]In the ideal situation, it would be preferable to condition the judgment tasks on a range of different earthquake scenarios, to explore thresholds in consequences. The obvious tradeoff that arises in exploring more scenarios is the time and effort required from the experts to complete the elicitation tasks. The

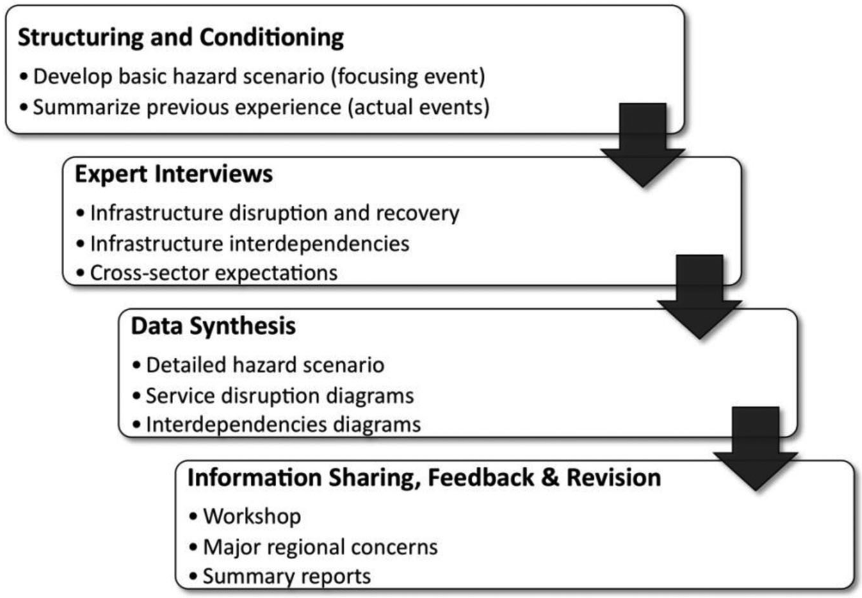

Fig. 2. Methodological approach.

in both the expert interviews and the workshop process to provide a realistic conditioning event for the judgment tasks and frame a consistent discussion for each of the infrastructure representative interviews. The specific scenario selected—an *M*7.3 shallow, crustal earthquake with epicenter near Vancouver in the Strait of Georgia—was one that the British Columbia provincial government had been developing for regional emergency planning purposes. An earthquake of this location and magnitude is realistic for the study area, although it does not represent a worst-case event. Working with the Provincial Emergency Program's seismologist, we developed a map of ground shaking intensity for the event and an associated one-page description of the event including limited damage predictions. Modified Mercalli Intensity (MMI) levels for the scenario earthquake range from VI to VIII in the majority of the study area (a region of 2.2 million people), indicating strong to severe shaking levels in specific locations depending on soil types.

3.2.2. Previous Experience

We conducted research regarding the infrastructure failures and interdependencies that have occurred in previous earthquake disasters. This review covered 10 critical infrastructure sectors as defined by Infrastructure Canada,[6] an agency of the federal government. The summaries focused on urban earthquakes that had occurred in industrialized countries with similar development patterns and infrastructure systems to those in Canada.[7] In addition to information on past earthquakes, we explored a database regarding infrastructure interdependencies in non-earthquake disasters that we developed for related research.[16,49] The hazard scenario and summaries of other disasters were provided to the experts before the interviews discussed later. These were intended to help expand their thinking about the range of infrastructure interactions, as well as inform them about the extent of loss of system function, and time to recovery, which have actually occurred in previous events comparable to the scenario. These efforts were intended to help overcome the lack of experience with earthquakes or other extreme events in the Vancouver region, and bring available information from elsewhere to the local experts.

individuals we interviewed are employees of infrastructure providers with no obligation or incentive to participate in this work, other than the opportunity to learn from the process.

[6] These included: energy and utilities, communications and information, finance, healthcare, food, water and wastewater, transportation, safety, government, and manufacturing.

[7] They included the *M*6.9 1995 Kobe, Japan, earthquake; the *M*6.7 1994 Northridge (Los Angeles) earthquake; the *M*6.9 1989 Loma Prieta (San Francisco Bay Area) earthquake; the *M*6.6 2004 Niigata Ken Chuetsu, Japan, earthquake; and the *M*6.8 2001 Nisqually (Seattle) earthquake.

3.3. Expert Interviews

Expert interviews are the primary means of data collection in this approach. Recruitment of experts was conducted on the basis of two principles: first, that the interviewees be the most knowledgeable persons in their organizations to provide the information requested; and second, that the experts collectively represent the entire cross-section of interdependent critical infrastructure sectors. Sectors represented in this study included: utilities (electric power, water, wastewater, natural gas); transportation (bridges and highways, public transit, airports, seaports); telecommunications; healthcare (regional health authorities, hospitals); and provincial, regional, and local governments.

Appropriate experts within each infrastructure organization were identified on the basis of their professional roles, as well as through recommendations from other infrastructure experts. Individuals selected for the interviews were organizational specialists on emergency response or infrastructure engineering and system performance, or both. Often, they were the only individuals within the organizations with the knowledge and experience to provide the expert judgments sought. Note that an expert interview approach is not based on ideas of a representative sample within a sampling frame. Rather, each expert provided the best available information about his/her own infrastructure system, often based on input from others in the organization. A total of 13 interviews involving 18 professionals were conducted in person, always with two individuals from our research team. With a single exception (a municipality), all organizations contacted for this study agreed to participate. Interviews typically lasted one to two hours and interview notes were sent back to all participants for verification.

The main objective of the interviews was to gather information on the resilience of the infrastructure systems in terms of their ability to withstand and rapidly recover from extreme events, and to characterize steps that can be taken to increase this ability. Our questions were intended to elicit judgments about how the particular system would function, in terms of service provision, at three time periods: just after an extreme event, three days later, and two weeks later (see also the interview script in the Appendix).[8] We also inquired into interdependencies among systems, in terms of other systems on which the given system depends for inputs and the extent to which other systems depend on the given system for outputs in order to function. We asked questions about that system's planning for extreme events, about the interviewees' sources of information and the degree to which they participate in multisectoral discussions about performance of interdependent systems in extreme events. We were particularly interested in ways to reduce regional vulnerability to interdependencies among infrastructures. All interviews began with a discussion of the hypothetical scenario and its associated map. In the 2009 interview process, we developed a table to more directly capture and summarize the resilience judgments. We also developed tables to elicit how one sector (e.g., electric power) is expected to perform by other sectors dependent on it (see interview script in the Appendix).

We are aware of the potential for overconfidence in such judgment tasks. We cautioned the experts about this potential problem in keeping with other such protocols,[(19)] and also informed them of the experience of infrastructure interdependencies in other similar events, noted earlier. We believe our iterative process, with subsequent meetings and feedback regarding the judgments of other experts, helped lessen the potential for overconfidence, compared to a one-time interview. The interview format was pretested with an informed colleague who is also an expert on one of the region's major infrastructure systems, and revised somewhat before implementation.

3.4. Data Synthesis

Information from the interviews was synthesized into two types of diagrams that initially documented the interview results and later served as the basis for cross-sectoral discussion and revision. The first, *service disruption diagrams*, provide a regional overview of expected system function loss and recovery over time for all the infrastructure sectors interviewed. These diagrams summarize information on robustness and recovery time that helps characterize system resilience as depicted conceptually in Fig. 1. In the initial version of these diagrams, information for each sector was provided by the informant for that sector; the final version incorporated revisions at the workshop. The second, *interdependency diagrams*

[8]We did not ask for information on the location of specific infrastructure facilities. This helped to overcome the infrastructure representatives' potential concerns regarding security and confidentiality of information.

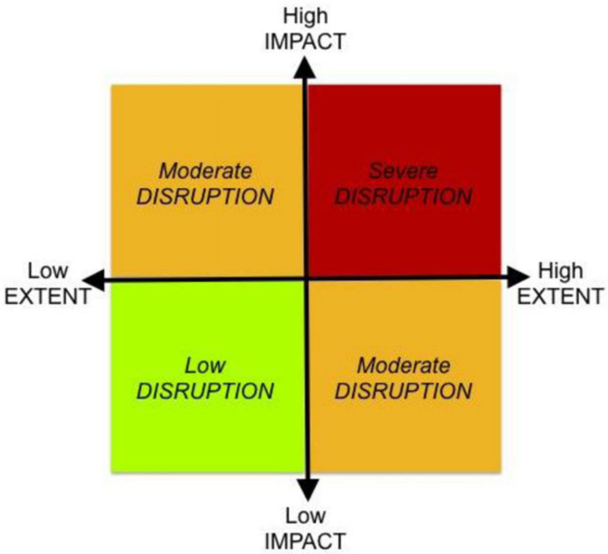

Fig. 3. Classification of service disruption levels.

(in the spirit of Rinaldi *et al.*[(50)]), captured the functional interdependencies among sectors and helped in visualizing how disruptions in one sector might affect other dependent infrastructures. These two types of diagrams are shown and discussed in Section 4 (Results).

This synthesis required a succinct scale to broadly characterize the societal impacts from the system function loss, which would be applicable for all sectors. We adapted a scale employed in Chang *et al.*,[(51)] as well as input from the infrastructure professionals, to develop the scale shown in Fig. 3. Overall service disruption is rated according to four levels: "no loss," "low disruption," "moderate disruption," and "severe disruption." Disruptions are rated by characterizing two dimensions—*spatial extent* and *severity of impact*—along a scale that ranges from "low" to "high." *Impact* considers the severity of consequences and the duration of the disruption. For example, complete loss of water supply indicates a high impact (independent of how many people are affected), whereas a boil-water advisory lasting a couple of days represents an inconvenience, or low impact. *Extent* considers the spatial reach of the disruption as well as the proportion of people within the area that are affected. A disruption that caused a single death, for example, would be considered to have high *Impact* but low *Extent*. Fig. 3 translates the measures of extent and impact into an overall rating of service disruption: infrastructure outages that have both high extent and high impact, for example, are considered "severe" disruptions.[9]

When providing their judgments about levels of their system's function over the whole region, at the time of the event and up to two weeks after that, the participants were told to condition their assessments on the state of their systems as they exist at present, the stated disaster scenario, and assumptions regarding the "rest of the world" outside of the affected areas as it exists at present. The experts were told to average the performance of their system over the whole region, recognizing some areas (e.g., those with more intense shaking) would be more severely affected, and some areas less affected. This conditioning of judgments on assumptions is crucial in expert elicitation.

3.5. Information Sharing, Feedback, and Revision

The final component of the approach involved a one-day invitational workshop, held in Vancouver, British Columbia. The 2008 event regarding the earthquake scenario involved 13 infrastructure representatives, including most of those who had been interviewed, as well as others who had been unable to participate in the interviews. The participants collectively represented a substantial proportion of major infrastructure organizations in the region. The purpose was to (1) provide all participants with an overview of the interview findings, (2) provide opportunities for feedback and revision, and (3) develop a consensus perspective on potential IFIs and system resilience based on the earthquake scenario.

The research team began with a review of the disaster scenario, and then summarized key interview

[9]Cox[(52)] has critiqued the use of categorical, qualitative risk matrices, with probability and consequence as two dimensions of the matrix, which at first glance might resemble Fig. 3. In fact, our approach differs from that of concern to Cox in several ways. It is conditioned on an earthquake or flood scenario. Given this event, we seek to characterize the consequences on society in two dimensions—the areal extent and severity of impact—with no consideration of probability. Although some of the criticisms raised by Cox may also be applicable to our approach (such as limited resolution), we do not believe the risk of technical errors is any greater than with any other possible approach, given the complete lack of other sources of information about resilience of systems after an extreme event. We recognize these broad categories do not provide details of impacts, but rather are intended for overall comparisons, in broad classifications, across many kinds of systems. Hence the potential uses of the information from this work offset to some degree the low precision of the results. The method also recognizes tradeoffs between insight, precision, and effort, given the information at hand.

findings using the service disruption and interdependency diagrams. Through discussion and workbook exercises, participants were asked to consider, revise, and augment the information captured by these diagrams. Section 4 provides a discussion of the revisions to the diagrams.

4. RESULTS

In what follows, we emphasize the results of our 2008 project regarding earthquake, with some observations from our 2009 work on floods added where noted. Overall, the 2008 interviews indicated that IFIs receive widely varying levels of attention in current preparedness and mitigation efforts. When asked about the organizations' sources of information about potential disruptions to *upstream* infrastructure sectors, 62% (8 of 13 interviews) mentioned industry associations, consulting studies, publications, and similar sources that may provide experience-based information from other disasters. Some 54% indicated cross-sector discussions with specific infrastructures in the region. Only 31% indicated drawing information from both experience-based sources and regional cross-sectoral discussion. When asked about specific cross-sectoral discussions in their planning processes, interviewees mentioned on average just two other sectors, most commonly federal, provincial, and/or local governments (54%) and electric power (50%). These discussions are largely bilateral. Only 46% mentioned regional emergency preparedness and/or regional infrastructure coordinating bodies. Moreover, interviewees were able to identify "upstream" infrastructure sectors (those on which they depend) with much greater confidence and specificity than "downstream" sectors (those that depend on them). Infrastructure organizations thus appear to be lacking a comprehensive view of how a disaster is likely to affect all the various interdependent infrastructure sectors.

4.1. Assessment of Service Disruption Levels

To help address this gap, we synthesized information from the interviews into an initial diagram of sectoral disruption levels and presented it to infrastructure providers at the workshop for review, revision, and feedback. We also discussed the experience in other similar events as a means of avoiding overconfidence in assessments. We sought information on the perspectives of other sectors regarding their views on a given sector's expected function. Participants had the opportunity to revise their own sector's service disruption rating after taking into account other sectors upon which they rely. A number of sectors chose to change their ratings and in many cases raised their expected disruption level, thus providing a more informed assessment of expected service-level disruptions. Fig. 4 represents the final diagram of service disruption levels after revisions were made by workshop participants in the 2008 workshop.[10] Participants commented that although the diagram was helpful in understanding what to expect from other infrastructure providers, there were concerns with the specific accuracy of aggregating across different agencies within sectors. Another concern was the aggregation across the spatial dimension, in that some areas of the Lower Mainland would face much more serious infrastructure disruptions while others may remain relatively undamaged. (In the interviews, however, they had been unable or unwilling to provide information on how service disruption might vary across the study region.)

Fig. 4 can be interpreted as a regional, multisectoral version of the conceptual resilience diagram (Fig. 1) for a potential earthquake event in the Metro Vancouver region. It shows that all sectors except government and natural gas are expected to experience *severe* service disruptions in the immediate aftermath of the specified earthquake scenario. Causes range from physical damage of hard infrastructure (such as roads, bridges, and power distribution systems) to overwhelmed telecommunication systems. After 72 hours, all infrastructure sectors expect to be experiencing *moderate* disruption. After two weeks, electric power, government, and the natural gas sectors expect to have recovered to *low* service disruptions. No infrastructure sector is expected to have completely returned to *no loss* service disruption levels at this stage. Interestingly, some infrastructure providers commented that after the initial time

[10]Note that after our 2009 workshop, discussion and revisions to the diagrams continued for over two months, based on evolving understanding of potential interactions. In the workshop, two significant failure modes for one major infrastructure sector were identified that had not been originally reflected in the first round of interviews. These failure modes had to do with the impacts of a dyke breach and the depth of flooding in our flood scenario. These two potential failure modes could adversely affect two of the most significant infrastructure sectors in the region, in ways that had not been considered previously. We then consulted existing engineering studies to clarify that these failure modes were indeed possible, and highly likely with floods over a given level, based on the dyke breach scenario used in our 2009 work.

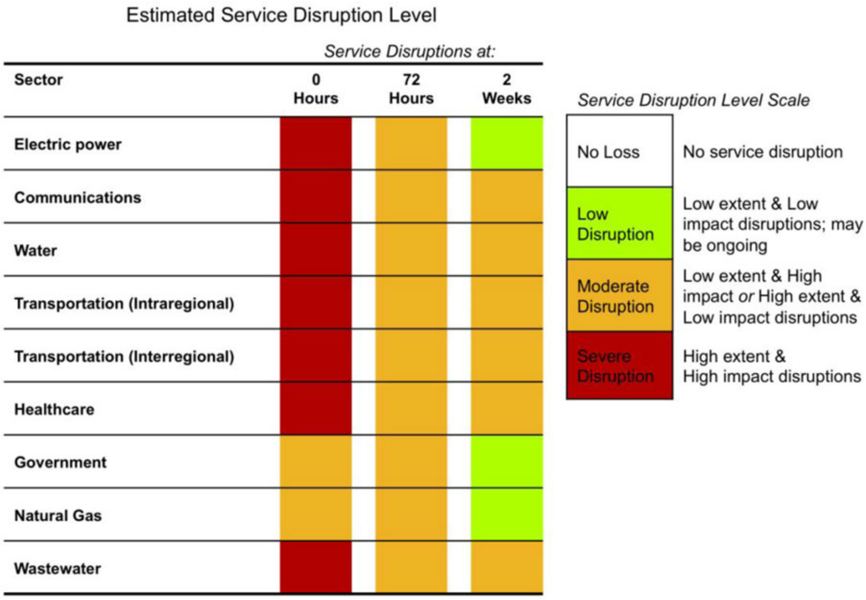

Fig. 4. Estimated service disruption levels, *M*7.3 earthquake scenario.

period, service levels might actually deteriorate due to the effects of service losses in upstream infrastructure systems and depletion of backup resources; however, they did not go so far as to revise the diagram to reflect this possibility.

4.2. Interdependency Diagrams

Diagrams were also developed to overlay the expected disruption levels in each sector with information on interdependencies between sectors. Fig. 5 provides a comprehensive overview of the upstream and downstream effects in the immediate aftermath of the earthquake. The dependencies are indicated by links or arrows that point in the direction of the downstream sector. Line widths of the links indicate the degree of functional dependency. Colors of the links and ovals refer to service disruption levels (e.g., red denotes "severe" service disruption and yellow signifies "moderate" disruption) consistent with the classification scheme in Figs. 3 and 4. Service disruption information, obtained from the interviews, accounts for upstream dependencies and backup systems that may already be in place. Fig. 5 reveals the status of upstream sectors, allowing each sector to revise its expectations of the likelihood of receiving materials or service from other sectors, and to plan and implement measures accordingly (e.g., acquire backups, stockpile resources, design redundancies). For example, one of the links indicates that the health-care sector is highly dependent on water, which in turn is expected to experience severe service disruption. This knowledge helps the health-care sector make decisions regarding alternative options, such as constructing wells onsite, to supplement potable water sources.

Fig. 5 indicates that some sectors are much more extensively linked than others. *Core* and *peripheral* sectors can be distinguished by the number of downstream dependencies, weighted by the strength of the dependencies. In this sense, the data indicate that electric power is the most connected infrastructure, followed by land transportation and telecommunications, in that order. These sectors can be considered the region's core infrastructures.

It is interesting to compare Fig. 5 for Metro Vancouver with the generalized interdependencies diagram from Rinaldi *et al.*,[50] which provided its conceptual framework. From a conceptual standpoint, Rinaldi *et al.*[50] suggest that electric power and telecommunications are interdependent with all other infrastructures, that transportation is interdependent with most others, and that natural gas is more peripheral. This study provides empirical confirmation for these suggestions in the case of Metro Vancouver. A key difference relates to water: both Rinaldi *et al.*[50] and experience in major disasters[13] indicate that most other infrastructures are dependent on water, yet this was not found in the Vancouver study. Further study is required to

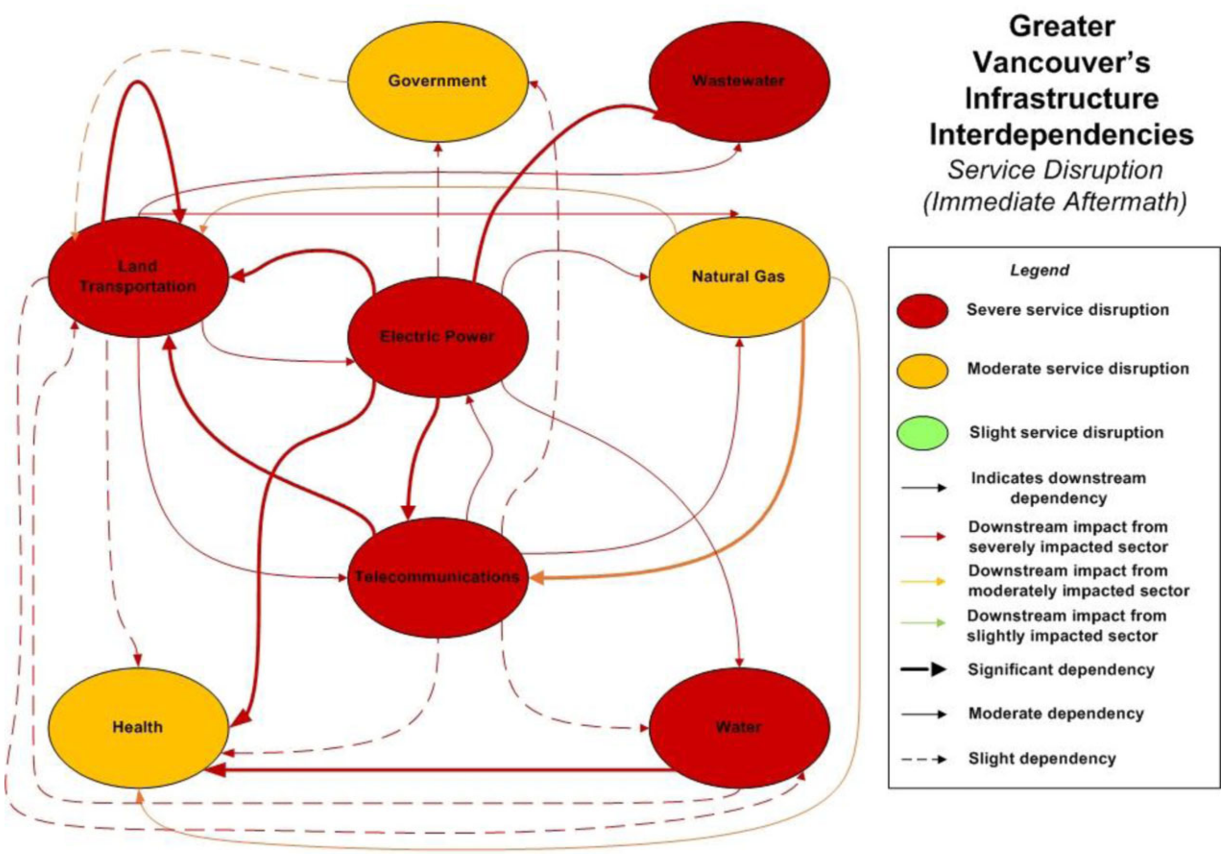

Fig. 5. Infrastructure interdependencies and service disruptions.
Note: Sea and air transportation have not been represented on this diagram due to less perceived interactions with the other sectors. The main downstream dependency for the Vancouver Port is to ensure online communication, while the airports have a significant dependency on ground transportation, and moderate dependencies on electric power, telecommunications, and water.

investigate whether this reflects an actual or simply a perceived lack of reliance on water.

4.3. Workshop Discussion

The study approach culminated in a workshop that provided a number of benefits for characterizing and addressing the region's infrastructure vulnerability and resilience. Participants gained a more comprehensive and complex understanding of infrastructure interdependencies and their potential outcomes in disasters. In several cases, participants revised judgments they had provided in the interviews after considering and discussing the expectations of service disruption in other infrastructure sectors. Typically, participants increased the degree of dependency on other upstream sectors once they realized the potential levels of service disruption. Discussion also revealed that upstream service losses would likely be exacerbated in the days and weeks following the disaster as a result of backup resources becoming depleted. Participants also became more aware of how sectors directly upstream were in turn dependent upon other sectors in a complex chain of interdependencies. The diagrams also precipitated discussion of facets they could not capture, including variation in impacts across urban space and specific facilities. Participants recognized additional interdependencies that they had not considered at the individual interviews; for example, the dependence of other infrastructures on the health-care sector for medical treatment for staff and their families. Finally, discussions allowed resolution of some discrepancies in expectations that had been revealed in the interviews. Telecommunications, for example, had assumed that electric power distribution would be devastated in a major earthquake, whereas the electric power sector in fact did not expect substantial system damage. The health-care sector expected that local roads would be damaged but largely usable in a seismic event. The land transportation sector, however, expected traffic to be unable to move in many areas. By opening the discussion on these types of discrepancies in expectations, the process allowed infrastructure providers to develop common understandings across sectors, as well as a sounder basis for making planning decisions.

4.4. Validation

In the realm of *quantitative* modeling, verification of data and validation of results are important norms. When attempting to model a complex phenomenon based on *expert judgments*, there are also norms for verification and validation, but they are naturally somewhat different. Earlier, we stressed that both quantitative and qualitative modeling rely heavily on judgments. The approach outlined here seeks to make those judgments more explicit and open to discussion and revision. Expert elicitation assumes only that (i) it is possible to characterize uncertainty as degrees of belief in specific judgments, which is a fundamental precept of Bayesian statistics, and (ii) the views of the best-informed experts available are a reasonable source of information, when structured and elicited appropriately.(19) These assumptions are minimal compared to those needed to make use of, say, quantitative input-output approaches to characterizing impacts of extreme events.(53,54) Hence, the requirements for validation are markedly different.

For obvious reasons, expert judgments regarding patterns of consequences from extreme events cannot be validated through experience until an event has occurred. Yet that does not mean these judgments are without content or value. The value of such judgments is in part a function of the decision context, or how the information is intended for use. For decades, decision analysts have made use of elicited judgments as a basis for comparing the performance of alternatives, using specific sets of beliefs (probabilities) and values (tradeoffs).(46) In other contexts, probability elicitation has been used almost as a form of traditional science consolidation and augmentation, to characterize outcomes (say, given future climate change scenarios) even if no direct mitigation or adaptation options exist.(55,56)

Given that one cannot validate these findings in terms of *outcomes*, it is nevertheless important to consider validation in terms of the *process* employed to obtain the judgments.[11] The process employed to elicit the judgments in this work, summarized in Fig. 2, has been informed by three sources. One is the writing on the design and practice of probability elicitation, noted earlier.(19,47) A second source is the writing on steps to improving judgmental forecasting.(58,59) A third is writing on the Delphi (i.e., consensus-based) approach to eliciting expert judgments.(60) From these sources, the approach in Fig. 2 was developed as our overall strategy. The method is iterative, as is the Delphi approach, but does not attempt to force any consensus.

One approach used in probability elicitation for validation of judgments is *convergence*, achieved by asking the same basic question in several different ways. Here we instead asked the questions *multiple times*, first in the interview process, and then subsequently in the workshop process after learning about the initial results and the views of others. A second approach in probability elicitation is to ensure that all terms are clearly defined and all participants have the same scenarios in mind when providing the judgments. We addressed these points through direct interview processes in which we could explain all terms and questions, and with a clearly defined earthquake scenario. A third precept of probability elicitation is to ensure all participants are familiar with key literature, and that they use all available information to inform the judgments. We distributed information before the interviews and workshop on the effects of five previous earthquakes in various urban areas around the world. Later, when we reconsidered the initial judgments in the workshop process, we made reference to these previous events once again to ensure the information was salient for the participants.

Some steps could be taken in the future to improve the validity of the judgments in subsequent applications of this work. One obvious step would be to elicit judgments from more experts.[12] One reason we did not adopt that approach here is

[11] This reasoning is in keeping with approaches to evaluating the quality of decisions based not on outcomes, but rather on the process, structure, and information base.(57)

[12] If multiple experts were employed in future studies, additional steps could be taken to evaluate and assess the quality of judgments for such a process. For example, in a previous study(56) we omitted some expert views because they were highly incomplete, and in one case indicated misunderstanding of the questions. One can create histograms of sets of judgments for a given variable, to serve as a basis for considering strategies for combining experts. Beyond these steps, one can draw insights by comparing the views of groups of experts (say with different backgrounds).(19)

because this work is deliberately *extensive* (all the major infrastructure systems in a region) rather than *intensive* (with several experts considering one system in a more constrained location). The argument in favor of interviewing multiple experts is simply that in contexts with extreme uncertainty, no one view about the future is likely to be accurate.[58] Yet, in almost every situation, including this one, obtaining more expert views is far easier said than done. We sought the views of infrastructure owners about whom they wanted to provide the judgments regarding the performance of their system in a specific earthquake scenario. The individuals they selected are those whom the organizations trust to provide this information. There are no alternative experts familiar with these specific systems.

A second way to validate the judgments provided here would be to compare these judgments to the actual experience with infrastructure systems in previous major earthquakes. Although that approach has appeal, it is of limited value here because we already provided data on actual impacts for five major earthquakes to the participants as part of the background preparation for the survey and workshop. Moreover, the vulnerability of infrastructure systems depends on local conditions (e.g., siting with respect to topographic, soil, and other geographic conditions; vintage of physical components; design and network configuration) and earthquake damage depends on event characteristics (e.g., epicentral location, depth, magnitude), so that detailed validation using experience data from other events and cities remains challenging.

Yet another perspective on validation can be discerned from the writing on confidence in expert judgment, which indicates that experts (like all people) tend to be overconfident in judgments, leading to too little recognition of the nature and likelihood of extreme events, and thus too narrow a representation of uncertainty.[48,61] In that vein, one should expect that the estimates in Fig. 4 for duration and disruption are more likely to be underestimates than overestimates. Beyond that, the challenges of judgments about dynamics of complex systems are formidable when the potential for threshold effects and emergent surprises are recognized. However, our focus here on failure interactions among systems is a step toward understanding and representing these thresholds, surprises, and complexities.

A final issue is that validation should reflect the purpose of doing the analysis. Here our purpose in this work is not to evaluate any single alternative or sets of alternatives to enhance regional resilience. There are literally tens of millions of alternatives that could be considered, which need to be analyzed at markedly different levels than in terms of the performance of all infrastructure systems in the region after a specific extreme event. Our purpose is not to provide the "right" estimates of the consequences of an earthquake like that in our scenario, since these cannot be verified before the fact. Our purpose is instead to develop and apply an approach that could tackle the informational market failure we outlined in the first section of this article. The intent is to help inform regional managers for individual systems, and managers for society as a whole, about the infrastructure interdependencies within the region, how they could be affected by an extreme event such as a major earthquake, and the potential consequences for society. Regional planners and infrastructure owners could greatly benefit from the information summarized in Figs. 4 and 5; we know of no other ways to obtain such information.

5. CONCLUSIONS

Understanding infrastructure vulnerability and resilience is essential to the planning and decision making that can enhance the disaster resilience of cities and their vital infrastructure systems. This research has provided a new, practical method for characterizing infrastructure resilience, emphasizing the critical but often overlooked factor of IFIs, and applied it to the Metro Vancouver study region. It has, moreover, demonstrated a process that we believe can be applied by other communities to characterize and address their infrastructure vulnerabilities.

The approach outlined here provides a means to help overcome the informational market failures of partial incentives, limited and asymmetric information, and lack of experience. To our knowledge, this is the first method available to characterize the resilience of a community or region to a given extreme event scenario, in terms of all its component infrastructure systems, reflecting the potential for interdependent failures in these systems. It builds on probabilistic elicitation approaches, but with several key differences, primarily the direct elicitation of resilience (robustness and recovery) rather than probability of a given outcome, within a series of steps that includes interaction among different infrastructure systems to provide learning and the potential for revised estimates. This represents an extension and elaboration of established elicitation methods, within a new application context of great importance for risk management efforts and for societies.

Findings indicated the need for greater information sharing among infrastructure organizations regarding the likely effects of a major disaster. Specific results for the case study pertain to the likely severity of infrastructure disruptions in an earthquake scenario, with severity defined in terms of the impact intensity and spatial extent of disruption. For the hypothetical *M*7.3 earthquake, severe infrastructure service disruptions can be expected in most infrastructure sectors in the immediate aftermath. Economic, social, and health-related impacts are likely to be severe immediately after the event, particularly in locations where ground shaking is expected to be most pronounced. Emergency restoration efforts are anticipated to reduce service disruptions to moderate levels within 72 hours, but full restoration would require more than two weeks. Results also indicate that government and natural gas are expected to be more resilient in such an event than other infrastructure sectors.

In addition to developing information on resilience, the overall approach also fosters the capacity of the infrastructure organizations to address risk. The workshop format allowed infrastructure managers to share information on vulnerability, resilience, and interdependencies in a structured and efficient manner in order to develop a community or regional perspective of infrastructure resilience beyond their own systems. As noted, participants also gained new understanding on IFIs that allowed them to revise their expectations of their own infrastructure system's resilience. Although this overall approach cannot substitute for detailed, long-term planning within infrastructure organizations, it can provide new knowledge and networks from a regional perspective that help motivate, inform, and support such planning.

A number of limitations should be noted regarding the methodology developed here. The approach developed one specific earthquake scenario (and in the subsequent year of the study, one flood scenario) in order to focus participants' attention on a common context. Consequently, variations in effects across other potential earthquakes and other types of hazards were not discussed. In addition, the approach emphasized regional-scale characterizations of infrastructure interdependencies and service provision. It does not delve into the technical, largely engineering specifics of these interdependencies. Further, in most cases, we interviewed only one representative of each organization; while the most knowledgeable expert, this person may not always have a complete understanding of the organization's activities.

It is also important to recognize how this work should be interpreted and employed. Like all applications of expert elicitation, the process outlined here is not meant to eliminate the need for quantitative analysis of major systemic failures in extreme events. We do not expect that experts engaged in such a process will be able to capture all the complexities, interdependencies, and related emergent behaviors of such critical infrastructures. Rather, the judgment-based analysis outlined here is a fundamental initial step in identifying vulnerabilities and critical interdependencies. It also provides structured information and knowledge needed to conduct further quantitative analyses. The work of Kroger[(62)] is helpful in showing what kinds of quantitative analysis could contribute to identifying robust alternatives. But as Kroger notes, the state-of-the-art of modeling interdependencies is still far from routinely operational. Hence it is important to tackle such assessments in a stepwise and integrated fashion. The analysis discussed here is an important first step in more in-depth analysis of critical infrastructure interdependencies in extreme events.

Overall, the study has developed and demonstrated a practical approach that can be readily applied by disaster managers to reduce risks associated with IFIs in their communities.[13] The problem of IFIs is challenging from both a technical standpoint and a planning perspective: there are disjunctures between infrastructures' private interests and the broader societal interests, barriers to information sharing, and few opportunities for learning from experience. To address these challenges, the approach developed here—consisting of a linked sequence of informational summaries, a regional disaster scenario, expert interviews, synthesis diagrams, and interactive workshops—emphasizes both developing information on regional risk and engaging the spectrum of infrastructure organizations in this process.

[13] We have documented outcomes of the research on the project website (www.chs.ubc.ca/dprc_koa/) in formats appropriate to practitioner audiences, including a searchable database and practitioner-oriented short reports.

Further research is needed to validate and refine the approach developed here. In particular, methods are needed that can efficiently and effectively elicit expert judgments regarding a range of potential hazard events that can cause a range of infrastructure disruptions and interdependencies. Experience from our 2009 flood application suggests that one promising approach may be to fully develop a single scenario and from there, to explore variations (e.g., in flood depth, duration, location, timing) that could trigger significant threshold effects. For example, a particular infrastructure may only fail if flood levels exceed a certain depth. Validation of expert elicitation for rare events is not possible with standard methods. On the other hand, validation may be possible in the future through expanded databases of the consequences of extreme events such as earthquakes for comparable regions, and expanded databases of IFI events, in order to compare elicited judgments to patterns in actual events. Calibration of the quality of judgments for a given expert may be possible in the future, if one adopts the assumption that calibration in one domain translates into calibration in other domains.[23]

Further research is also needed on developing, analyzing, and implementing alternatives to increase regional resilience to IFIs. The scope and number of alternatives is enormous, and the tasks of comparing and setting priorities among these alternatives merits substantial further research.[63,64]

Our experience in conducting this work also points to a major gap in governance for disaster management in terms of infrastructures. Although emergency response is a standard activity for governance contexts, and efforts are underway to help coordinate security measures for facilities in various locations, we know of no governance context that addresses issues of infrastructure interdependencies and their implications for regional resilience. Hence, there seems to be a role for new (formal or informal) governance efforts that involve coordination of efforts and information sharing as discussed in this article, and are also provided with mandates to reduce such risk. We hope this work spurs interest in developing such governance mechanisms.

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APPENDIX: INTERVIEW AND WORKSHOP MATERIALS

This appendix includes selected materials to help document the methods described in this study, specifically an interview script used in the flood interviews (i.e., a refinement of the interview script used in the earthquake study), including associated judgment elicitation tables.

INTERVIEW SCRIPT

Part 1: Introduction to Research and Scenarios

Please read over the attached scenario regarding a flood in the Chilliwack region and refer to the accompanying map. Please note that the infrastructure that is affected by this flood services the Greater Vancouver Regional District (GVRD). As such, we are most interested in the effects on Greater [Metro] Vancouver. The purpose of this scenario is to provide a specific focus for your thinking about your sector given a major system shock.

(1) Does your organization use a flood scenario for planning, and if so, how does it differ from this one?
(2) Do you have any concerns or comments about the scenario? Is there anything you would modify or add?

Part 2: Sector Impact

(3) Please use Table I to indicate how the flood scenario would affect your ability to provide services to consumers at various time points. Please consider only how the flood would affect your system (i.e., assume that other infrastructures do not suffer any damage or disruption). What is your rough estimate of the total duration of service loss? What do you expect to be the severity of service disruption?

Table I[14]

	Service Disruptions to Your System (Nature and Severity)		
Scenario	0 Hours	72 Hours	2 Weeks+
Flood	☐ *No loss* ☐ *Slight disruption* ☐*Moderate disruption* ☐ *Severe disruption* Description:	☐*No loss* ☐ *Slight disruption* ☐*Moderate disruption* ☐*Severe disruption* Description:	☐*No loss* ☐ *Slight disruption* ☐*Moderate disruption* ☐ *Severe disruption* Description:

Part 3: Upstream IFIs

(4) To what extent are you dependent on other infrastructures? Please consider your dependency in the postdisaster time frame. When answering, please consider your degree of reliance on these infrastructures, as well as your implemented flood-related mitigations to reduce this reliance. Please use Table II for your responses.

[14]The interviewer guidelines included additional prompts and clarifications for use when needed, including for Table I: "Explain the types of service disruptions to your sector for each of the three times. Please consider any measure of service loss that is appropriate to your system." Further, the service disruption levels were defined as follows: Slight = Disruptions with low spatial extent and low impact; Moderate = Disruptions with low spatial extent & high impact, OR high spatial extent & low impact; Severe = Disruptions with high spatial extent & high impact disruptions.

Table II[15]

	Extent of Dependence on Sector				
Sector	None	Slight	Moderate	Significant	Do not know
Power					
Communication					
Water					
Transportation					
Government					
Natural gas					
Wastewater					
Health system					
Other					

(5) How do you expect other infrastructures to be affected by the flood scenario? Please use Table III for your responses.

Table III

	Type of Disruption to Sector				
Sector	None	Slight	Moderate	Severe	Do not know
Power					
Communication					
Water					
Transportation					
Government					
Natural gas					
Wastewater					
Health system					
Other					

(6) With regards to potential upstream disruptions, are there any specific concerns you may have about certain sectors?
(7) Now considering how you expect these other infrastructures to be disrupted, how would the flood affect your system?

After participant has completed both tables:

(8) Now consider if the flood were smaller or larger than in the scenario. How would your answers change? What variables regarding your system are most affected by the severity of the flood?

[15]The interviewer guidelines defined dependence levels as: Slight = Minimal reliance on sector; Moderate = Large reliance on sector with significant backup available, or, moderate reliance on sector with no backup available; Significant = Large reliance on sector with limited backup available.

Wrap Up

(9) What information sources influence your views on these effects?
(10) Is there any important information that we failed to cover in our interview? Is there anything else that you would like to add?
(11) Are there any people within or not within your organization that you recommend that we talk to?
(12) Is there any information that you shared with us today that you would like us NOT to share with others at our upcoming workshop?
(13) Overall, how confident are you in your answers? Please fill out Table IV with a check mark for your level of confidence.

Table IV

	1 (Not at All Confident)	2	3 (Confident)	4	5 (Highly Confident)
Your system					
Upstream sectors					
Earthquake-related questions					
Flood-related questions					

Finally, we plan to send all participants a brief summary of their interview. We would welcome your comments on this report.

Thank you very much for your participation in this interview!

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